Project 47 Clean-Sheet Supersonic Aircraft Engine Design and Performance

Massachusetts Institute of Technology

Project Lead Investigator

Prof. Steven R. H. Barrett
Professor of Aeronautics and Astronautics
Department of Aeronautics and Astronautics
Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge, MA 02139
617-452-2550
sbarrett@mit.edu

University Participants

Massachusetts Institute of Technology (MIT)

- P.I.: Prof. Steven R. H. Barrett
- FAA Award Number: 13-C-AJFE-MIT, Amendment Nos. 052, 059, 074, 076, 090, and 106
- Period of Performance: March 29, 2019 to August 31, 2023 (with the exception of funding and cost-share information, this report covers the period from October 1, 2021 to September 30, 2022)
- Tasks:
    1. Evaluate the impact of improved technology on relative performance benefits of clean-sheet and derivative engines
    2. Evaluate the impact of advanced take-off trajectories for supersonic transport (SST) using variable noise reduction systems (VNRS) on community noise

Project Funding Level

This project received $1,250,000 in FAA funding and $1,250,000 in matching funds. Sources of match are approximately $288,000 from MIT, plus third-party in-kind contributions of $177,000 from Byogy Renewables Inc., $634,000 from NuFuels LLC, and $151,000 from Savion Aerospace Corporation.

Investigation Team

- Prof. Steven Barrett - P.I. (Tasks 1 & 2)
- Dr. Raymond Speth - co-P.I. (Tasks 1 & 2)
- Dr. Choon Tan - co-P.I. (Tasks 1 & 2)
- Dr. Jayant Sabnis - co-investigator (Tasks 1 & 2)
- Mr. Prakash Prashanth - graduate student (Task 1)
- Mr. Laurens Voet - graduate student (Task 2)
- Mr. Wyatt Giroux - graduate student (Task 1)

Project Overview

Engines for supersonic aircraft, compared with those for subsonic aircraft, present unique challenges in terms of their fuel consumption, noise, and emissions impacts because of their unique operating conditions. The propulsion systems currently proposed by the industry are derivative engines (Figure 1) designed around the unmodified core (high-pressure compressor [HPC], combustor, and high-pressure turbine [HPT]) of existing subsonic engines, with modifications to the low-pressure spool (fan and low-pressure turbine [LPT]).

This project is aimed at evaluating the design space of "clean-sheet" engines designed specifically for use on civil supersonic aircraft, and to determine the resulting environmental performance of such engines. Unlike previous commercial supersonic engines, which were adapted from military aircraft, or planned propulsion systems derived from current commercial engines, a clean-sheet engine takes advantage of recent advances in propulsion system technology to substantially improve performance, and reduce emissions and noise footprints. This project will quantify these benefits for a range of engine designs relevant to currently proposed civil supersonic aircraft.

Specific goals of this research are as follows:

- Develop a framework for quantifying the noise and emissions footprints of propulsion systems used on civil supersonic aircraft
- Assess the difference in environmental footprints between a derived engine and a clean-sheet engine for a civil supersonic aircraft
- Assess VNRS used during noise certification of Supersonic Level 1 type aircraft and their effects on landing and take-off (LTO) emissions
- Develop a roadmap for technology development, focusing on reducing the environmental footprint associated with engines for civil supersonic aircraft

