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UPDATE ON UNDERSTANDING OF POTENTIAL IMPACTS OF SUPERSONIC AIRCRAFT

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CAEP IMPACTS AND SCIENCE GROUP (ISG)- UPDATE ON UNDERSTANDING OF POTENTIAL IMPACTS OF SUPERSONIC AIRCRAFT

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SUMMARY

In this report, developed during the 13th cycle of the Committee on Aviation Environmental Protection (CAEP/13, 2022-2025), we provide an update on our Impacts and Science Group(ISG) report on understanding the potential environmental impacts from supersonic aircraft (further referred to here as CAEP/12 ISG report Wuebbles et al., 2022) [1]. As outlined in the key messages below, new research has further added to the knowledge base for these impacts. Regarding effects on climate and stratospheric ozone, the overarching finding remains unchanged that supersonic aircraft are likely to affect concentrations and the distribution of stratospheric ozone (increasing ozone amounts in the lower altitudes of the stratosphere and destruction above, depending on where the emissions occur) with concomitant climate impacts. However, the potential for adoption of sulphur-free, low-soot sustainable aviation fuels has re-raised the question of the role of aerosols, on which there is currently a lack of scientific consensus. On noise, there is potential for new designs to create quieter booms, although this is still the subject of research. Meanwhile air quality impacts from supersonic aircraft remain largely unstudied.

Key messages

- Recent studies continue to show that the emissions and resulting impacts on ozone and climate from an assumed fleet of (Supersonic Transport) SST aircraft will depend especially on the fleet size, flight characteristics, Mach speed, cruise altitude, fleet fuel use at cruise, Nitrogen Oxides (NO_x) emission index, and assumptions about sulphur in the fuel and soot emissions.
- In general, it is expected that the climate impact (measured in terms of the proxy radiative forcing (RF)) from non-CO_2 emissions will be larger than that from CO_2, with the total RF from CO_2 depending on the lifespan and size of the fleet as well as the fuel composition. As well as reducing CO_2 emissions, the use of sustainable aviation fuels would likely greatly reduce sulphur and (depending on the fuel composition) soot emissions. The resultant changes in aerosol-related impacts on climate and ozone are as yet poorly understood.
- Supersonic aircraft are still expected to produce more than three times as much CO_2 per revenue-passenger kilometre (RPK) as subsonic aircraft. Furthermore, the non-CO_2, non-contrail warming from supersonic aircraft is still projected to exceed that (per revenue-passenger kilometre) from

[1] This report is the update of “ICAO CAEP/12 Assessment Report: Understanding the potential environmental impacts from supersonic aircraft: an update”, ICAO-CAEP12-Assessment-Report-on-the-potential-environmental-impacts-from-supersonic-aircraft.pdf

subsonic aircraft due largely to emissions of stratospheric water vapour and the ozone-depletion effects of emitted NO_x.

- Additional research is needed to examine potential changes in the ozone and climate response from aerosol emissions reductions associated with the use of Sustainable Aviation Fuel (SAF) as a replacement for current aviation fuel. Studies are ongoing to understand these impacts relative to those from using Jet A fuel.
- Much research has been dedicated to modelling and mitigating the effect of sonic booms from supersonic flight. However, the scientific view of supersonic en route noise impacts (i.e., sonic boom noise impacts) has not changed in recent years. No supersonic civilian aircraft are flying, therefore there are no current and actual data available to assess noise impacts. NASA's Quesst demonstration aircraft may provide such information within a few years. The landing and takeoff (LTO) noise impacts of supersonic aircraft could be different from the noise impacts of conventional subsonic aircraft due to the higher velocity take-offs and landings, and the high-thrust performance operational capabilities of supersonic aircraft. For the developing certification standard for LTO noise from supersonic aeroplanes, it will be expected that SST certify and comply with the same noise limits as subsonic jet aircraft (ICAO Annex 16, Vol 1, Chapter 14).
- Ongoing research to assess the impact on the public indicates that future low-boom supersonic aircraft have the potential to create quieter sonic booms that may be less annoying than conventional sonic booms.
- The potential for differences in local and global air quality impacts from supersonic, rather than subsonic, aircraft has not been adequately researched.

