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Review

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Review

A Review of the Current Regulatory Framework for Supersonic Civil Aircraft: Noise and Emissions Regulations

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Abstract: The request for 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 of protection for citizens. The availability of novel propulsive technologies, together with the development of new civil supersonic passenger aircraft configurations and missions, is pushing international authorities to update the regulatory framework to limit nuisances on the ground and the contribution to climate change. Existing ICAO noise and emissions standards are outdated as they were developed in the 1970s and tailored to Concorde, the only SST that has ever operated in Western airspace. This article provides (i) a comprehensive review of current environmental regulations for SST, encompassing noise and pollutant emissions near airports (LTO cycle) as well as CO_2 emissions and sonic booms, and (ii) updated information about the ongoing rulemaking activities by ICAO, FAA and EASA. This review clearly highlights the following findings: (i) the need to revise current rules to better fit future SST design, operations and technologies; (ii) the need to introduce new regulations to cover additional aspects, including stratospheric water vapour emissions and ozone depletion; and (iii) the need to support regulatory activities with solid technical bases, fostering cooperation with academia, research centres and industry in R&D projects. Eventually, a practical example of how SST rulemaking activities are supported by the collaborative research H2020 MORE&LESS is reported.

Keywords: supersonic aircraft; regulation; standard; noise; sonic boom; emissions; climate impact; sustainability

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1. Introduction

Throughout its history, supersonic civil aviation has always represented a niche market compared to the impressive expansion of subsonic civil aviation since the beginning of the jet age in the 1950s. Only one civil supersonic transport (SST) aircraft type, the Concorde, has ever operated in Western airspace.

One of the main reasons for this was the extremely high fuel consumption of SSTs [1], which resulted in ticket prices typically 50% over a first-class ticket on a subsonic flight, but without the generous cabin space offered to first-class passengers on intercontinental subsonic flights [2]. Contrary to the subsonic aviation sector, which developed into a mass market since the advent of the Boeing 747 and saw a continuous decrease in ticket prices due to scale effects and continuous efforts in efficiency improvements [3], supersonic flight has always remained a luxury product accessible only to a very narrow class of travellers.

The other factor hampering the expansion of the supersonic flight market was the very high environmental impact of SST aircraft [4–6]. The noise and pollution of the Concorde were a multiple of large subsonic aircraft such as the Boeing 747, which made the acceptance of Concorde flights by airport neighbours more and more difficult.

An additional phenomenon not existing for subsonic flight is the sonic boom, generated along the whole trajectory flown at supersonic speed. Due to the strong nuisance generated by the sonic boom, supersonic flights have been forbidden over land in many countries of the world [7–9], with the result being that the SST could only benefit from supersonic speeds on trajectories over the sea, such as transatlantic or transpacific routes, whereas on routes with large portions over land, e.g., between Europe and parts of Asia, the SST offered only very little time gain or none at all [10], unless a not-too-long diversion route over the sea is possible [11].

The introduction of Concorde (the first flight was in 1969, with commercial entry into service in 1976) coincided with the increasing awareness of the environmental impact of aviation and the development of the first-ever noise regulations for subsonic aircraft (ICAO Annex 16, Vol. I, Chapter 2) [12], which was adopted in 1971. A requirement for SSTs (Chapter 12) was added in 1981, but it only consisted of the obligation to not exceed the noise levels of the first certified Concorde [13,14]. As no new SST types were built after that date, the regulation was of no relevance for new developments.

The situation changed in the 2010s when new SST developments appeared. Remarkably, these occurred first in the business jet category [15], which is well adapted to the limited market of very busy and/or wealthy customers for whom the time saved by supersonic travel has the highest value, and also in the small commercial jet category (50–100 passengers). Due to their mere size, the absolute levels of sonic boom, as well as of landing and take-off (LTO) noise and emissions, are expected to be lower for these SST aircraft than for the larger Concorde-sized ones [16]. Low-boom design and other environmental improvements have developed in the meantime and are also considered feasible for passenger aircraft today. The revival of high-speed civil flights has triggered intense research activities, and it is confirmed by recent market studies [17,18] that highlight how customers of commercial and private jet services, as well as cargo shippers, are willing to pay for more expensive tickets to arrive sooner.

The request for faster and greener civil aviation is urging the worldwide scientific community and aerospace industry to develop a new generation of supersonic aircraft that can be environmentally sustainable and guarantee a high level of protection for citizens. The availability of novel propulsive technologies, together with the development of new civil supersonic passenger aircraft configurations and missions, is pushing international authorities to update the regulatory framework to limit nuisances on the ground and the contribution to climate change.

The Committee for Aviation Environmental Protection of the International Civil Aviation Organization (ICAO-CAEP) [19] has taken up the challenge of investigating the noise and emissions characteristics of modern SSTs in view of reviewing and updating existing ones as well as developing future certification standards. Both CAEP's Working Groups WG1 (noise) and WG3 (emissions) have been including tasks on SSTs in their work programme since the CAEP/10 cycle (2013–16) and have been working intensely on the topic since the CAEP/11 cycle (2016–19) [20,21]. For the CAEP/12 meeting in February 2022, a collaborative exploratory study [22,23] was carried out on noise and emissions and the possibilities to reduce them. In the current CAEP/13 cycle (2022–25), the work in WG1 on supersonic aircraft LTO noise and sonic boom and en-route noise and in WG3 on LTO and climate-relevant emissions is continuing with the target of creating a set of certification standards suitable to maintain the environmental impact of future supersonic aircraft within acceptable limits. Details will be provided in Sections 4–6 below.

In this context, this article provides (i) a comprehensive review of current and potential future environmental regulations for SST, encompassing noise and pollutant emissions near airports (LTO cycle) as well as CO_2 emissions and sonic boom, and (ii) updated information about the ongoing rulemaking activities by ICAO, FAA and EASA. Due to the confidentiality of the ongoing negotiations between rulemaking authorities, it is not possible to reveal details on the expected outcomes of the regulation to come nor on many of the ongoing studies accompanying the rulemaking process prior to their publication. However, in each section of this paper, the authors highlight the main topics of discussion at the international level.

The review clearly highlights the following findings: (i) the need to revise current rules to better fit future SST design, operations and technologies; (ii) the need to introduce new regulations to cover additional aspects, including stratospheric water vapour emissions and ozone depletion; and (iii) the need to support regulatory activities with solid technical bases, fostering cooperation with academia, research centres and industry in R&D projects.

A practical example of how institutions believe that SST rulemaking activities shall be supported by collaborative research is provided by the Horizon 2020 call LC-MG-1-15-2020, "Towards global environmental regulation of supersonic aviation" [24].

The H2020 MORE&LESS project [25], funded under this call, addresses the challenge of contributing to help Europe, together with the international community, and shapes high environmental standards in line with ICAO Assembly Resolution A39-1 [26] by a thorough and holistic analysis of the environmental impact of supersonic aviation through basic and advanced research and experimental activities. In particular, the main efforts are devoted to noise and pollutant emissions modelling, validated thanks to dedicated test campaigns, as well as to the development of environmental impact models for noise and atmospheric composition changes, including air quality, ozone layer and climate. Furthermore, in line with the emerging issues on supersonic aviation, MORE&LESS provides the scientific community with an integrated multidisciplinary framework consisting of validated and accepted tools to holistically assess the environmental impact of supersonic aeroplanes on the future global air transport system [27].