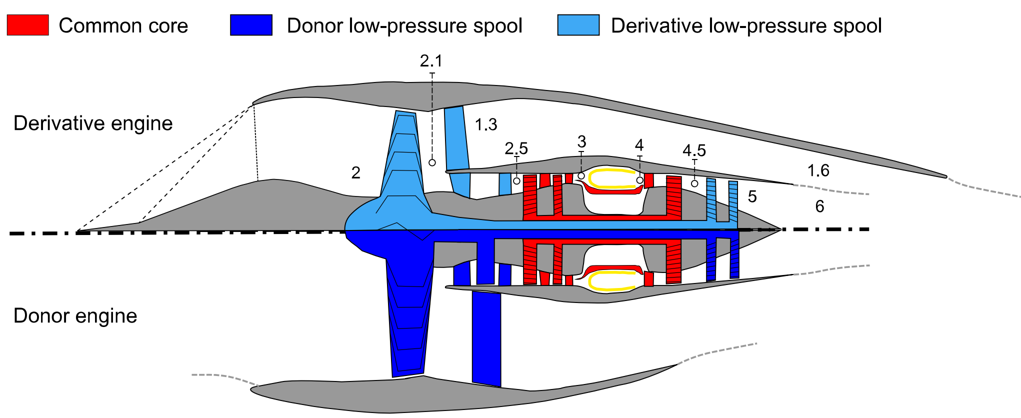

Figure 1. Engine architecture schematic. Lower half shows the subsonic donor engine. The high-pressure spool (red) core is used in the derivative engine (top half) along with modifications to the inlet, fan, and nozzle, as shown in the top half.

Task 1 - Evaluate the Impact of Improved Technology on Relative Performance Benefits of Clean-Sheet and Derivative Engines

Massachusetts Institute of Technology

Objective

The objective of this first task is to quantify the impact that improvements in technology will have on the relative performance of clean-sheet engine designs over derivative designs. Specifically, we consider the impact of technology improvements in the turbomachinery design, turbine material, cooling technology, and combustor design for low nitrogen oxide (NO_x) emissions for the Supersonic Transport Concept Aircraft (STCA) developed by NASA (Berton et al., 2019).

Research Approach

We parameterize the technology level of various components as follows:

Turbomachinery
The technology level of the turbomachinery components (fan, compressor, and turbines) is quantified by the polytropic efficiency (η_p) of the components.

Turbine material and cooling technology
The turbine material limits, such as advanced ceramic matrix composites, thermal barrier coatings, and cooling technology, are quantified by the metal temperature that the turbine vanes and blades are allowed to reach (T_{vane} and T_{blade}, respectively).

Combustor technology
The design space benefits of a clean-sheet engine design would be more readily accessible if the emissions of NO_x were reduced by using a more advanced combustor model. The combustor technology can be parameterized by using a previously developed reactor network model.

Major Accomplishments

The sensitivity of the thrust specific fuel consumption to the technology levels of the turbomachinery, turbine material, and cooling were calculated for both clean-sheet and derivative engines. Figure 2 shows that the derivative engine benefits from a 0.33% and 0.46% improvement in SFC per percentage-point improvement in the polytropic efficiency of the LPT and fan, respectively. These sensitivities are calculated for an optimal engine, sized for a fixed propulsion system requirement (on the basis of the thrust requirement of the STCA). Specifically, each point on the graph represents an engine optimized for minimum SFC with the constraints outlined in the previous section. Because the derivative engine uses the donor core, only the fan and LPT can be designed by using the improved technology.

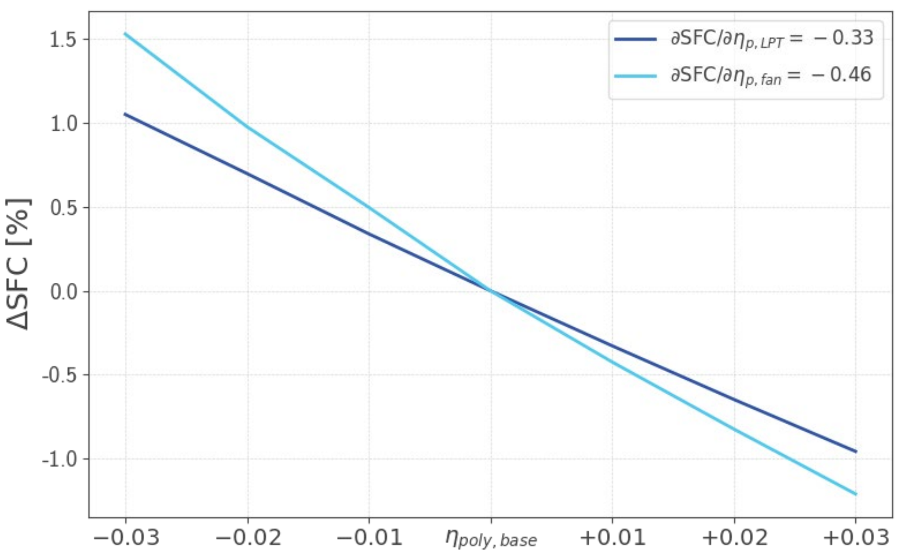

Figure 2. Sensitivity of a derivative engine SFC to the polytropic efficiency of the low-pressure spool components (LPT and fan)

The sensitivities of the clean-sheet engine are different from those of the derivative engine because the core of the engine can be redesigned to obtain an SFC optimal engine at each point. Because the high-pressure spool of the clean-sheet engine is designed, we also calculated the sensitivity of SFC to the polytropic efficiency of the HPC and HPT in addition the low-pressure spool components, as shown in Figure 3.