INTRODUCTION

The basis for concern

Interest in supersonic transports has continued since the publication of the previous ISG report in 2022 (Wuebbles et al., 2022). Despite the closure of Aerion Supersonic in 2021, several companies have continued to develop supersonic business jets and larger commercial aircraft with the aim of achieving certification by 2030. However, since the 1970s studies have reported that emissions of water vapor (Harrison, 1970) and nitrogen oxides, or NO_x (Johnston, 1971), at the greater altitudes flown by supersonic aircraft could result in depletion of the global ozone layer and magnified climate impacts relative to subsonic aircraft emissions. Similar concerns have been raised regarding the potential impacts of aerosols resulting from emissions of sulphur and black carbon (Kawa et al., 1999). Meanwhile supersonic flight over land by commercial aircraft continues to be banned in most airspace due to the potential for annoyance, health impacts and perhaps property damage, resulting from population exposure to supersonic boom noise. This report summarizes new findings which have been published since the 2022 ISG report, including new concerns specific to the environmental impacts of SSTs.

PREVIOUS ESTIMATES OF THE POTENTIAL FOR COMMERCIAL SSTs

The CAEP/12 ISG report on fleets of commercial SST aircraft highlighted the prior national and international programs to understand the potential environmental effects from these aircraft. Here we provide a short, updated summary of those programs.

The first studies of potential SST commercial aircraft considered three major aircraft platforms: the Boeing SST in the United States, the Concorde in Europe (led by the United Kingdom and France), and the Tupolev Tu-144 in the then Soviet Union. The U.S. Climatic Impacts Assessment Program (CIAP) evaluated potential fleets of these aircraft (Grobecker et al., 1974). The U.S. National Academy of Sciences had a parallel program that reviewed CIAP as well as undertaking its own assessment (NRC, 1975). Other major efforts were from the Australian Academy of Sciences (1972), the United Kingdom's Committee on the Effects of Stratospheric Aircraft (COMESA, 1976), and France's Comité d'Études sur les Conséquences des Vols Stratosphèrique (COVOS, 1976). These programs were pioneering, with outcomes including: providing the first measurements of nitrogen oxides and other gases and particles in the stratosphere; greatly advancing the understanding of stratospheric composition through one-dimensional (vertical) models and the first two-dimensional zonally-averaged models; conducting comprehensive laboratory measurements of relevant reactions and their rates; and studying the economic impacts and biological damage caused by ultraviolet radiation. The new observations and scientific assessments resulting from these programs came to similar conclusions; namely, that the magnitude of the effects on stratospheric ozone from NO_x emissions could be significant depending on the size and cruise altitude of the SST fleet.

The next major concerted effort towards understanding the environmental effects of commercial supersonic aircraft began in the late 1980s (e.g., Johnston et al., 1989). The NASA High Speed Research Program (HSRP) and Atmospheric Effects of Stratospheric Aircraft (AESA) project provided a comprehensive effort to analyse the potential impacts of a future fleet of supersonic aircraft. Major assessment reports include Kawa et al. (1999) and a special international Intergovernmental Panel on Climate Change (IPCC) that considered fleets of both subsonic and supersonic aircraft (IPCC, 1999). The NASA and IPCC assessments assumed a specific SST design known as the High Speed Civil Transport aircraft (HSCT), which was assumed to be a large (300 passenger), long range (5000 nautical miles), Mach 2.4 supersonic transport aircraft with 84% of the emissions occurring in the Northern Hemisphere. For the 1999 assessments, HSCTs were projected to have fleets of 500 and 1000 aircraft by the year 2015. Zonally averaged two-dimensional (2-D) models were the primary tools for these studies and three early generation three-dimensional (3-D) models also provided analyses.

More recent were the European SCENIC (Scenario of aircraft emissions and impact studies on chemistry and climate) and HISAC (Environmentally friendly high-speed aircraft) projects that assumed specific aircraft concepts to develop different emission scenarios relative to those used in the NASA and IPCC assessments (Grewe et al., 2007, 2008, 2010a, b).

Research from several recent and ongoing studies are providing further analyses into the potential environmental impacts from supersonic aircraft, including: the U.S. FAA ASCENT Research Program; NASA Aeronautics (https://www.nasa.gov/aeronautics/supersonic-flight/); RUMBLE (RegUlation and norM for low sonic Boom Levels), EU H2020, 2017-2020; SENECA ([LTO] noiSe and EmissioNs of supErsoniC Aircraft); and MOREandLESS (MDO and REgulations for Low-boom and Environmentally Sustainable Supersonic aviation) EU H2020, 2021-2024.

NEW ESTIMATES OF THE POTENTIAL FOR COMMERCIAL SSTs

While commercial supersonic aircraft have already been shown to be technically feasible, there remain questions about whether these aircraft would be an economical success (e.g., see Rutherford et al., 2021). Questions remain about whether there would be sufficient demand at the higher ticket prices likely to be required, especially if significant parts of the flights would need to be flown at subsonic speeds. As already mentioned above, some companies have already dropped their development considerations, at least in the near term. Nonetheless, companies like Boom Supersonic and Spike Aerospace continue to develop commercial supersonic aircraft.