A comprehensive review of the past and current regulatory situation covering all aspects of the environmental impact of supersonic aviation is important, both to guide regulators in identifying needs for new rulemaking and to define research supporting the rulemaking process. As no real evolution in environmental regulation has happened for supersonic aviation since the early times of Concorde, the historic aspect is of particular importance. To our knowledge, no such study integrating all environmental aspects in a single paper has been undertaken so far, though a number of reviews exist for specific environmental aspects. In the EC-5th Framework Research Programme, the NEPAIR project, which ran from 2000 to 2003, produced a historic overview of the evolution of emissions standards at the ICAO and national level, including supersonic flight [28]. Much of the historical material in Section 2 of this paper is adapted from information presented in NEPAIR. Matthes et al. described the evolution of scientific research in view of future ozone regulations [29]. Similarly, a review by Henderson and Huff [30] provides an overview of jet noise research at NASA in conjunction with the evolution of noise regulation, including for supersonic aircraft. Recent activities initiating rulemaking processes in ICAO, the EU and the US have brought so much new momentum into the topic that a comprehensive new study reviewing the current regulatory framework was felt to be highly useful.

2. Environmental Sustainability: A Historical Perspective

2.1. Emissions and Noise Standards

By the mid-1960s, the rapid growth in demand for civil aviation, coupled with the introduction of commercial jet aircraft, led to higher noise levels, worsening air quality at airports and very obvious black smoke trails [31]. At that time, the growing public awareness led to a demand for stronger action. The international nature of commercial aviation and the impracticability of individual aircraft visiting different states and regions each day and having to meet differing sets of requirements were recognised as issues at an early stage.

In 1968, the International Civil Aviation Organization (ICAO)—a specialised agency of the United Nations organisation—had already begun to establish internationally accepted standards to control aircraft noise, publishing them as ICAO Annex 16 in 1971, applicable to subsonic aircraft [32]. The first hint for the application to SSTs was added in 1981 as Chapter 12 of Annex 16, but with the only requirement being that the noise of individual aircraft of types with an existing type certificate (i.e., Concorde) should not exceed that of the first certificated aircraft of that type. It was explicitly noted that no noise certification limits for new SST-type certifications had been developed. Noise “regulation” of commercial supersonic aircraft was subsequently enacted on a state basis using a range of operational procedures [7–9]. For details, see Section 6.

Following initial work by the newly established US Environmental Protection Agency (EPA), ICAO then took up the emissions task, initially through a small Aircraft Engine Emissions Study Group (AEESG) from 1973–77 and then through a more broadly based Committee on Aircraft Engine Emissions (CAEE) from 1978–80 [28,33]. It gave priority to turbojet and turbofan engines for commercial subsonic and supersonic aviation.

The outcome of this intense effort was an internationally agreed certification test and measurement procedure, with limits (standards) for emissions of carbon monoxide, unburnt hydrocarbons, nitrogen oxides (NOx) and smoke. These standards apply to subsonic and supersonic aircraft turbojet and turbofan engines for a reference LTO cycle in the vicinity of airports. This material was published in 1981 as ICAO Annex 16, Volume II [34].

Since then, the development of both noise and emissions standards has continued under the ICAO Committee on Aviation Environmental Protection (CAEP) with the addition of an engine emissions standard for non-volatile particulate matter (nvPM) (2017) [35], which substantially replaces the smoke standard, and an aeroplane CO_2 emissions standard (2017) [36] to begin to address the growing concern over the climate impact of commercial aviation. The aeroplane CO_2 emissions standard currently only applies to subsonic aeroplanes, while similarly, the nvPM emission standard applies to the engines of subsonic aircraft.

It is worth noting that, procedurally, ICAO standards and recommended practices (SARPs), to become valid, need to be enacted by direct regulation in individual States or regions, the vast majority of times practically identically to the ICAO recommendation [37]. The ICAO needs to be notified of any differences made to the SARPs in any national regulations, indicating, at least, the expectation that standards will also be implemented.

2.2. *Early Work on Supersonics and Climate Impacts*

From a purely supersonic aircraft point of view, it is worth recognising the context in which the emissions regulations were originally developed.

Most of the aircraft air pollution concerns had been with air quality in the vicinity of airports. However, the development of commercial supersonic aircraft during the 1960s raised other issues, primarily of stratospheric ozone depletion by NOx and sulphur compounds by a fleet of supersonic transport aircraft [38,39]. These developments in scientific understanding took place alongside the technical development programmes for SST aircraft in Europe and the USA.

Considerable debate raged over the potential ozone (O_3) impacts from water and NOx emitted by such aircraft, ultimately concluding that there was a concern over the potentially significant O_3 depletion by SSTs [38,40].

Although the US SST program was cancelled in 1971, the prospect of a substantial fleet of other SSTs (Concorde, Tu144) was a key factor in the setting up of three major research and assessment programmes [41] in the US [40], UK [42] and France [43] that ran between 1971 and 1975 and an independent review by the US National Academy of Sciences. Broadly, the conclusions of all of these agreed that large-scale stratospheric emissions of NOx lead to reductions in stratospheric O_3 that might be judged as unacceptable. As a consequence, the production of tropospheric O_3 by the addition of NOx from aircraft became an issue. With the growing perspective that there was little likelihood of a substantial fleet of SSTs, the issue of stratospheric O_3 depletion receded. However, in the US, research continued under the FAA High Altitude Pollution Program (HAPP) [44], which undertook a comprehensive comparison of the findings of the US Climatic Impact Assessment Program (CIAP) [40], the UK Committee on Meteorological Effects of Stratospheric Aircraft (COMESA) [42], the US National Academy of Science (NAS) [45] and a new NASA initiative, the Upper Atmosphere Research Program (UARP), not specifically aimed at SST impacts. Since then, UARP has contributed substantially towards a better understanding of stratospheric processes and chemistry [46,47]. However, at that time, concerns about the atmospheric impact of SST operations were largely alleviated when it became clear that only very few commercial supersonic aircraft were going to be produced (two prototypes, two pre-production and 16 production standard Anglo-French Concorde aircraft, with a similar number of USSR Tu144 aircraft) [48]. In the 1970s, the EPA [49] and ICAO took the findings of the then-available research programmes into account in developing their regulatory material, but neither organisation attempted to do more than develop an LTO cycle and local emissions standards for SST engines [34].

In the late 1980s, there was renewed interest in global atmospheric processes, both from the US in support of a possible new high-speed civil transport (HSCT) and from Europe responding to concerns over the tropospheric impacts of the emissions from the growing subsonic fleet.

In the US, NASA initiated a new High-Speed Research Program [50] aimed at underpinning a new generation of high-flying SST aircraft. This incorporated, amongst other elements, a substantial effort to address atmospheric impacts, the Atmospheric Effects of Stratospheric Aircraft (AESA) [51]. In late 1993, NASA added the Subsonic Assessment Element (SASS) [52] under a revised umbrella of the Atmospheric Effects of Aviation Program (AEAP) [53].

In Europe, the European Commission (EC) launched the research programme AERONOX (the impact of NOx emissions from aircraft upon the atmosphere at flight altitudes of 8–15 km, 1992–95) [54], which was aimed at understanding the impact of subsonic aircraft NOx emissions at cruise altitudes. This triggered a number of other EC research programmes in the mid-1990s, e.g., POLINAT (Pollution From Aircraft Emissions in the North Atlantic Flight Corridor) [55], AEROTRACE (measurement of trace species in the exhaust of aero engines) [56], CHEMICON (chemistry and microphysics of Contrail formation) [57] and AEROCHEM (modelling of the impact on ozone and other chemical compounds in the atmosphere from aeroplane emissions) [58], some of which, e.g., POLINAT, involved collaboration with US programmes and were focused on subsonic aviation. Supersonic EC projects with industry cooperation were carried out with Airbus (SCENIC, scenario of aircraft emissions and impact studies on chemistry and climate [59]) and Dassault, Alenia Aeronautica, Sukhoi Civil Aviation (HISAC, environmentally friendly high-speed aircraft [60]).

