# Project 47 Clean-Sheet Supersonic Aircraft Engine Design and Performance

## Massachusetts Institute of Technology

## Project Lead Investigator

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## University Participants

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- PI(s): Prof. Steven R. H. Barrett
- FAA Award Number: 13-C-AJFE-MIT, Amendment No. 052
- Period of Performance: March 29, 2019, to March 28, 2020 (with the exception of funding and cost share information, this report covers the period from March 29, 2019, to September 30, 2019)
- Task(s):
    1. Identify mission profiles and operating requirements for propulsion systems
    2. Develop an engine cycle model for a supersonic aircraft propulsion system
    3. Assess environmental footprint of an engine for a supersonic transport aircraft

## Project Funding Level

$250,000 FAA funding and $250,000 matching funds. Sources of match are approximately $73,000 from Massachusetts Institute of Technology (MIT), plus third-party, in-kind contributions of $177,000 from Byogy Renewables Inc.

## Investigation Team

- Prof. Steven Barrett (MIT) serves as PI for the A47 project as head for the Laboratory for Aviation and the Environment. Prof. Barrett coordinates internal research efforts and maintains communication between investigators in the various MIT research teams.
- Dr. Raymond Speth (MIT) serves as co-investigator for the A47 project. Dr. Speth directly advises student research in the Laboratory for Aviation and the Environment focused on assessment of fuel and propulsion system technologies targeting reduction of aviation’s environmental impacts. Dr. Speth also coordinates communication with FAA counterparts.
- Dr. Jayant Sabnis (MIT) serves as co-investigator for the A47 project. Dr. Sabnis co-advises student research in the Laboratory for Aviation and the Environment. His research interests include turbomachinery, propulsion systems, gas turbine engines, and propulsion system–airframe integration.
- Dr. Choon Tan (MIT) serves as co-investigator for the A47 project. Dr. Tan directly advises student research in the Gas Turbine Laboratory focused on unsteady and three-dimensional flow in turbomachinery and propulsive devices, aerodynamic instabilities in aircraft gas turbine engines, and propulsion systems.
- Mr. Prashanth Prakash is a PhD student in the Laboratory for Aviation and the Environment. He is responsible for developing engine models in the Numerical Propulsion System Simulation (NPSS) tool, for developing the combustor reactor network model, and for analyzing the sensitivity of engine emissions to design parameters.
- Mr. Laurens Voet is a graduate student researcher in the Gas Turbine Laboratory. Mr. Voet is responsible for determining propulsion system requirements for supersonic aircraft designs, for relating the noise footprint to the

relevant engine parameters, for estimating the effective perceived noise level (EPNL) for given aircraft trajectories, and for proposing clean-sheet engine design solutions to reduce its noise footprint.

## Project Overview

A number of new civil supersonic aircraft designs are currently being pursued by industry in different Mach regimes and for different size classes (e.g., supersonic business jets at low-supersonic Mach numbers and airliners at high-supersonic Mach numbers). Compared with those for subsonic aircraft, engines for supersonic 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 developed around the core (high-pressure compressor, combustor, and high-pressure turbine) of existing subsonic engines, with modifications to the low-pressure spool (fan and low-pressure turbine).

ASCENT Project 47 aims to evaluate 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 propulsions systems derived from current commercial engines, a clean-sheet engine takes advantage of recent advances in propulsion system technology to significantly 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 include:

- Development of a framework for quantifying the noise and emissions footprints of propulsion systems used on civil supersonic aircraft
- Assessment of the difference in environmental footprint between a derived engine and a clean-sheet engine for a civil supersonic aircraft
- Development of a roadmap for technology development, focusing on reducing the environmental footprint associated with engines for civil supersonic aircraft

A summary of accomplishments to date include the following:

- A survey of supersonic transport concepts and existing designs was carried out, and the Stanford University Aerospace Vehicle Environment (SUAVE) was selected to analyze mission profiles and derive propulsion system requirements.
- Multiple engine models were developed in the NPSS tool. The baseline engine chosen for the derivative engine analysis was the CFM56-5B engine.
- A reactor network framework was developed to estimate $NO_x$ emissions. The model was calibrated to the International Civil Aviation Organization (ICAO) data for the CFM56-5B3 engine.
- A framework was set up to estimate the noise footprint (sound pressure level, SPL) of the engine given the relevant engine parameters using a semi-empirical model.