Supersonic aviation and sustainable aviation fuel

Supersonic aviation constitutes a unique challenge with regards to the reduction of aviation's climate impacts due to the different consequences of using sustainable aviation fuel (SAF) for supersonic rather than subsonic travel. For subsonic aviation, the key contributors to climate impacts are emissions of CO_2, emissions of NO_x, and formation of contrails. Adoption of SAF may reduce lifecycle CO_2 emissions, and the fuel composition changes expected with most SAF could also reduce overall contrail impacts - although the size of the effect of fuel composition on contrail impacts remains uncertain and combustion of SAF is not expected to result in a significant reduction in NO_x emissions. The other (non-contrail, non-CO_2) effects anticipated due to the different composition of SAF relative to conventional, fossil-derived jet fuel – a small increase in water vapour emissions, the potential for reduced emissions of non-volatile particulate matter (nvPM), and elimination of fuel sulphur – are expected to have only relatively minor climate consequences in the context of subsonic aircraft, although uncertainty remains high regarding the potential for aerosol-cloud interactions (Lee et al., 2021).

SAF adoption will have different consequences in the context of SSTs. Water vapour emissions into the stratosphere have consistently been identified as being either the largest or second- largest non-CO_2 component of SST climate impacts (Grewe et al., 2007; Pitari et al., 2008; Eastham et al., 2022; Zhang et al., 2023). As such, the potential for SAF adoption to result in an increase in water vapour emissions on the order of 10% (due to an increased hydrogen content per unit of energy release) could mean an associated increase in climate impacts. Simultaneously, the reduction in emissions of sulphur and nvPM would mean that SST emissions may not add significantly to the existing stratospheric aerosol layer. Simulations by Pitari et al. (2008) and Eastham et al. (2022) estimated that this layer would absorb and scatter a fraction of incoming solar radiation, resulting in radiative forcings (climate impacts) of the same order of magnitude as radiative forcing from ozone and water vapor but potentially of the opposite sign (cooling). Meanwhile, the relatively low humidity of the stratosphere means that contrails are not expected to be a significant contributor to SST climate impacts. However, much more research on the effects of SAF when used for SSTs is needed – the only publication on the specific topic of SAF usage for SSTs to date is an International Council on Clean Transportation (ICCT) report (Rutherford et al., 2022), which was not subject to peer review.

The concerns about noise from SSTs

Flying at supersonic speeds can create sonic booms which can be heard at ground level. Since there are no supersonic civilian aircraft currently flying, the impacts of noise from these aircraft on humanity are difficult to predict. The best data we have for supersonic en route noise are from military jet operations, and in the past from the Concorde, so existing regulations for supersonic aircraft are based on these datasets. Other than the Concorde legacy, there is little consensus science available either from the literature or from working groups to predict how people will react to repeated exposures to sonic booms (Sparrow, et al., 2019a, b). NASA's Quesst mission now plans to obtain community noise and perception data from supersonic overflights of their X-59 demonstration aircraft, designed for substantially reduced supersonic en route noise. These studies should produce the first sonic boom impact data in many years, but the science community will need to wait for those results. Landing and take-off (LTO) noise could be quite similar to that from subsonic aircraft with lower bypass-ratio engines, since the sound source will likely be jet-noise dominated and thus broadband in nature. Supersonic aircraft are anticipated to have faster take-off and landing speeds, leading to individual noise events with shorter durations and exposure times, than for subsonic aircraft. There is no available data to assess if this will result in increased annoyance.

There are no published studies in recent years to obtain human subjective data that could lead to insights for the supersonic aircraft noise community to assess in advance the typical annoyance impacts or health impacts such as sleep disturbance, onset of cardiovascular disease, or detrimental effects on children's learning.

New Studies on Climate and Ozone Impacts

Emissions from historical and projected fleets

The CAEP/12 ISG report (Wuebbles et al., 2022) describes the recent studies up to that point of the potential effects on stratospheric ozone and climate associated with emissions assumed for fleets of commercial supersonic aircraft that have been proposed. Here, we update those analyses to include studies published through the early fall of 2023.