A number of substantial reviews of the impacts of aviation on the global atmosphere were undertaken, culminating in the Intergovernmental Panel on Climate Change Assessment—Aviation and the Global Atmosphere [61], the seminal work on this topic. Within the currently executed EU project SENECA ((LTO) noise and emissions of supersonic aircraft), a review of the work on atmospheric impacts from supersonic aviation has been performed [29] that also includes the American projects funded by the Aviation Sustainability Center (ASCENT) [62].

3. Current CAEP Emissions and Noise Regulatory Practice

3.1. Principles

This section describes the principles of current regulatory practice for emissions and noise standards in general terms.

The Committee on Aviation Environmental Protection (CAEP) [19] is a technical committee of the ICAO Council established in 1983. CAEP assists the council in formulating new policies and adopting new standards and recommended practices (SARPs) related to aircraft noise and emissions and, more generally, to aviation's environmental impact. CAEP undertakes specific studies, as requested by the council. Its scope of activities encompasses noise, local air quality (LAQ) and the basket of measures for reducing international aviation CO_2 emissions, including aircraft technology, operational improvement, sustainable aviation fuels and market-based measures (CORSIA [63]). CAEP informs the council's and assembly's decision making with the ICAO Global Environmental Trends, which assesses the present and future impact of aircraft noise and aircraft engine emissions. The Global Environmental Trends is crucial to the work of ICAO as it provides a robust single reference for sound discussion and decision making. The council reviews and adopts CAEP recommendations, including amendments to the SARPs, and in turn reports to the ICAO Assembly, where the main policies on environmental protection are ultimately defined.

CAEP noise and emissions standards and recommendations are applied at the time of certification of the aircraft or engine type, prior to production of the first aircraft or engine, with the purpose of effectively limiting the emissions and noise from commercial aircraft. The regulatory emissions and noise levels are not set to be technology-forcing in the sense that new technology or new methods need to be developed in order to meet the standard. Rather, the standards are set to be "technologically feasible" [19], i.e., they can be met by more than one manufacturer by incorporating existing technologies and methods available around the time the standard is agreed upon. As environmental needs and new technologies/methods emerge, CAEP decides to tighten the stringency of emissions and noise standards by reducing certification limits at irregular intervals every couple of 3-year CAEP working cycles; standards, therefore, provide an ever-tightening "backstop" to reduce noise and emissions.

In the context of supersonics, it is important to recognise that the purpose of noise and emissions standards has not, to date, been to prevent the introduction of new concepts or the addressing of new markets. Rather, when these new concepts or markets emerge, new or revised standards are developed to ensure the incorporation of the best available noise and emissions technology and methods.

Within the general principles outlined above, Sections 4–6 of this report will examine the existing noise and emissions standards applicable to supersonic aircraft and the challenges in applying them to emerging supersonic aircraft projects.

3.2. Recent Developments in CAEP

With the advent of new supersonic civil aircraft projects and the need for manufacturers to design them according to known certification rules, CAEP reinforced its activities in its relevant working groups, namely WG1 (noise) and WG3 (emissions) (see Figure 1). During the CAEP/12 cycle (2019–22), an "Exploratory Study" on the noise and emissions of supersonic aircraft was carried out, covering investigations of LTO noise, LTO NOx emissions (affecting air quality) and cruise NOx emissions (impacting climate), as well as LTO and full-flight fuel burn [22]. The study predicts the outcome of analytically adding supersonic transports to the existing civil aircraft fleet, assessing their impact on operations, fuel consumption, airport noise and air quality. A practical example of how technical activities supporting the CAEP work through solid scientific bases is provided by NASA's extensive investigations of a Mach 1.4 concept [22,64,65].

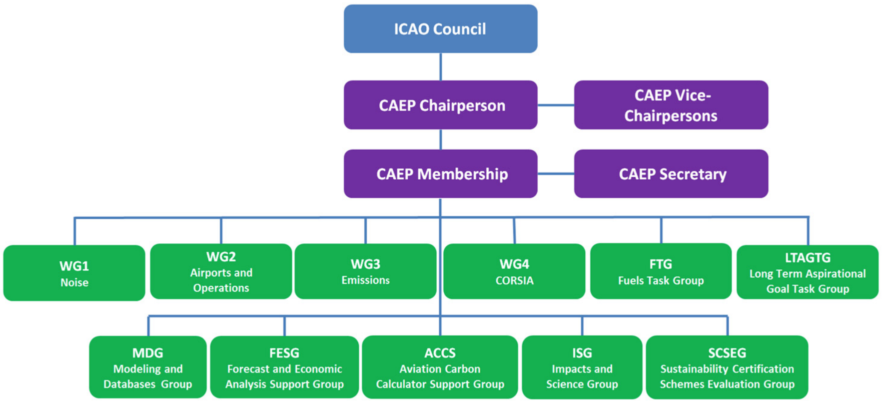

Figure 1. CAEP structure (leading up to CAEP/13 in 2025) [66].

In the current CAEP/13 cycle (2022–25), the focus of WG1 is on monitoring research on sonic boom and en-route noise and, in particular, on developing an LTO noise standard by the CAEP/13 meeting. The focus of WG3 is on developing an LTO emissions standard, assessing the elements of a potential future CO_2 emissions standard for SSTs and monitoring trends in supersonic technology and their impact on CO_2 emissions. Details will be provided in Sections 4–6 below. For en-route noise and CO_2 emissions, progress reports are due by CAEP/13, but unlike for LTO noise, no target date for creating a standard has been foreseen so far.

3.3. Relevant Aspects of Fuel Specifications

As part of the efforts to reduce the environmental impact of supersonic flight, the compatibility of SST engines with using sustainable aviation fuels (SAF) is extensively investigated. According to the Air Transport Action Group [67], sustainable aviation fuel is a generic term including biofuels, produced from plant or animal material, as well as fuels produced from other alternatives, including non-biological resources, such as power-to-liquid (PtL) fuels [68]. The American Society for Testing and Materials (ASTM) has developed standard specifications to define kerosene-type fuels for aviation engines [13]. A set of technical standards (mainly ASTM D7566 [69] and the British Def Stan 91-91 [70]) and sustainability requirements (EU Renewable Energy Directive (RED II) [71,72] and ICAO CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation) [63,73]) for SAF has been disclosed over the last years, which, however, do not differ between application to subsonic or supersonic aircraft. Furthermore, the use of SAF, due to its low aromatics content, also leads to reduced particulate matter emissions, with beneficial effects on both local air quality and contrail avoidance. Research is ongoing on these effects in supersonic engines.