For a clean-sheet engine design, the pressure ratio of the engine is limited not by the material limits of the last stage of the HPC but by the imposed constraint on the NO_x emissions index, EI(NO_x). We found that a 1% increase in the allowable turbine metal temperature results in 0.25% decrease in the clean-sheet engine SFC.

The cumulative effects of improvements on each of the above engine components are shown for both the derivative and clean-sheet engine in Figure 4. Table 1 shows the assumed magnitude of improvement to the engine components. Improvements in the low-pressure spool and low-NO_x combustor designs have the largest benefit in clean-sheet engine SFC. The clean-sheet engine with advanced technology has a 4.1% lower SFC than the derivative engine with advanced low-pressure spool components.

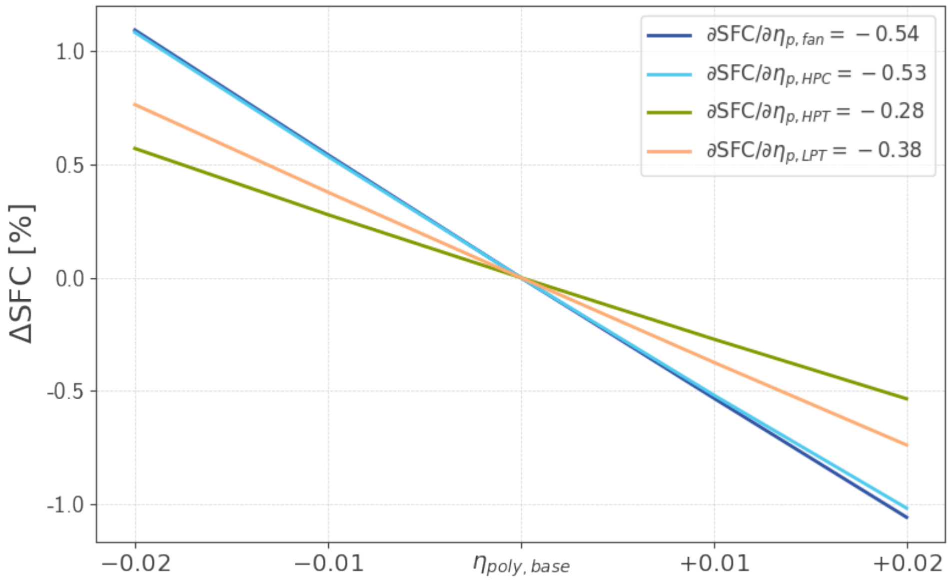

Figure 3. Sensitivity of clean-sheet engine SFC to the polytropic efficiency of the turbomachinery.

Table 1. Assumed magnitude of technology improvements for clean-sheet and derivative engines.

Components	Derivative engine	Clean-sheet engine
$\Delta\eta_p$ of low-pressure spool turbomachinery	+0.02	+0.02
$\Delta\eta_p$ of high-pressure spool turbomachinery	-	+0.01
$\Delta T_{metal,HPT}$	-	+100 K
EI(NO_x)	-	Improved low-NO_x combustor modeled on the PW1133G TALON-X combustor