Matthes et al. (2022) reviewed the current understanding of the potential effects on ozone and climate from supersonic aircraft emissions as well as the process for emissions inventory development for a fleet of SSTs. The assumptions needing to be made in developing such inventories, such as those discussed in this report, include:

- The number of supersonic vehicles available and the market that they serve (passenger mainliner and/or business jet), including the airports that they will operate from.
- Whether the supersonic demand is in addition to existing subsonic demand or replacing existing subsonic operations (entire operation or part of the operation such as business class only in passenger mainliner).
- The rate of supersonic fleet growth and subsonic fleet replacements, if any, and the number of vehicles available for this.
- Whether the supersonic vehicle is permitted to fly at supersonic speeds over land and consequently if the flight will traverse the coastline(s) to save flight time,.
- If specific flights will require a fuel stop.
- Emissions indices for atmospheric gases and particles such as NO_x that are dependent on engine performance and atmospheric ambient conditions.
- Whether the emissions generated are uni- or bi-directional (i.e., the outbound flight characteristics are assumed to be the same as the inbound).

The answers to these questions have differed between recent studies of SST impacts, complicating the interpretation of their results. Three different fleets, each assessed for environmental impact in different studies and developed using a different methodology, are described below.

Using vehicle performance modelling, market demand projection and global atmospheric chemistry-transport modelling, Eastham et al. (2022) examine potential impacts from fleets for two specific designs, one for Mach 1.6 (15-17 km cruise altitude) and one for Mach 2.2 (18-20 km cruise altitude). The market projections and experimental design used for Eastham et al., along with a detailed evaluation of impacts for a wider range of aircraft, are described in Speth et al. (2021). The SST45-1.6-60 fleet corresponds to an aircraft with a range of 4500 nmi, a cruise speed of Mach 1.6, and 60 passenger seats. The SST35-2.2-60 fleet correspond to an aircraft with a range of 3500 nmi, a cruise speed of Mach 2.2, and 60 seats. NO_x emissions are assumed to be 8.8 g/kg fuel for the Mach 1.6 aircraft and 19 g/kg fuel for the Mach 2.2 aircraft. Based on the projected market demand, the estimated fleet sizes in these analyses are 440-470 (SST45-1.6-60) and 160-170 (SST35-2.2-60) (see Speth et al., Table 9). Both supersonic fleets are assumed to be able to travel supersonically over land. Total annual fuel burns are assumed to be 19.3 Tg and 14.9 Tg for the Mach 1.6 and Mach 2.2 aircraft fleets, respectively.

Zhang et al. (2023) examines the effects on ozone and climate from a different design and fleet size for a commercial supersonic aircraft, as proposed by Georgia Tech University. The aircraft considered in this study is a Mach 2.2 55 seat commercial airliner with a design range of 4500 nmi. Details of the development of this vehicle are available in Mavris et al. (2019, 2020). The routes with associated demand represent the expected upper limit for the total potential market for commercial supersonic operations in 2050 consisting of just over 2.35 million annual flights globally with the vehicle characteristics described previously. The number of flights translates into about 6800 supersonic commercial aircraft globally. The projected fuel burn and NO_x emission are 122.32 Tg/yr and 1.78 Tg (NO_2)/yr respectively for this proposed fleet of supersonic aircraft, which gives a NO_2 emission index around 15 g/kg fuel burn.

Pletzer et al. (2022) investigate the atmospheric impacts of a fleet of hypersonic aircraft using hydrogen fuel. Two different aircraft are considered, a Zero Emission High Speed Transport (ZEHST) fleet at Mach 4-5 with cruise altitude at 26 km and another Long-Term Advanced Propulsion Concepts and Technologies (LAPCAT) at Mach 8 flying at 35 km. The aircraft designs differ in terms of passenger seats, with 60 for ZEHST and 300 for LAPCAT. Approximately two-thirds of the water vapor emissions occur at stratospheric altitudes and one-third in the troposphere. Total water vapor emissions are 21.6 Tg/year and 13.4 Tg/year, respectively for the Mach 4-5 and Mach 8 aircraft. Around 60% to 65% of the small emissions of NO_x are emitted below 18 km, and the small hydrogen (H_2) emissions assumed is emitted to around 75 % at stratospheric altitudes. A revision of the emission estimate of the aircraft concept utilizing measurements and modelling approaches leads to a much larger NO_x emission index of around 30-35 gNO_2/kg-kerosene-equivalent for the whole trajectory and might even reach 60 for cruise conditions (Viola et al., 2021).

Ozone and climate impacts from new fleet projections

The CAEP/12 ISG report (Wuebbles et al., 2022) provides a thorough summary of the estimated climate and ozone impacts associated with projected SST fleets. We here update those impacts based on the studies identified above.