## Task 1 - Identify Mission Profiles And Operating Requirements For Propulsion Systems

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### Objective(s)

The first objective of this task is to identify representative mission profiles of commercial supersonic transport aircraft (i.e., characterize stages of the mission by defining parameters such as climb rates and accelerations). A second objective is to use these mission profiles and representative aircraft parameters (e.g., wing area, drag and lift polars) of civil supersonic aircraft operating in different Mach regimes to derive propulsion system requirements for supersonic aircraft.

### Research Approach

**Survey of the design space**

In Figure 1, we present a set of supersonic transport aircraft concepts and existing designs with their respective range and cruise Mach number.

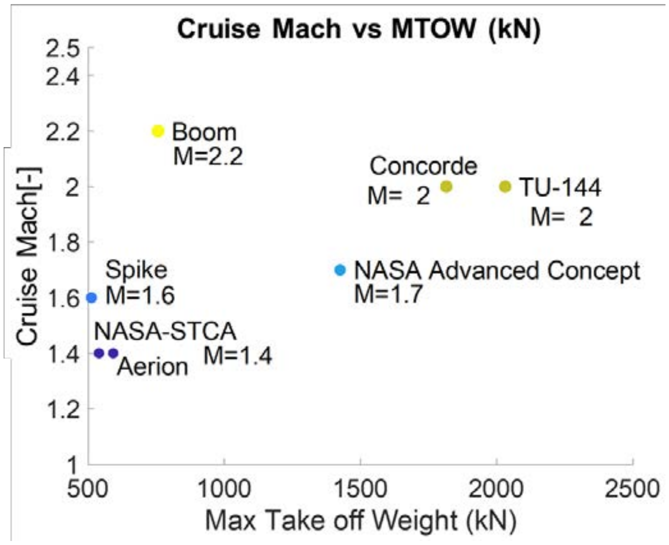

**Figure 1.** Range versus maximum take-off weight for civil supersonic transport aircraft concepts and existing designs.

Figure 1 shows the variability of different concepts and designs for supersonic transport. The only existing designs are the Anglo-French Concorde and the Russian Tupolev TU-144 in the Mach 2 regime. However, upcoming companies looking to bring supersonic transport back to the market are developing aircraft in different Mach regimes, including low-supersonic (M~1.4), mid-supersonic (M~1.6), and high-supersonic (M~2), and in different weight classes: small business jets and larger airliners.

## Mission profiles

The only existing supersonic transport aircraft were the Concorde and Tupolev TU-144. Morisset (1974) compared their performance and shows their mission profiles. A typical mission profile of Concorde is shown in Figure 2. This mission profile is chosen as a case to test the tool to derive propulsion system requirements for a supersonic transport aircraft. The mission profile is modeled in SUAVE (MacDonald et al., 2015). A comparison of the mission profiles can be seen in Figure 2. The descent profile in SUAVE is modeled as a single mission stage because it is assumed that the propulsion requirements during descent will not be critical.