Liquid hydrogen (LH_2) is another fuel considered for application in different supersonic and even hypersonic aircraft, especially in Europe [74,75]. Nevertheless, whether for subsonic or supersonic use, standards and specifications for hydrogen used in aviation are just emerging. The purity of liquid hydrogen is extremely high as no other substance is maintained in the liquid state at the temperatures of LH_2; therefore, the chemical composition requirements are much more straightforward than for fuels consisting of mixtures of liquid hydrocarbons. For the specific aspects of stratospheric water vapour emissions by supersonic flights, see Section 5.2.2. According to the ICAO Environmental Report 2022, Chapter 7 [76], key partnerships will be necessary in the years to come to organise the appropriate regulatory framework for commercial aircraft using hydrogen. Indeed, the urgency for energy transition and guiding investments into it shall trigger the establishment of related future regulations. In this context, it should be noted that the application of hydrogen for aviation will largely benefit from synergies with ground mobility.

4. Air Quality-Based Emissions Regulations

4.1. Current Regulated Species for Subsonic Aircraft

The current Annex 16, Vol. II, requirements for engines intended for propulsion at subsonic speeds [34] stipulate limiting levels of emission of the following:

- Oxides of nitrogen (NOx);
- Carbon monoxide (CO);
- (unburnt) Hydrocarbons (HC);
- Smoke (now replaced by nvPM, see below);
- Fuel venting (none permitted);
- Non-volatile particulate matter (nvPM).

For each of these pollutants, the emissions are determined over a standardised landing and take-off (LTO) cycle composed of several operational modes with given duration and engine thrust settings (see Table 1, left part). Carbon dioxide (CO_2) emissions, which do not affect air quality but climate change, are regulated in Annex 16, Vol III [36], and are discussed in Section 5 of this report.

Table 1. LTO cycle definition for subsonic and supersonic aircraft.

	Subsonic Aircraft		**Supersonic Aircraft**	
Mode	**Thrust Level**	**Duration**	**Thrust Level**	**Duration**
Take-off:	100%	0.7 min	100%	1.2 min
Climb	85%	2.2 min	65%	2.0 min
Descent	-	-	15%	1.2 min
Approach	30%	4.0 min	34%	2.3 min
Taxi/ground idle	7%	26 min	5.8%	26.0 min

Since the original regulations in 1981, the regulatory levels for Nox have been tightened four times for subsonic aircraft at CAEP/2, CAEP/4, CAEP/6 and CAEP/8. The introduction of nvPM requirements in 2017 has largely superseded the visibility-based smoke requirement, but again, only for engines intended for subsonic aircraft. There have also been numerous updates to the emissions standards and recommendations regarding test methods, test fuels and clarified terminology.

The air quality standards in Annex 16, Vol. II are engine-based, unlike noise and CO_2, which are aircraft-based, and for subsonic aircraft, are primarily applicable to engines above 26.7 kN rated sea-level standard (SLS) thrust.

4.2. Application of the Annex 16 (Air Quality) Emissions Regulations to Supersonic Aircraft

The current Annex 16, Vol. II, requirements for engines intended for propulsion at supersonic speeds are contained in Chapter 3, plus relevant appendices. These current requirements were based on a modified landing and take-off (LTO) cycle for the then-current operational supersonic aircraft (see Table 1, right part), based on the cycle specified for the Concorde aircraft. This LTO cycle, with an additional descent mode, different times-in-mode (apart from taxi-idle) and power settings compared to the LTO cycle for subsonic aircraft, was in recognition that aircraft then designed for supersonic cruise flight had low-speed flight characteristics significantly different from subsonic aircraft.

As for the engines of subsonic aircraft at the time, regulatory levels for the engines of supersonic aircraft were set for NOx, HC, CO and smoke. However, these and their attendant test methods have not been updated since the original issue of the regulations in 1981, and it is generally accepted that after 40 years, they are outdated. The more recent nvPM requirements are not currently applicable to supersonic aircraft.

It is worth noting that the regulatory levels and test methods were designed for use with afterburning engines. The use of afterburners is not envisaged in current supersonic aircraft projects; their use for acceleration to supersonic speed might, however, be reconsidered in the future.

Environmentally effective emissions regulation for supersonic engines needs to take into account information on the latest aircraft projects and latest developments in emissions control technology, along with technical and economic factors.

Reviewing the current Chapter 3 and other supersonic-related issues in Annex 16, Vol. II, confirms that the current Chapter 3 is outdated, specifically the following:

- Chapter 3 was written around one large supersonic aircraft with afterburning engines in an age when the understanding of air quality and climate impacts of aviation was in its infancy. The chapter has not been amended for almost 40 years;
- The applicability of the smoke requirements is now out of step with subsonic engines, where these are replaced by nvPM requirements;
- During the original development of the regulations, the five-mode supersonic LTO cycle was not recommended for future use beyond Concorde. It needs updating to apply to current supersonic projects (i.e., time-in-mode and thrust settings);
- The 40-year-old regulatory levels for all emissions do not reflect recent combustion technology, current understanding of environmental needs and the emerging supersonic aircraft projects;

- Regulatory amendments made to the equivalent text in Chapter 2 are not reflected in Chapter 3, making the chapter out of date and out of step with subsonic requirements;
- Appendix 5 of Annex 16, Vol. II, on instrumentation and measurement techniques needs to be brought into line with subsonic measurement requirements (Appendix 3).

Considering these needs, CAEP WG3 has the following remits for work on LAQ emissions in the current CAEP/13 cycle (for CO_2 emissions, see Section 5):

- Certification Requirements—SST:
- Update all elements of Annex 16, Volume II, and ETM, Volume II, including the regulatory limits for modern supersonic engines (without afterburning technology) based on emissions data availability;
- Work in parallel with WG1 while also taking into account that the development of each standard may occur at a different pace based on data availability and readiness and that CAEP should not delay the process of approval of one standard if both are not ready at the same time, provided that interdependencies are evaluated.

4.3. Air-Quality-Related Issues to Be Addressed for Supersonic Aircraft

For almost all airports and their environs, supersonic aircraft are expected to form only a minor fraction of operations and, therefore, a relatively small fraction of airport air quality impacts. From a public acceptance and policy point of view, it would be ideal for supersonic aircraft to meet the same LTO emissions requirements as for subsonic aircraft. However, engine cycle constraints for supersonic aircraft and operational differences within the LTO cycle may prevent this.

Issues to be addressed, therefore, include the following:

- LTO cycle—Technical and policy discussions are ongoing in CAEP WG3 as to whether the original pre-CAEP recommendation to apply the same LTO cycle to sub- and supersonic aircraft can be implemented, at least for aircraft up to approximately M2.5 cruise speeds. If not, one or more representative supersonic LTO cycles will need to be developed, and issues such as variable thrust setting should also be addressed;
- Engine cycle design constraints for supersonic aircraft need to be studied to determine whether they prevent supersonic designs from meeting current and envisaged subsonic emissions regulatory levels. If not, what criteria should be used to set alternative regulatory levels and/or alternative measurement and test procedures;
- If an LTO-based regulation is to be used as a proxy for climate impacts (see Section 5), what criteria should be used to set alternative regulatory levels and/or alternative regulations?

This list is to be continued if additional issues are identified. CAEP work in all these fields is progressing; however, outcomes are confidential while negotiations are ongoing.

5. Climate Impact Emissions Regulations

5.1. General Aspects

There are currently no direct climate-impact-based emissions regulations for supersonic aircraft.

When developing the original emissions regulations for supersonic aircraft and their engines, considerable effort was expended to determine the potential climate impacts, which was then focused on ozone resulting from the stratospheric cruise altitudes of a fleet of supersonic aircraft. As mentioned in Section 2.2, actual climate-specific regulations were never developed as the concern over ozone reduced, and it became apparent that there would only be a few SSTs in service. The principle of potentially developing climate-based regulation was, however, clear.