The conclusions reached by studies discussed in the 2022 report is that emissions of water vapor and NO_x are the dominant contributors to the non-CO_2 climate impacts resulting from supersonic aviation, due primarily to the greater altitude of the emissions. Fritz et al. (2022) found that, for emissions altitudes of 14 to 25 km, ozone depletion attributable to NO_x increases monotonically and non-linearly from near-zero to over 100 mDU per Tg of fuel burned in the mid-stratosphere. Assuming typical emissions indices for NO_x and water vapor, and fuel sulphur content of 600 ppm, they also found that both water vapor and sulphur could contribute significantly to ozone depletion, but that NO_x would dominate.

These findings are echoed by studies of specific supersonic and hypersonic emissions inventories. In the studies already discussed above, Zhang et al. (2023) and Eastham et al. (2022) both investigated fleets of small civil airliners carrying up to 60 and 55 passengers, respectively. The fleet modelled in Eastham et al. burned 14.9 Tg of fuel per year, emitting 280 Gg of NO_x, and cruising at altitudes of 18-20 km at Mach 2.2;

the Zhang et al. (2023) fleet burning 122 Tg of fuel and emitting 1.8 Tg of NO_x at similar altitudes. Both studies found that stratospheric ozone loss would be expected, with a total global ozone layer depletion of 0.78 and 0.74% respectively. Given the differences in NO_x emissions this suggests roughly a factor of five difference in sensitivity between the models underlying the two studies.

The recent studies discussed above, assuming the use of traditional jet fuel in a fleet of supersonic aircraft, show that the annual CO_2 emissions could be on the order of 4.5% to 37.3% of the total CO_2 emissions of the "current" 2018 subsonic fleet (Lee et al., 2021). The Eastham et al. (2022) and Zhang et al. (2023) studies also found that the changes in ozone – in combination with stratospheric water accumulation - would be expected to produce a positive radiative forcing (warming) despite differences in fleet NO_x emissions indices, total fuel burn, and cruise altitude. Eastham et al. (2022) found a warming of 25 mW/m^2 from these two factors, compared to Zhang et al. (2023) who found a warming of 70 mW/m^2, suggesting a similar order of magnitude of response. Both studies found that the radiative forcing due to ozone loss would exceed that due to water vapor accumulation. In contrast, the "current" 2018 subsonic fleet as analysed by Lee et al. (2021) gives an RF of 115 (35-194) mW/m^2 and an effective radiative forcing (ERF) of 66.6 (21-111) mW/m^2 for the non-CO_2 effects – the difference primarily being due to the ERF metric greatly reducing the effect of contrails and other particle emissions relative to the RF metric. With the long-lived effects of CO_2 emissions included, the 2018 subsonic fleet results in a RF of 149 (70-220) mW/m^2. In summary, the climate impact from a fully develops supersonic aircraft fleet could be comparable in magnitude to that from the entire projected subsonic fleet.

The work by Pletzer et al. (2022) on emissions from a hydrogen-powered hypersonic transport similarly found that NO_x and water vapor emissions would cause radiative forcings of 32 to 56 mW/m^2, with water emissions and their impacts magnified by using hydrogen as fuel instead of kerosene. Pletzer and Grewe (2024) analyse sensitivities with respect to altitude and latitude of the hypersonic emissions and show that the water vapor perturbation lifetime continues the known tropospheric increase with altitude and reaches almost six years in the middle stratosphere.

Although ozone loss and water vapor are already well understood as impacts of high-speed civil aviation, aerosol emissions constitute a re-emerging concern. When burned, sulphur in the fuel will form sulphur dioxide which eventually forms sulphate aerosols, while incomplete combustion can result in the formation of carbonaceous aerosol (soot). Both Zhang et al. (2023) and Eastham et al. (2022) found that the additional scattering and absorption of radiation by sulphate and carbonaceous aerosols could provide a net cooling effect which is magnified by the long lifetime of aerosol in the stratosphere. This effect was calculated to be 35 and 100% respectively of the positive forcing resulting from changes in stratospheric ozone due to supersonic aircraft NO_x emissions. Earlier studies had calculated that ozone depletion resulting from sulphur emissions could be a significant concern with a strong dependence on pre-existing levels of sulphate aerosol (e.g. from volcanic eruptions), and that there may be climate consequences (Weisenstein et al., 1996; Pitari et al., 2008) but others had assumed its elimination in future fuels (e.g. Kinnison et al., 2001; Zhang et al., 2021a,b).