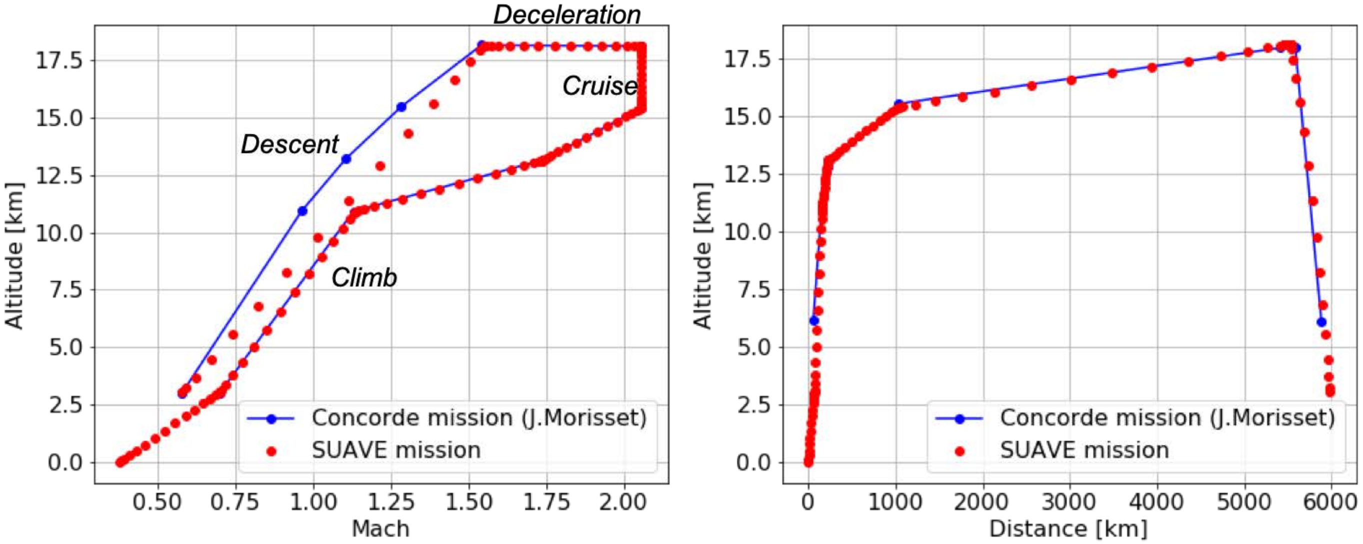

**Figure 2.** Typical mission profile of Concorde.

**Propulsion system requirements**

The SUAVE tool is used to estimate propulsion system requirements for the Concorde aircraft based on the Concorde flight reports (Morisset, 1974). The standard aircraft parameters and aerodynamic coefficients of the Concorde aircraft from the SUAVE tool are used. The propulsion system requirements (i.e., thrust) of the Concorde mission are given in the top graph of Figure 3. The variation in the drag coefficient of the aircraft during the mission is given in the bottom graph of Figure 3. The discontinuities in the thrust profile come from jumps in climb rates and in acceleration rates. In Figure 3, the drag coefficient can be seen to sharply increase when crossing the sound barrier. From the thrust profile, the most critical points in the mission can be identified. The engine will need to be able to generate the specified thrust at these points. Therefore, the thrust at these critical points will be a direct input in Task 2 when developing the engine cycle model.