At that time, reducing CO_2 emissions was not a priority, and no certification standards for CO_2 emissions of aircraft were agreed upon until 2016. As CO_2 emissions are directly proportional to fuel burn, historically, fuel costs, as a significant proportion of operating costs, were seen by many as an adequate driver of better fuel burn technology. The 2016

CO_2 regulations were specifically developed by CAEP and are currently applicable only to subsonic aircraft.

Unlike the other regulated emissions, applying the current CO_2 regulatory metric system to supersonic aircraft is not a trivial task. Details are provided in Section 5.2.1.

Although developed with a focus on air quality, the current LTO engine emissions regulations generally also have a beneficial effect on limiting non-CO_2 aviation climate impact. It has been established that for current and past technologies, reductions in LTO NOx will result in reductions in full-flight NOx [77]. Although less clear, this principle is probably true for the other emissions as well.

However, trade-offs exist between different emission species, e.g., NOx and CO_2 (incorporation of heavier noise or NOx reduction technologies will cause increased fuel burn). For subsonics, this problem has been recognised in the literature (see, e.g., [78]), and for supersonics, a similar dilemma is likely.

5.2. Climate Impact-Related Regulatory Issues to Be Addressed for Supersonic Aircraft

The climate impact of a fleet of supersonic aircraft differs from a subsonic fleet primarily by the higher cruise altitudes. Whilst CO_2 emissions are still the most important emissions species, whose impact is understood with the highest certainty, non-CO_2 impacts also need to be given appropriate consideration in a new regulatory framework. While it is likely that flight in the stratosphere produces significantly fewer contrails than in subsonic flight, water vapour emissions are expected to have a much stronger climate impact in the stratosphere [79]. NOx and SOx emissions can influence the ozone layer [59]. Progress in the scientific determination of the impacts of non-CO_2 emissions species is to be closely monitored and considered in future rulemaking.

CO_2 and non-CO_2 impacts are considered in the following sections.

5.2.1. CO_2 Climate Impact Regulation

Continued exemption of supersonic aircraft from CO_2 regulation would seem unacceptable from a policy viewpoint. Extension of the current subsonic CO_2 regulations to supersonic aircraft could potentially provide the same "anti-backsliding" function as it does for fuel consumption of supersonic aircraft. However, the existing CO_2 regulations are specifically formulated for current and near-term future subsonic aircraft and extension to future supersonic aircraft requires an adaptation. To highlight the issues, some understanding of the existing CO_2 regulation metric system is required:

- *CO_2 Metric System:*

  In its simplified form, the CO_2 regulation metric system [36] is

$$MV = 1/(SAR \times RGF^{0.24})$$

where

- *MV* is the CO_2 metric value which must not exceed a regulatory level, which is a function of the aircraft's certificated Maximum Take-Off Mass (MTOM);
- *SAR* is the specific air range (the inverse of specific fuel consumption), which is measured at three different aircraft weights at cruise and averaged over these three points;
- *RGF* is a factor measured using a definition of fuselage area at floor level.

Although not expressed directly in this form, the metric system has terms for (environmental) cost, i.e., 1/SAR, versus (societal) benefit, i.e., RGF (carrying capacity) and MTOM (carrying capacity and range).

An important feature of this metric system is that it allows one regulatory level (as a function of MTOM) to cover all current types of subsonic aircraft, including single-aisle, twin-aisle, double-deck passenger and freighter aircraft, business jets, regional jets and regulated turboprops.

For application to supersonic aircraft, there are a number of key issues with this system which need to be addressed. These include the following:

- *Speed:*

  The similar speeds of the currently regulated types allowed a term for speed to be omitted from the current metric system. However, higher speeds imply higher fuel consumption, and in the case of supersonic aircraft, this might prevent SSTs from meeting the current regulatory levels, which were shaped for subsonic aircraft.

- *Reference Geometry Factor (RGF):*

  While almost all current and near-term future subsonic aircraft types have similar tube and wing configurations and engine positioning, supersonic aircraft are longer and thinner, well outside the ratios common for subsonic aircraft. Other parameters describing the cabin might be more relevant for SSTs (e.g., cabin volume, which also influences drag).

- *Cruise Fuel Consumption Measurement Points:*

  The 3 SAR measurement points were chosen to represent features of subsonic aircraft operation. Analysis work has started to verify whether these points are appropriate for supersonic operations. First, preliminary outcomes show that this is not the case, mainly due to the much higher relative fuel consumption during climb and acceleration to supersonic cruise speed at the beginning of a flight mission, and they should be replaced by points at other aircraft masses.

- *MTOM variants:*

  The CO_2 metric system with the 0.24 exponent has been defined in a way that variants of the same subsonic aircraft family with different certified Maximum Take-Off Mass (MTOM) have similar margins to the regulatory level. Extending this principle to supersonic aircraft types will require significant data analysis.

- *Afterburning:*

  The previous generation of supersonic transports included the use of afterburners to attain and sometimes maintain cruise speed. Although current projects do not envisage the use of afterburners, regulators need to consider whether to include afterburners in any CO_2 regulations, as with other supersonic emissions regulations, or whether to explicitly exclude afterburners from the regulatory scope for the time being.

- *(Lack of) Data Issues:*

  For subsonic aircraft, emissions regulations and their regulatory levels (including CO_2) were developed using close-to-certification standard performance and emissions data for tens, sometimes hundreds, of existing aircraft types. For supersonic aircraft, these data are not available as there are no SSTs that are currently certified (the Concorde design being quite far away from modern requirements)

- *Comparison to subsonic standards:*

  For noise and engine emissions around airports, meeting the current subsonic standards may be challenging for supersonic designs but may still be feasible. For CO_2 emissions, on the other hand, it is expected that the existing limits for subsonic aircraft are not within reach of supersonic aircraft designs.

5.2.2. Non-CO_2 Climate Impact Regulation

Other than CO_2 regulation of subsonic aircraft, no other species is regulated by CAEP regarding full flight or cruise emissions. The LTO cycle used for NOx, HC, CO, smoke and, more recently, the focus regarding nvPM is primarily on limiting airport air-quality-related impacts. For species such as sulphur, hydrogen and, indirectly, nvPM, the fuel specification also acts to limit emissions at altitude, albeit somewhat loosely.

At the moment, the impact of non-CO_2 emission species from supersonic aviation is still actively being researched. However, a recent review clearly indicates that the key findings of the IPCC (1999), as well as subsequent results from, e.g., European projects (SCENIC [59] and HISAC [60]), are still valid. One key aspect is the increasing importance of water vapour climate impacts that increase with altitude of emission because of the increase in water vapour perturbation lifetimes. Recent studies from the H2020 STRATOFLY project showed that this trend even continues to hypersonic altitudes (up to 30 km cruise altitude) [80]. In general, two main areas of interest ought to be considered: the impact on the global climate and also the potential impact on the ozone layer's composition. In contrast to the regulations for subsonic aviation, the latter is disproportionately important for supersonic aircraft, as these skirt the lower ozone layer at cruise altitude, directly affecting its chemistry. This is discussed in Section 5.2.3 below.