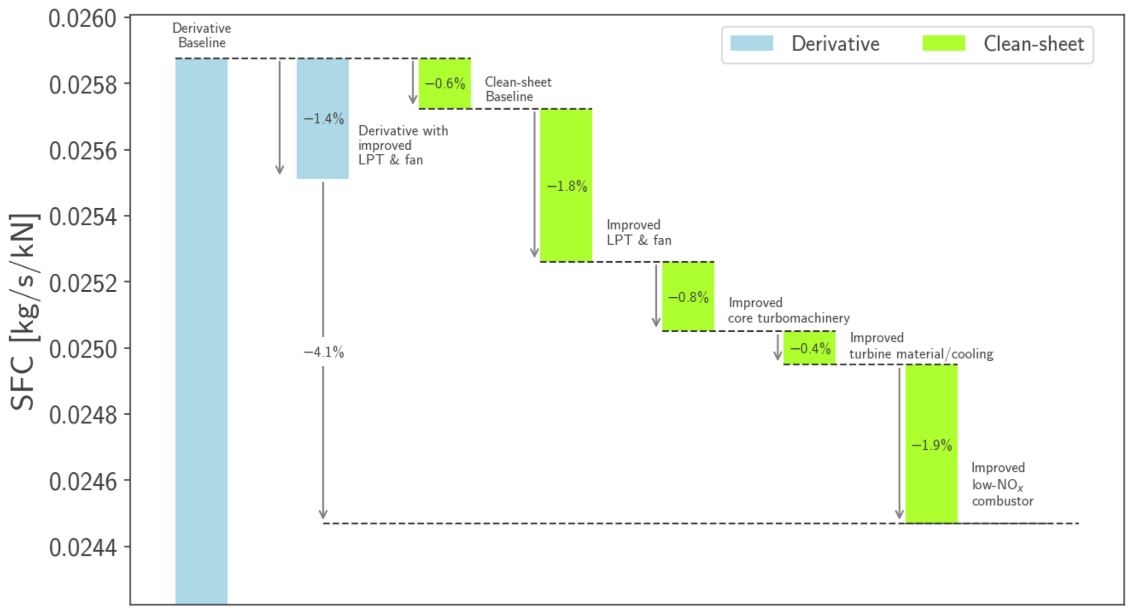

Figure 4. Impact of technology improvements on the SFC of derivative and clean-sheet engines for the STCA.

Publications

None.

Outreach Efforts

- Presentation at the ASCENT Advisory Committee Spring Meeting (April 5–7, 2022)
- Presentation at the Aviation Emissions Characterization Roadmap Annual Meeting (May 24–26, 2022)

Awards

None.

Student Involvement

This work was performed primarily by graduate research assistant Prashanth Prakash working under the supervision of Dr. Jayant Sabnis, Dr. Raymond Speth, and Dr. Choon Tan.

Plans for Next Period

In the next period, we will quantify the effects of a fan diameter constraint on the emissions and noise of SST aircraft. The results presented above focus on engines with a fixed fan diameter, prescribed for the NASA STCA. Varying the fan diameter will alter the engine design characteristics (fan pressure ratio, nacelle drag, etc.) for the same mission requirements, thereby affecting mission fuel consumption, NO_x/CO_2 emissions, and noise.

We will also assess the potential for using unconventional engine architectures to decrease the environmental impacts of SST, both in cruise and LTO. The difference between the LTO and cruise requirements of SST engines is greater than that of subsonic equivalents because of the supersonic design conditions. We will investigate the use of electrical machines (motors and generators) to be used along with variable geometry components to design "variable cycle" gas turbine engines for SST that can lead to lower noise and emissions from SST aircraft.

References

Berton, J. & Geiselhart, K. (2019). *NASA 55-tonne Supersonic Transport Concept Aeroplane (STCA) release package.* NASA GRC/NASA LaRC.

Task 2 - Evaluate the Impact of Advanced Take-off Trajectories for SST Using VNRS on Community Noise

Massachusetts Institute of Technology

Objectives

The objective of this task is to extend our evaluation of the noise impacts of advanced take-off trajectories to incorporate VNRS. These advanced take-off trajectories are designed and optimized by using the take-off certification noise level as a representative metric for noise around airports. The take-off certification noise level incorporates noise levels measured at two locations, i.e., the lateral and flyover microphones. To assess whether these advanced take-off trajectories are effective in community noise reduction, we calculate community noise contours.

Research Approach

- The pyNA aircraft noise estimation tool (Voet et al., 2021) is used to calculate the community noise contours around airports for the advanced take-off trajectories for SST using VNRS.
- The community noise contours are applied to an existing airport. In this work, the New York John F. Kennedy (JFK) airport is chosen. The departure from JFK is from runway 31L.