The climate response to ozone changes resulting from sulphur removal is also different from the response to increased NO_x. Eastham et al. (2022) found that sulphur removal for a low-altitude SST fleet could reduce ozone depletion by 52% but that the net ozone radiative forcing would be increased, implying that the ozone changes incurred by sulphur and NO_x emissions are qualitatively different. Since sustainable aviation fuels (SAF) are likely to not contain sulphur and are expected to produce fewer carbonaceous aerosols, SAF-fuelled supersonic aircraft may lose the "masking effect" of aerosol emissions while perhaps also inducing a larger ozone-related radiative forcing. Several other studies of the environmental impacts from SAF are ongoing but no scientific consensus has been reached. Additional research for actual SAF emissions is also needed.

One area which requiring more analysis and research is the potential for changes in local and global air quality due to supersonic aviation. This is subject both to the nature of the regulations which will be applied to future supersonic aircraft, and uncertainty regarding the atmospheric response to higher-altitude emissions.

NOISE IMPACTS

The noise impacts of SST aircraft are discussed in two distinct sections representative of specific noise domains. The first addresses the unique supersonic en route noise of low sonic boom shaped signatures and, the second addresses the SST landing and takeoff (LTO) noise around airports.

In 2024 the knowledge base related to sonic boom noise only has moderate updates since the release of the 2019 CAEP Environmental Report and the 2021 update (ICAO, 2021). Hence the section on sonic boom noise from those white papers is the basis of what is to follow. The permission of the authors (A. Loubeau of NASA and V. Sparrow of Penn State) to reproduce these next paragraphs has been secured. Almost all ongoing noise research regarding supersonic aircraft is focused on certification of those aircraft and on preparations for community noise surveys.

Introduction to sonic booms

Sonic booms are the unique sounds produced by supersonic aircraft as a result of traveling at speeds at or greater than Mach 1. This section summarizes many of the properties and impacts of sonic booms, as we know them today.

Conventional sonic booms are widely considered to be loud, and this forms the basis of current regulations in many countries that prohibit supersonic overland flight. However, new research (Sparrow, et al., 2019a, b) has provided aeronautical engineers with the tools necessary to develop quieter “low-boom” aircraft designs that may be available in 5 to 10 years (Sparrow, et al., 2019a,b; Kirz and Rudnik, 2019). Hence, sonic boom research needs to clearly distinguish whether the sonic booms are the conventional N-wave sounds, so called because of their letter N pressure versus time shape, or the new, quieter sounds, most recently denoted acoustic pressure signatures within Working Group 1, which are considerably smoothed. Research has thus-far suggested that the new acoustic pressure signatures could be as much as 35 dB quieter than conventional booms under certain cruise conditions (Morgenstern et al., 2010). It is less clear if the same noise reduction can be achieved in other flight phases, such as that of acceleration focus and when the supersonic aircraft is operating off-design, i.e., not at the designed cruise speed.

Human response studies

Sparrow, et al. (2019a, b) showed that sonic booms can be reproduced quite accurately in the laboratory, and this makes it possible to perform subjective experiments under controlled conditions. Although no actual supersonic aircraft has yet produced a quiet acoustic pressure signature, a similar surrogate sound can be created using a special aircraft dive manoeuvre. This makes it possible to conduct tests with real military aircraft outdoors for either loud or quiet acoustic pressure signatures, complementing the laboratory tests.

Several subjective tests have been conducted. One trend seen in studies from both the U.S. and Japan (Sparrow, et al., 2019a, b) is that annoyance due to sonic boom noise is greater indoors compared to outdoors. The findings show that indoor annoyance can be estimated based on the outdoor sonic boom exposure. There has been recent work to establish that both rattle and vibration contribute to indoor annoyance of sonic booms. One interesting point is that although conventional N-waves can be accompanied by a startle response, it turns out that low-booms are of low enough amplitude that they don't induce a consistent physiological startle response (Sparrow, et al., 2019a, b).

There has been substantial work in recent years to establish metrics to assess sonic boom noise. Out of a list of 70 possible metrics, a group of six metrics has been identified for the purposes of use in en-route noise certification standards and in developing dose-response curves for future community response studies (Sparrow, et al, 2019a, b). While low-booms are much quieter than the conventional N-wave booms, additional community studies with a low-boom aircraft need to be conducted to assess public response.

The potential for new human subject noise response data in the future is much more plausible now that NASA has built and is getting ready to fly its new X-59 demonstration aircraft as part of its Quesst mission. Test plans are ongoing to overfly communities in the 2026-2028 time frame. These studies are expected to yield the first high-quality annoyance data of acoustic pressure signature noise.