Contrary to subsonic aircraft, water vapour strongly contributes to the climate impact of supersonic aircraft using conventional fuel. Emissions of nitrogen oxides and sulphur also have a large impact through their contribution to the ozone concentration [59], although for sulphur, scientific understanding is still rather limited. Compared to these, CO_2, soot and contrails play a minor role, and CO and HC are negligible (e.g., [81]). Only recently has a review study comparing the results of multiple studies and providing robustness estimates been produced in the framework of the Horizon 2020 project SENECA [29]. The impact of some emissions, particularly water vapour, is furthermore strongly dependent on the emission (and therefore flight) altitude, with emissions at higher altitudes having a greater climate impact.

Based on the mentioned findings, water vapour regulation ideally should include water vapour emissions depending on altitude, taking into account the perturbation lifetime as a function of cruise altitude. Similar to CO_2 emissions, the amount of water vapour emitted by the engines is also proportional to fuel burn. Hence, a similar approach as for the CO_2 metric might be feasible.

Whether the usage of hydrogen fuel instead of conventional fuel increases or decreases the climate impact of supersonics still has to be studied. However, the decrease in impact through absent emissions of sulphur, CO_2, soot and possibly NOx is very likely to be even largely over-compensated by an increased impact through higher water vapour emission.

Further studies on climate impacts of SSTs should also include impacts on contrail formation (especially to confirm and quantify reduced contrail formation likelihood with the higher cruise altitudes of SSTs in the stratosphere), as well as impacts of low aromatic SAFs on radiative forcing and contrails.

5.2.3. Ozone Impact

The ozone layer is regulated by a complex and delicate balance of chemical reactions, and previous research [59,81,82] has indicated that the emission of specific chemical species (e.g., NOx, SOx) may cause changes to ozone layer chemistry. With regard to ozone chemistry, the impact of water vapour and aerosol emissions is expected to be minor compared to NOx and SOx, but they are expected to be of importance with regard to the climate impact. As SAFs (can) have reduced sulphur content compared to conventional jet fuel [83], this is one of the areas where their use could help partially mitigate the ozone impact of supersonic flight.

Further research, based on emerging climate impact understanding, is required to determine what regulatory action is needed to ensure the protection of the ozone layer. This research should include fuel properties.

6. Noise Regulations

This section provides an overview of the current noise regulations for civil supersonic transport.

6.1. Aspects of Noise Regulation for Supersonic Aviation

6.1.1. Supersonic LTO Noise

As described in Section 3, the ICAO addresses aircraft noise via Annex 16, Volume I, where “different aircraft classifications form the basis of noise certification” [84]. The classification is mainly focused on subsonic types, i.e., different masses and engines, but Chapter 12 of Annex 16, Volume I, explicitly addresses supersonic aeroplanes. As already mentioned, this chapter was formulated with the SST Concorde in mind and has never been updated since. According to [85], one of the indispensable premises for the design of low-noise future supersonic aircraft is the integration of breakthrough technologies and flight procedures aimed at reducing noise, especially during LTO operations. To ensure that future supersonic aircraft will meet low-noise requirements, it is essential to move LTO noise evaluations up to the early stage of the design process. In detail, for subsonic aircraft design, the idea is to directly elicit requirements from certification standards and use them as a benchmark during the design process. Conversely, for supersonic aviation standards, flight procedures have not been defined yet. However, in order to guarantee an adequate public consensus towards future SSTs, the scientific community is anticipating the possibility of extending the current subsonic flight procedures to civil supersonic aircraft [86]. The section for newer supersonic aeroplanes only contains a note that standards and recommendations for SST have not been developed yet, but maximum noise levels from subsonic jet aeroplanes could be used as guidelines. On the other hand, it is stated that acceptable levels of sonic boom have not been established and “compliance with subsonic noise standards may not be presumed to permit supersonic flight” [87].

6.1.2. Supersonic En-Route Noise: The Sonic Boom

The note on new supersonic aeroplanes reveals part of the specific challenges to their noise regulation: While the initial deployment of (subsonic) noise regulation was motivated by the noise in the surrounding aerodromes and, thus, mainly focuses on LTO procedures and measures, supersonic flight, on the other hand, introduces a totally new principle of aircraft en-route noise: the sonic boom, which is emitted throughout the whole stage at supersonic speed. During accelerations and sharp turns, several shock waves can interfere in some regions, creating a so-called “focused boom” [88] that has a higher magnitude in general and can be even more of a nuisance.

On the other hand, it is possible to adapt the airframe in a way that the annoyance of the sonic boom can be diminished significantly. This approach is referred to as “low-boom” or “shaped boom” and is usually a trade-off between favourable acoustic and desired aerodynamic characteristics (and thus, e.g., emissions).

There are different opinions on how annoying the sonic booms of future SSTs should be or will be. While low-boom aircraft will probably introduce a significant improvement to the problem of sonic booms during cruise flights, the problem of focused booms during acceleration phases may need special consideration.

To further understand the impact of low-boom aeroplanes, a low-boom demonstrator is currently being manufactured at NASA Langley Research Center in the United States [89]. Next, for the purpose of demonstrating the low-boom technology in flight for the first time on a specifically designed aircraft, it will also perform overflight tests over selected communities in the United States. The sonic boom community needs such experimental data to define psychoacoustical scales for the perception of such newly shaped booms. Since these acoustical events can hardly be compared to natural sounds, the quantification of such audible events remains a challenge. The derived acoustic scales might help regulators to define limiting values on the issue of sonic boom eventually. However, shaping the aircraft for low boom poses major technical and operational challenges, including increased manufacturing costs and complexity, lower aerodynamic performance and reduced internal available volume. An acceptable compromise is difficult to find, especially in the case of large aircraft [90]. Recently, other strategies have been patented, and their nuisance reduction potential shall be properly investigated before introducing new regulations.

These novel approaches include the introduction of a nose spike [91,92], the adoption of shock wave dispersion techniques [93], the introduction of anti-boom jet streams [94], suction/injections wing slots [95], sonic boom suppression techniques using pulse energy addition [96], etc.

6.2. Sonic Boom Regulations

While no standard limiting the strength of sonic booms exists, sonic boom generation or supersonic flight over land is, in general, either forbidden on a national basis or not explicitly regulated yet.

For example, Australian authorities state that "Supersonic aircraft have not operated commercially in Australia" [7] to explain why no noise standards for the certification of newer SSTs exist in Australia at the moment.

The Russian Air Code states: "An aircraft supersonic flight shall be allowed at an altitude where a hazardous sonic boom effect upon the environment is precluded. The procedure of carrying out aircraft supersonic flights shall be established by the federal aviation regulations." [8].

However, specific procedures usually only address exceptional cases. European examples of such procedural regulations of supersonic flight can be found in the Standardised European Rules of the Air (SERA). SERA.5005 (d) on Visual Flight Rules (VFR) states: "VFR flights shall not be operated [. . .] at transonic and supersonic speeds unless authorised by the competent authority" [9].

SERA.8015 (c) on Air Traffic Control Clearances states for transonic flight:

"(1) The air traffic control clearance relating to the transonic acceleration phase of a supersonic flight shall extend at least to the end of that phase.

(2) The air traffic control clearance relating to the deceleration and descent of an aircraft from supersonic cruise to subsonic flight shall seek to provide for uninterrupted descent at least during the transonic phase." [9].

Since ICAO has no further regulations in place, the operational regulations for supersonic flight have oftentimes remained the same since the early days of Concorde.