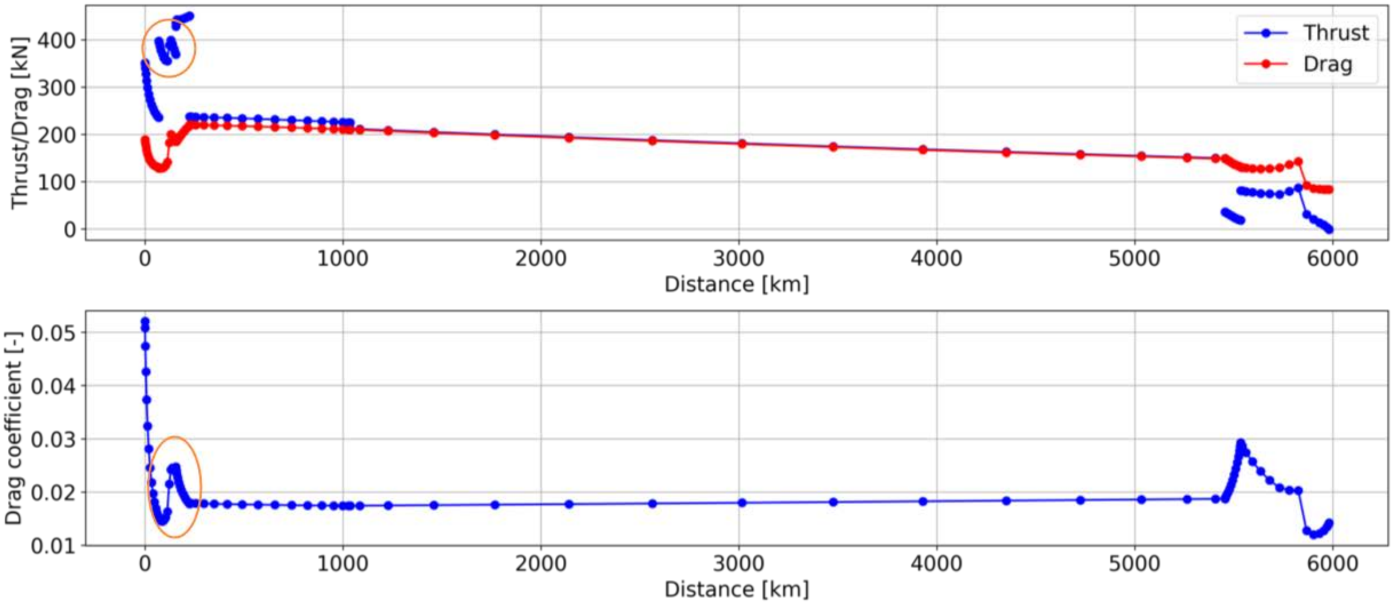

**Figure 3.** Propulsion system requirements (i.e., thrust and drag) and drag coefficient throughout the mission given in Figure 2. The circled areas indicate the transonic acceleration.

**NASA 55-tonne STCA**

NASA has designed a 55-tonne Supersonic Transport Concept Aircraft (STCA) with a cruise Mach number of 1.4 (Berton & Geiselhart, 2019). The aircraft configuration of the STCA will be used in future work to derive propulsion system requirements for a small business jet in the low-supersonic Mach regime.

## Milestone(s)

A review of the supersonic transport concepts and existing designs was conducted, and the appropriate tools to derive propulsion system requirements for a supersonic transport aircraft flying a specific mission were identified.

## Major Accomplishments

### Literature review

A survey of supersonic transport concepts and existing designs was conducted. Upcoming players in the supersonic transport market are developing aircraft in different Mach regimes (i.e., low-, mid-, and high-supersonic regimes) and weight classes (i.e., business jet and airliner).

### Framework

SUAVE was selected to derive propulsion system requirements for a supersonic aircraft flying a specific mission profile.

## Publications
N/A

## Outreach Efforts
Our team contacted Boom Supersonic on October 15, 2018, to discuss representative mission profiles and aircraft parameters.

Prof. Steven Barrett gave a presentation titled “Clean-sheet supersonic engine design and performance” at the ASCENT meeting in Atlanta, GA, on April 19, 2019.

Dr. Jayant Sabnis gave a presentation titled “Clean-sheet supersonic engine design and performance” at the ASCENT meeting in Alexandria, VA, on October 22, 2019.

## 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
1. Apply the framework to derive propulsion system requirements to the NASA 55-tonne STCA (expected completion: February 2020)
2. Define the critical operating point at which the engines are sized for different missions of supersonic transport aircraft (expected completion: April 2020)

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

Lukaczyk, T., Wendorff, A.D., Botero, E., MacDonald, T., Momose, T., Variyar, A., Vegh, M.J., Colonno, M., Economon, T.D., Alonso, J.J., Orra, T.H., and da Silva, C.I. (2015). SUAVE: An open-source environment for multi-fidelity conceptual vehicle design. AIAA Multidisciplinary Analysis and Optimization Conference. AIAA-2015-3087

Morisset, J. (1974). Tupolev 144 and Concorde – The official performances are compared for the first time. NASA Technical Translation TT F15,446.

# Task 2 - Develop An Engine Cycle Model For A Supersonic Aircraft Propulsion System
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## Objective
The objective of this task was to develop an engine cycle deck to analyze clean-sheet and derivative propulsion systems for commercial supersonic aircraft.

## Research Approach
The NPSS tool is chosen to develop the engine cycle decks for clean-sheet and derivative engines, because it is an industry standard tool that facilitates future collaboration with other users of the tool.