Major Accomplishments

Figure 5 summarizes the noise levels of the advanced take-off trajectories for the NASA STCA using VNRS when the certification noise metric is applied. Reduced cut-back altitudes (from 260 m to 35 ft) and increased take-off speeds (from 200 kts to 250 kts) enable as much as 7 EPNdB of cumulative noise reduction. When continuous thrust control (also described as programmed thrust cut-back) is used, an additional 3.6 EPNdB of cumulative noise reduction can be achieved. The inherent tradeoff between lateral and flyover noise for the discrete high-altitude and low-altitude thrust cut-back trajectories can be seen in Figure 5. At increased take-off speed, the advanced take-off trajectory with continuous thrust control avoids this tradeoff by reducing flyover noise without increasing lateral noise, with respect to those with the low-altitude cut-back.

Programmed high-lift devices are found to be ineffective in reducing take-off noise for the NASA STCA. Figure 5 shows that, even with the use of advanced take-off trajectories, the NASA STCA is unable to meet current noise limits for subsonic transport set by the International Civil Aviation Organization (ICAO) in Annex 16 Chapter 14. Additional noise reduction might be achieved by incorporating reduced thrust take-off procedures, as explored by Berton et al. (2019) and Olson (1992).

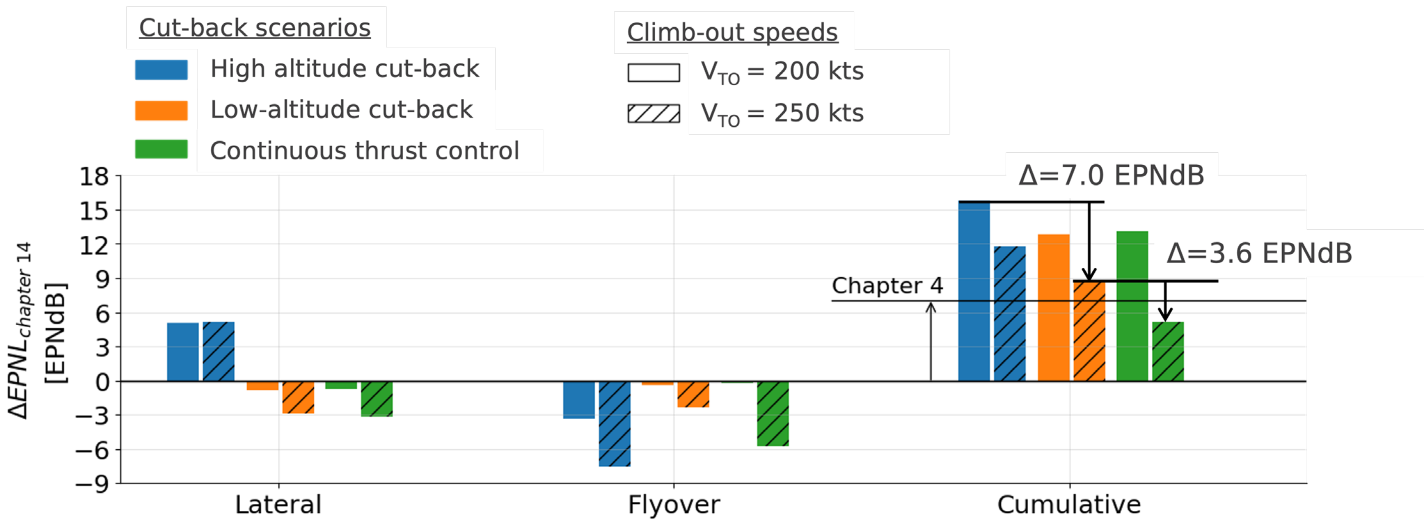

Figure 5. Comparison of the lateral, flyover, and cumulative certification noise levels of standard and advanced trajectories with the ICAO Annex 16 Chapter 14 noise limits. The Annex 16 Chapter 4 noise limits are also indicated for reference.

The impact of the advanced take-off trajectories on community noise is shown in the sound exposure level (SEL) line contours and ΔSEL color contours in Figure 6. The top left plot shows the community noise contours for the standard take-off trajectory, abiding by the current noise standards for subsonic transport in ICAO Annex 16. The noise is highest underneath the flight path on the centerline and decreases when laterally moving away in the *y*-direction. The center plot on the top row shows the ΔSEL between the high-altitude and low-altitude cut-back.