6.3. ICAO Work on SST Noise

ICAO has also intensified its efforts to update the current regulatory framework on SST noise. A general approach is from the 39th ICAO Assembly (2016), where "the importance of ensuring that no unacceptable situation for the public is created by sonic boom from civil supersonic aeroplanes in commercial service was reaffirmed. ICAO, in CAEP WG1, is attempting to reach international agreement on the definition of the expression 'unacceptable situations for the public' and the establishment of the corresponding limits." [20] As mentioned in Section 4, both WG1 and WG3 carried out "an exploratory study to provide CAEP with a better understanding of airport noise impacts resulting from the introduction of supersonic aircraft. WG1 will also continue to develop a scheme for en-route noise/sonic boom certification for supersonic flight." [97].

WG1's work programme in the current CAEP/13 cycle comprises:

- Developing an LTO noise certification standard for supersonic aircraft: this is CAEP's current main priority.
- Monitoring SST research:
- Research to characterise, quantify and measure (including metric) climb and en-route noise, including Mach cut-off conditions and community response;
- Assist in promoting and defining such research.
- SST standard development (supersonic regime):
- Continue work on new standards and recommended practices (SARP) for en-route noise/sonic boom certification;
- Continue to refine certification procedures and initiate approaches to specification of limits;
- Continue to gather data on "other factors" relevant to SARP development, e.g.:

    - Boom at "off design" Mach numbers, from accelerations and turns and secondary booms;
    - Impacts on aquatic life, mammals and cruise ships, sleep and booms at night, rattle, effects on animals, and avalanches.
- SST coordination:
    - Update the Air Navigation Commission with the SSTG Report on the progress of SST noise activities.
- Monitoring SST projects:
    - The status of SST projects and the expectations of supersonic development.

7. Recent Regulatory Initiatives

7.1. United States

Some effort to update these older regulations has been made by the Federal Aviation Administration (FAA) in order to support the development of a new generation of SSTs in the United States of America.

To date, the existing regulation [98] from 1972, yet again based on the nuisance of Concorde's sonic boom, "prohibits anyone from operating a civil aircraft at a true flight Mach number greater than 1 over land in the United States and from a certain distance offshore where a boom could reach U.S. shores. There is a procedure that allows supersonic operation under certain conditions granted on an individual basis" [99].

To support the national industry and its attempt to develop new supersonic aircraft, "FAA initiated [. . .] two proposed rulemakings for manufacturers interested in developing supersonic aircraft" [100].

One rule is already finalised and basically clarifies the existing procedure to apply for special flight authorisation. Applicants now need to follow the instructions in 14 CFR Part 91.818 [101]. FAA emphasises that this finalised rule changed basically nothing in the existing procedures that have been in place since the 1970s, and the general prohibition of supersonic flight, specifically, remains untouched.

The second proposed rule is in the status of the Notice of Proposed Rule Making (NPRM) and attempts to expand certain subsonic LTO noise certification procedures to supersonic aeroplanes with a maximum take-off weight no greater than 150,000 pounds [102]. The proposed rule would provide noise certification reference procedures and establish noise limits for take-off and landing for supersonic aeroplanes. The proposed standards include noise limits that are quieter than the Stage 4 limits at which most of the current subsonic jet fleet operates, though louder than the current certification level of Stage 5 for the same aircraft weights. Eventually, the proposed standards would allow Variable Noise Reduction Systems (VNRS) [103]. While no rulemaking decision has been made so far, FAA plans to pursue this process and has included it in a recent document on FAA Reauthorisation Issues for the 118th Congress [72,104].

7.2. European Union

In the absence of applicable environmental protection requirements from ICAO, EASA has published the following documents for consultation in May 2022:

- Notice of Proposed Amendment (NPA) 2022-04 'Regular update of the SERA regulatory framework';
- Advance NPA (A-NPA) 2022-05 'Environmental protection requirements for SST aeroplanes'.

NPA 2022-04 'Regular update of the SERA regulatory framework' [105] proposes, amongst other aspects not related to SSTs, to introduce a speed restriction to prevent both VFR and IFR flights at transonic and supersonic speeds over the territory of the EU. The proposed speed restriction would apply over land and territorial waters, which usually include a 12-mile zone off the coast, in line with the territorial scope of the SERA regulatory framework. The proposed speed restriction would not apply over the high seas.

Potential future rulemaking steps could assess the implementation of an appropriate coastal buffer beyond the 12-mile zone for flights at supersonic speed, as well as more specific requirements for the operation of SSTs, including consideration of advanced technology (e.g., sonic boom reduction/mitigation technologies).

Concerning certification requirements for SST aeroplanes, EASA has published A-NPA 2022-05 'Environmental protection requirements for SST aeroplanes' [106]. Unlike an NPA, which proposes draft amendments of rules/requirements, an A-NPA is an interim step focusing on concepts for potential future requirements. The A-NPA covers concepts for LTO noise and CO_2 emissions. The proposals contained in the A-NPA are based on existing requirements for subsonic aeroplanes from ICAO Annex 16, Volumes I and III, adapted for use with SST aeroplanes where necessary.

The proposed LTO noise limits for SST aeroplanes in A-NPA 2022-05 correspond to the current limits for subsonic aeroplanes from ICAO Annex 16, Volume I ('Chapter 14' limits). Adaptations to the subsonic noise requirements have been identified to be required in the following areas:

- Adapted take-off reference procedures with or without Variable Noise Reduction Systems (VNRS), including an adapted reference speed range;
- Related adaptations to test procedures and evaluation methods.

A-NPA 2022-05 also includes concepts for measuring and reporting CO_2 emissions of SSTs. Adaptations to the subsonic requirements from ICAO Annex 16, Volume III, have been found to be required in the following areas:

- A revised specification of reference mass points for specific air range (SAR) measurements is proposed in the A-NPA;
- Amended provisions on reference speeds for SAR measurements, accounting for the specifics of SST aircraft performance. Reference points at both supersonic and subsonic speeds are proposed for measuring the SAR of SST aeroplanes.

The CO_2 metric value definition and reference geometric factor (RGF) were identified as acceptable to be re-used for SSTs, which would ensure comparability of results with subsonic aircraft. No CO_2 limit for SSTs is contained in A-NPA 2022-05, whose concepts could be used for the purpose of a reporting requirement for CO_2 emissions. Future work is proposed for the purpose of defining such CO_2 limits.

8. Ongoing Activities in H2020 MORE&LESS

The review presented in the previous sections clearly highlights the following findings: (i) the need to revise current rules to better fit future SST designs, operations and technologies, (ii) the need to introduce new regulations to cover additional aspects, including stratospheric water vapour emissions and ozone depletion, and (iii) the need to support regulatory activities with solid technical bases, fostering cooperation with academia, research centres and industry in R&D projects. This subsection provides the reader with a practical example of how SST rulemaking activities in Europe are currently supported by the collaborative research H2020 MORE&LESS [107].

MORE&LESS (MDO and REgulations for Low boom and Environmentally Sustainable Supersonic aviation), answering the EC call "Towards global environmental regulation of supersonic aviation" (LC-MG-1-15-2020) [24], aims to support Europe in shaping 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 multidisciplinary optimisation framework to assess the holistic impact of supersonic aviation onto environment.