Recent European research programs have aimed to provide additional information in this area. The European RUMBLE program attempted to garner sleep study results for shaped sonic booms, but in the end, only task/performance data while the subjects were fully awake was acquired (Marmel et al., 2024), and this new data is still being interpreted. The European program More&Less is focused on other subtopics related to supersonic flight and no new human subjective studies are planned.

Non-technical aspects of public acceptability for sonic boom

An additional aspect that should be considered for sonic booms includes the non-technical aspects of acceptability. The CAEP Steering Group specifically requested that ISG investigate this topic. A preliminary discussion has revealed a strong resemblance to the non-acoustical factors of subsonic aircraft noise, previously mentioned in Section 2 "Community Noise Annoyance" of the 2019 CAEP Environmental Report. There are currently no peer-reviewed studies on the topic of non-acoustical factors for sonic boom noise, but it seems plausible that the knowledge of subsonic aircraft non-acoustical factors could be extended for application to sonic boom noise non-technical aspects.

Impacts of noise on animals

Recently there has been renewed interest regarding the impacts of sonic boom noise on animals. Fortunately, there is an extensive literature extending from before the days of Concorde to recent years, mostly for conventional N-wave aircraft.

NASA conducted studies in the late 1990s and early 2000s to assess the impact of overwater sonic booms on marine mammals (Sparrow, et al., 2019a, b). Research regarding how much sonic boom noise transitions from air into water, has found that relatively little of the sound penetrates into the water, although this is dependent on environmental factors such as the state of the water/air interface (Sparrow, et al., 2019a, b).

In 1997 and 1998 a study of a colony of seals exposed to Concorde booms on a regular basis showed that the booms didn't substantially affect the breeding behaviour of gray or harbour seals. It instead seems that these animals substantially habituated to hearing these N-wave sonic booms on a routine basis (Perry, et al., 2002).

Most of what is known about noise impacts on animals comes from the literature of the effects of subsonic aircraft and other anthropogenic noise sources, not sonic booms, on animals. It is well known that human activities can interfere with animal communication, for example, and there is some evidence that aircraft noise can penetrate into the ocean (Erbe et al., 2018). However there have not been many specific studies on the effects of sonic boom noise on animals in recent years. Some species with good low-frequency hearing, such as elephants, have never been evaluated regarding sonic boom noise.

Landing and take-off noise

As has already been stated, with the absence of supersonic aircraft since the retirement of Concorde, there is no scientific literature on human reactions to landing and take-off noise (LTO) from supersonic aircraft around airports. In order to operate at supersonic speeds, aircraft will need to be designed to have sufficient cruise thrust that is reliant on higher jet exhaust velocity. This pushes the aircraft designer towards the use of lower bypass-ratio engines. In contrast, the evolution of subsonic aircraft to use higher bypass ratio engines has significantly reduced jet noise and overall LTO noise. Variable noise reduction systems (VNRS) could be incorporated into future supersonic aircraft designs to mitigate the noise impacts associated with the use of lower bypass-ratio engines. Consequently, during the CAEP/14 cycle, Working Group 1 (WG1), Noise, will continue to work on integrating variable noise reduction systems for supersonic aeroplanes into the ICAO Standards and Recommended Practices (SARPs).

In the absence of supersonic aircraft and associated scientific literature on reaction to supersonic aircraft LTO noise, we can broadly surmise that supersonic aircraft LTO noise may be similar to that from subsonic aircraft with lower bypass-ratio engines, since the sound source will likely be jet-noise dominated and thus broadband in nature. Thus, the sound character will not be distinctly different. Supersonic aircraft would be anticipated to have faster take-off and landing speeds, leading to individual noise events with shorter durations and exposure times but potentially greater noise magnitudes than for subsonic aircraft.

Research needs

Regarding noise concerns, much progress has been made to model and mitigate the effect of sonic booms from supersonic flight. Ongoing research to assess the impact on the public indicates that future low-boom supersonic aircraft designs will create quieter sonic 'thumps' that are much less annoying than conventional sonic booms. Upcoming NASA community tests with the X-59 demonstrator aircraft will collect important data relating to noise exposure and resulting public reactions.