With the low-altitude cutback, the community noise contours show the tradeoff between points in the airport vicinity and downstream, indicated by the blue and red regions. This tradeoff is also captured when the certification noise metric is used. At increased take-off speeds, the same tradeoff is observed; however, the average noise is reduced because of the reduced jet shear at higher take-off speeds.

The high-altitude cut-back achieves the largest noise reduction in downstream regions, whereas the low-altitude cut-back achieves the largest noise reduction in regions in the vicinity of the airport. With continuous thrust control (at increased take-off speeds), the advanced take-off trajectory achieves noise reduction in the combined region between airport vicinity and downstream. Overall, this trajectory achieves the largest noise reduction relative to all other advanced take-off trajectories.

Figure 7 compares the community noise contours for the high-speed advanced take-off trajectories with continuous thrust control and low-altitude cut-back, i.e., the two trajectories with lowest cumulative noise levels when the certification noise metric is used. With the continuous thrust control trajectory, noise is reduced in the areas where it was already low (away from the flight path, as shown in the line contour of Figure 5), and is not reduced underneath the flight path, where the noise was the highest. These findings illustrate where the certification and community noise metrics are not aligned, and thus suggest re-examination of the certification noise metric for SST using advanced take-off trajectories.

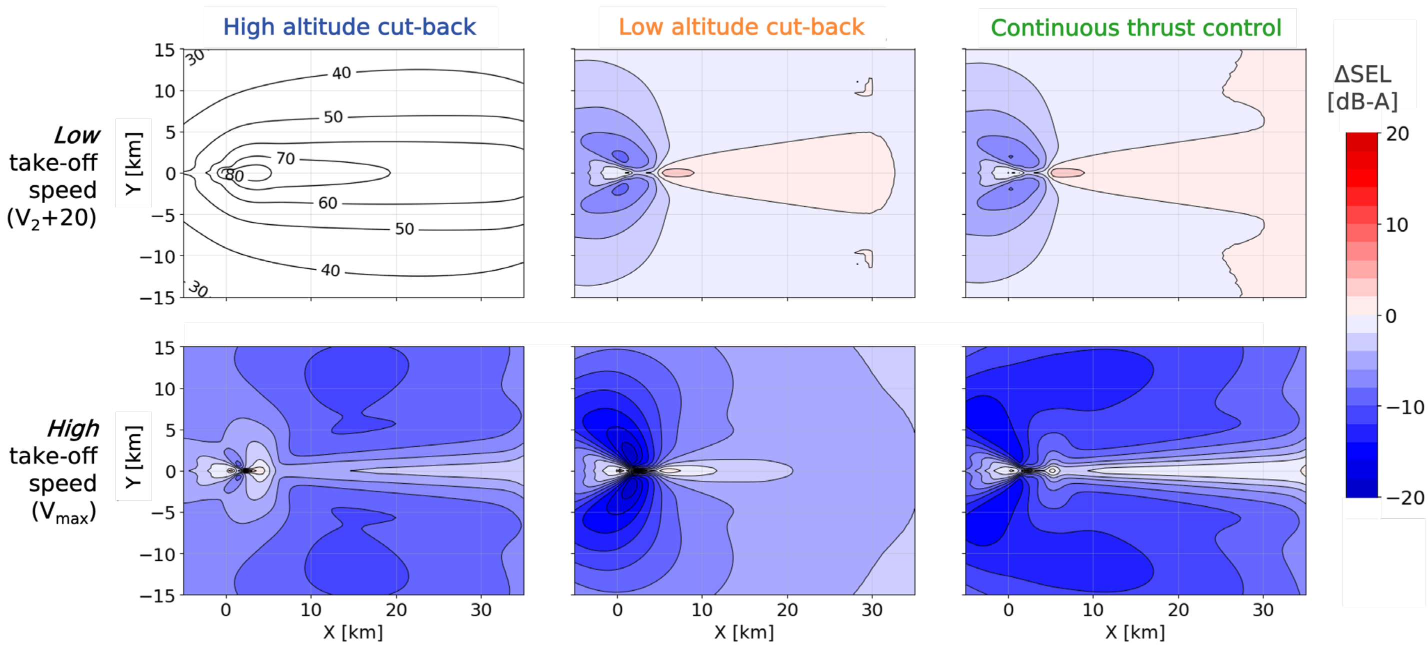

Figure 6. Top left: SEL line contours for the NASA STCA standard single thrust cut-back trajectory abiding by the noise standards for subsonic transport defined in ICAO Annex 16. Top middle and top right, bottom row: ΔSEL color contours for the NASA STCA advanced take-off trajectories. The origin is the aircraft brake release point.