To achieve this goal, MORE&LESS addresses the following objectives:

(1) To contribute to maintaining a high level of protection for citizens and the environment at local, regional and global levels. MORE&LESS pursues this objective by verifying the compliance of supersonic aircraft with the environmental requirements of current and next-generation civil subsonic aircraft or by assessing potential new

supersonic transport standards. Aircraft configurations, propulsive technologies, types of fuel and aircraft trajectories and operations play a crucial role in the ability to fulfill environmental requirements. MORE&LESS addresses this issue and indicates which aircraft configurations, propulsive technologies, types of fuel and trajectories and operations help match the requirements, thus allowing for the minimum environmental impact. In this context, MORE&LESS aims to verify the possibility for supersonic aviation to fulfil the following requirements and provide information to relevant international working groups, i.e., CAEP WG1 and WG3, including the following:

○ Providing potential noise-power-distance data, LTO noise and en-route noise (sonic boom intensity PLdB) estimations;
○ Noise emissions (in EPNdB) compatible with Chapter 14 noise limits;
○ Providing estimates on LTO and cruise pollutant emissions—pollutant emissions (oxides of nitrogen (NOx) as in ICAO CAEP/8 limits and non-volatile particulate matter (nvPM) compatible with the new CAEP/11 standard. The CO_2 standard is to be in line with existing Annex 16, Vol III (at both subsonic and supersonic speeds);

As a practical example, the H2020 MORE&LESS is contributing to maintaining a level of protection for citizens and the environment by developing novel multi-fidelity pollutant and greenhouse gas emissions estimation techniques, coupling high-fidelity large eddy simulations with combustion test campaigns for a wide range of SAF. Results from high-fidelity simulations and test campaigns are used to validate 0D chemical–kinetic mechanisms, which, in turn, are used as a solid basis for the development of simplified analytical formulations. This approach is expected to provide the regulatory community with a solid technical basis for the update of existing standards or elements to create new ones. In addition, the under-development of novel analytical formulations, such as [107], may be used to improve accepted and validated software tools such as IMPACT by EUROCONTROL or AEDT by FAA.

(2) To support the definition of regulations and procedures for the future supersonic aviation through solid technical bases. MORE&LESS pursues this objective by transposing the scientific findings in the fields of aerodynamics, aeroacoustics, propulsion, pollutant emissions and environmental impact into guidelines to support the regulatory community in shaping policy and regulations for the future supersonic aviation according to solid technical bases. In this context, MORE&LESS aims to develop a holistic framework able to assess the environmental impact of supersonic aviation at local, regional and global levels through a multidisciplinary approach, which encompasses the different disciplines and their mutual relationships, thus allowing for the performance of multi-objective optimisation of supersonic aircraft' trajectories and operations. Thanks to low- and high-fidelity modelling activities and test campaigns, already existing accepted and validated software tools that constitute the basic bricks of the holistic framework are enhanced and extended to cover supersonic aviation. The application of the multidisciplinary holistic framework to the case studies is the proving ground to verify that the enabling technologies of supersonic aircraft, their trajectories and operations comply with the environmental requirements, thus validating the concepts, trajectories and operations of future supersonic aviation. The definitions of recommendations to support the review of regulations and procedures to fit future supersonic aviation into the airspace stem directly from the results of the application of the multidisciplinary holistic framework, thus exploiting solid and robust technical bases. To guarantee the fulfilment of this objective, MORE&LESS includes representatives of the regulatory community as members of the Expert External Advisory Board (EUROCONTROL, ENAC, EASA and FAA) to provide feedback throughout the project and to acknowledge all the technical findings and derived suggestions for the definition of regulations and procedures to be adopted for the future supersonic aviation.

9. Conclusions

9.1. General

The plans by several manufacturers for the development of supersonic aircraft, both in the business jet and in the commercial passenger jet category, made it necessary for ICAO CAEP and its working groups, as well as individual certification authorities, to start working on a regulatory framework for the environmental impact of SSTs. The following elements have been considered for this framework:

- Certification standards: the application of standards in ICAO Annex 16 to SSTs and necessary adjustments from subsonic standards, which could affect certification flight conditions, definitions of measurement points, certification limits, or others;
- Operational limitations: mainly a restriction of supersonic flight to areas over water;
- An investigation of the need to consider currently unregulated effects such as stratospheric water vapour emissions or the impact on the ozone layer;
- An investigation of the need for modified fuel specifications, especially regarding the use of SAF and potentially hydrogen.

9.2. Emissions

For engine emissions affecting local air quality, a standard applicable to supersonic engines has existed but is widely recognised as outdated. Current CAEP WG3 activities try to close this gap.

The situation for emissions with climate impacts is more complex. The CO_2 standard established for subsonic aircraft would likely need some adjustments to allow certification of SSTs. In particular, it appears unlikely that upcoming SSTs would meet today's CO_2 standard certification levels for subsonic aircraft.

The climate impact of non-CO_2 emissions from supersonic flights is higher than from subsonic flights as they take place in the stratosphere at much higher altitudes. The highest additional contribution comes from water vapour, which, at subsonic flight levels, is almost negligible. The impact of SST flights on the ozone layer has been known for a long time, but no need for regulations was seen as long as the number of operating SSTs was extremely small; this might change in the near future. Concepts for suitable measures to control these impacts are to be developed, and further potential impacts are to be identified.

9.3. Noise

In conclusion, the regulatory framework for noise emissions of SST has been outdated due to a lack of relevance over the past decades.

Right now, there are discussions on how to introduce supersonic aeroplanes into the current regulatory framework based on LTO cycles: Should SST define a new category or should the current (and future) maximum noise limits for subsonic LTO cycles define the overall maxima for noise emissions?

Furthermore, the issue of sonic boom remains one of the main challenges in supersonics. Experimental data from a low-boom demonstrator are much needed to quantify the nuisance of future shaped booms and to support regulators in defining a regulatory framework for this supersonic-specific en-route noise phenomenon.

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Abbreviations

AEAP	Atmospheric Effects of Aviation Program
AEROCHEM	modelling of the impact on ozone and other chemical compounds in the atmosphere from aeroplane emissions
AERONOX	the impact of NOx emissions from aircraft upon the atmosphere at flight altitudes of 8–15 km
AEROTRACE	measurement of trace species in the exhaust of aero engines
AESA	Atmospheric Effects of Stratospheric Aircraft
ASCENT	Aviation Sustainability Center
CAEE	Committee on Aircraft Engine Emissions
CAEP	Committee on Aviation Environmental Protection
CHEMICON	chemistry and microphysics of Contrail formation
CIAP	Climatic Impact Assessment Program
COMESA	Committee on Meteorological Effects of Stratospheric Aircraft
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
EASA	European Union Aviation Safety Agency
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
H2020	Horizon 2020
HAPP	High Altitude Pollution Program
HISAC	environmentally friendly high-speed aircraft
HSCT	high-speed civil transport
ICAO	International Civil Aviation Organization
LAQ	local air quality
LTO	landing and take-off
MORE&LESS	MDO and REgulations for Low boom and Environmentally Sustainable Supersonic aviation
NAS	National Academy of Science
NOx	nitrogen oxides
NPA	Notice of Proposed Amendment
NPRM	Notice of Proposed Rule Making
nvPM	non-volatile particulate matter
POLINAT	Pollution From Aircraft Emissions in the North Atlantic Flight Corridor
R&D	research and development
RED	EU Renewable Energy Directive
SASS	Subsonic Assessment Element
SAF	sustainable aviation fuel
SARP	standards and recommended practices
SCENIC	scenario of aircraft emissions and impact studies on chemistry and climate
SENECA	(LTO) noise and emissions of supersonic aircraft
SERA	Standardised European Rules of the Air
SLS	sea-level standard
SST	supersonic transportation
UARP	Upper Atmosphere Research Program
VFR	Visual Flight Rule
VNRS	Variable Noise Reduction Systems

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