There are several recent and ongoing projects sponsored by governments around the world where analyses are being done related to potential environmental impacts from supersonic aircraft. Examples of these programs are summarized below:

- U.S. FAA ASCENT (multiple projects)
- NASA Aeronautics (https://www.nasa.gov/aeronautics/supersonic-flight/)
- RUMBLE (RegUlation and norM for low sonic Boom Levels), EU H2020, 2017-2020: A collaboration of European and Russian organizations committed to the production of scientific evidence for supporting the new international regulations regarding the low-level sonic booms.
- SENECA, ([LTO] noiSe and EmissioNs of the supErsoniC Aircraft), EU H2020, 2021-2024: A collaboration of academic and industrial aerospace entities from Europe aiming to focus on noise and emissions in the vicinity of airports and the global climate impact of supersonic aircraft.
- MORE&LESS, MDO and REgulations for Low-boom and Environmentally Sustainable Supersonic aviation, EU H2020, 2021-2024: A collaboration of European and US partners determined to improve the understanding of sonic boom, jet noise and pollutant emissions that will lead to a holistic assessment of the environmental impact of supersonic aircraft at local, regional and global levels.

Various companies are also considering the design and development of supersonic aircraft that will need to be evaluated as they get closer to fruition.

CONCLUSIONS

There has been relatively little new research on the environmental impacts of supersonic aircraft since the previous ISG report (Wuebbles et al., 2022). Many key factors regarding the environmental impacts of supersonic aviation remain unchanged. Supersonic aircraft are still expected to produce more than three times as much CO_2 per revenue-passenger kilometre as subsonic aircraft (Kharina et al., 2018; Wen et al., 2020; Eastham et al., 2022). Furthermore, the non-CO_2, non-contrail warming from supersonic aircraft is still projected to exceed that (per revenue-passenger kilometre) from subsonic aircraft due largely to emissions of stratospheric water vapour and the ozone-depletion effects of emitted NO_x (Eastham et al., 2022; Zhang et al., 2023). However, the commercial and research landscapes have both changed in ways which demand additional research.

First, the potential launch of a new commercial supersonic aircraft has increased the need for high-quality research into the health and environmental effects of supersonic aircraft. In particular, there is an urgent need for multi-model assessment of the effects that supersonic aircraft might have on the ozone layer, climate, and global air quality. Recent results are dominated by a relatively small number of research groups using a limited set of global models, compared to the larger assessments carried out in the 1990s. These recent studies have also only considered a small potential set of scenarios for both SST deployment and future atmospheric composition.

Second, the effect of changes in fuel composition on the environmental impacts from supersonic aircraft emissions must be addressed. Such changes in fuel composition could accompany large-scale adoption of sustainable aviation fuels (SAF) produced using certain pathways. Emissions of water vapour, sulphur, and soot are relatively minor considerations for subsonic aircraft but have disproportionately different implications for supersonic aircraft, and all three are expected to change by between 10 and 100% with the adoption of certain kinds of SAF.

Finally, research is needed to better understand the likely noise effects of the next generation of supersonic aircraft. This includes the need for new research into the effects of both conventional sonic booms and the potential of new quieter designs. With all the community survey data on supersonic noise exposure either over 20 years out of date or of limited relevance to the new generation of designs, it is difficult to predict the impacts that might result from a resumption of regular supersonic service. This is especially true if supersonic flight over land is permitted.

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LIST OF ABBREVIATIONS

AESA	Atmospheric Effects of Stratospheric Aircraft
CAEP	Committee on Aviation Environmental Protection
CIAP	Climatic Impacts Assessment Program
CO_2	Carbon Dioxide
COMESA	Committee on Meteorological Effects of Stratospheric Aircraft
COVOS	Comité d'Études sur les Conséquences des Vols Stratosphérique
ERF	Effective Radiative Forcing
EU	European Union
FAA	Federal Aviation Administration
HISAC	Environmentally Friendly High-Speed Aircraft
HSCT	High Speed Civil Transport
HSRP	High Speed Research Program
ICAO	International Civil Aviation Organization
ICCT	International Council on Clean Transportation
IPCC	Intergovernmental Panel on Climate Change
ISG	Impacts and Science Group
LAPCAT	Long-Term Advanced Propulsion Concepts and Technologies
LTO	Landing and Take-off
MOREandLESS	MDO and REgulations for Low-boom and Environmentally Sustainable Supersonic aviation
NASA	National Aeronautics and Space Administration
nmi	nautical miles
NOx	Nitrogen Oxides
NO_2	Nitrogen Dioxide
nvPM	non-volatile particulate matter
RF	Radiative Forcing
RPK	Revenue Passenger Kilometre
RUMBLE	RegUlation and norM for low sonic Boom LEvels
SAF	Sustainable Aviation Fuel
SCENIC	Scenario of aircraft emissions and impact studies on chemistry and climate
SENECA	[LTO] noiSe and EmissioNs of supErsoniC Aircraft
SST	Supersonic Transport
VNRS	Variable Noise Reduction Systems
ZEHST	Zero Emission High Speed Transport

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