### Baseline engine
To develop the derivative engine, a baseline engine is first chosen and modeled. The CFM56-5B engine was chosen for this task because it is the donor engine for the proposed GE Affinity engine. The baseline engine was modeled using published data from Jane’s Aero Engines (Gunston, 1996) and data published in the Emissions Databank (EDB) by the European Union Aviation Safety Agency (EASA) (EASA, 2019). The data published by EASA consists of fuel flow and emission indices of several

species at take-off, climb, idle, and approach conditions of various thrust variants of the CFM56-5B engine. The EDB data can be processed based on the serial number of the tested engines to relate multiple entries in the databank to a common engine, as shown in Figure 4.

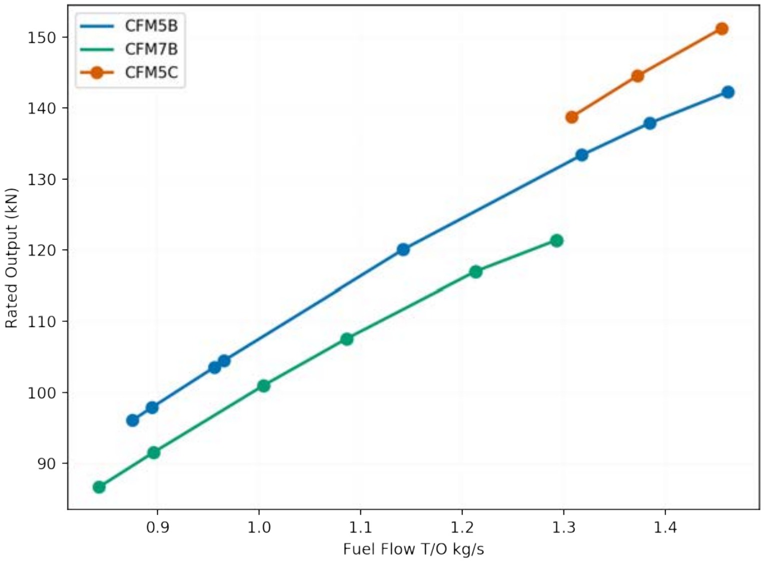

**Figure 4.** Variants of the CFM56 engine; the CFM56-5B TechInsertion engine is chosen for the baseline engine.

The engine model (see schematic below) consists of an inlet, fan, low-pressure compressor (LPC), high-pressure compressor (HPC), combustor, high-pressure turbine (HPT), low-pressure turbine (LPT), and nozzles for the bypass and core ducts.

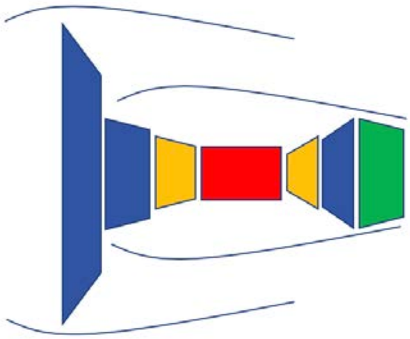

**Figure 5.** Schematic of the unmixed-turbofan model of the CFM56-5B, showing the low-pressure spool (blue), the high-pressure spool (yellow), combustor (red), and nozzle (yellow).

Component parameters such as efficiencies, pressure ratios, and bleed flows for the engine model were varied at a chosen design point. The point chosen for this was the sea-level static thrust of the highest thrust variant of the engine. Subsequent off-design runs were carried out to evaluate whether the model matched the published data on fuel flow at particular thrust levels.

Furthermore, the CFM56-5B and CFM56-7B engines share the same physical core. This information is used to validate the model representing the core specifically by using the core model calibrated to the CFM56-5B data to represent the CFM56-7B engine, by fixing the core components and varying only the low-spool components.

### Derivative engine

The core from the baseline engine is adopted along with a new low spool to meet the take-off thrust requirements of the NASA STCA aircraft. The common core is represented by holding the high-spool component map scaling factors and HPT bleed fractions constant at the CFM56-5B values. The LPC is removed from the CFM56-5B model and a mixer and the convergent nozzle is replaced with a convergent-divergent nozzle.

Work on sizing the derivative engine for the NASA-STCA aircraft is currently ongoing.