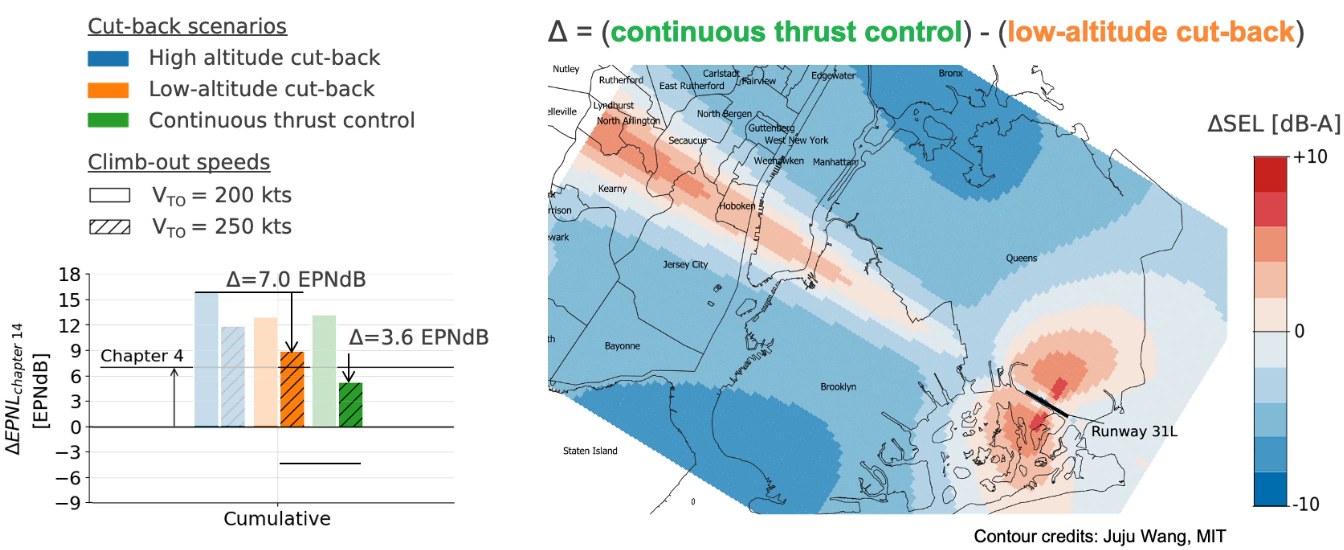

Figure 7: Left: comparison of certification cumulative noise levels between high-speed continuous thrust control and low-altitude cut-back trajectories. Right: ΔSEL color contours for high-speed continuous thrust control and low-altitude cut-back trajectories taking off from runway 31L at New York JFK airport.

Publications

Voet, L., Speth, R. L., Sabnis, J. S., Tan, C. S., & Barrett, S. R. (2022, June 14). *On the Design of Variable Noise Reduction Systems for Supersonic Transport Take-off Certification Noise Reduction*. 28th AIAA/CEAS Aeroacoustics 2022 Conference, Southampton, UK. https://doi.org/10.2514/6.2022-3052

Outreach Efforts

- Presentation at the ASCENT Advisory Committee Spring Meeting (April 5–7, 2022)
- Presentation at the Aviation Emissions Characterization Roadmap Annual Meeting (May 24–26, 2022)

Awards

None.

Student Involvement

This task was conducted primarily by Laurens Voet, a graduate research assistant working under the supervision of Dr. Jayant Sabnis, Dr. Raymond Speth, and Dr. Choon Tan.

Plans for Next Period

This task is complete.

References

Berton, J. & Geiselhart, K. (2019). *NASA 55-tonne Supersonic Transport Concept Aeroplane (STCA) release package*. NASA GRC/NASA LaRC.

Olson, E. D. (1992). *Advanced takeoff procedures for high-speed civil transport community noise reduction*. 921939. https://doi.org/10.4271/921939