### Clean-sheet engine

A clean-sheet engine with a new core is modeled by allowing the HPC, combustor, and HPT to be sized at the design point. That is, the high-spool component map scaling factors and the HPT cooling flows are allowed to vary (in contrast to the derivative engine scenario). The design space of the engine therefore grows in the clean-sheet scenario.

Work on sizing the clean-sheet engine for the NASA-STCA aircraft is currently ongoing.

## Milestone(s)

Multiple engines were developed in NPSS. The baseline engine modeled was the CFM56-5B engine, and the core from this engine was used to model the CFM56-7B engine. Work on the supersonic derivative engine and clean-sheet engine models developed are ongoing.

## Major Accomplishments

Publicly published data are used to build a CFM56-5B3 model in NPSS and calibrate it at sea-level static conditions as shown in Figure 6.

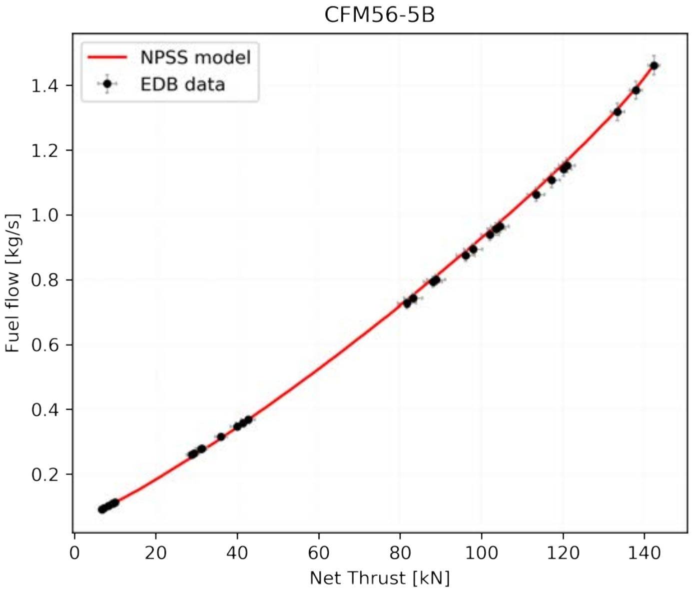

**Figure 6.** Off-design comparison of the Numerical Propulsion System Simulation (NPSS) model and International Civil Aviation Organization (ICAO) data from the Emissions Databank (EDB) for the CFM56-5B.

The model is compared with the data available in the EDB maintained by EASA on behalf of ICAO. The average root mean square (RMS) error for all the landing and take-off (LTO) data points is approximately 2%, suggesting a successful calibration.

The same core is used in a CFM56-7B engine and compared with EDB data as shown in Figure 7. The average RMS error was approximately 3% in this case (Figure 7).

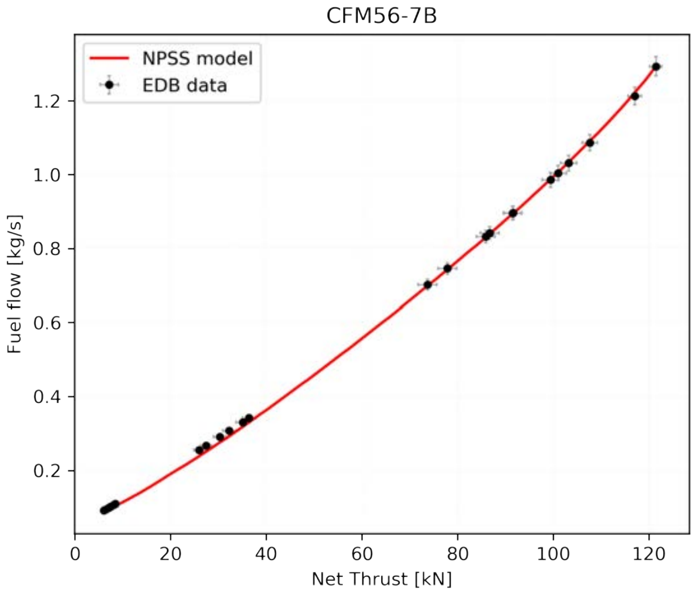

**Figure 7.** Off-design comparison of the Numerical Propulsion System Simulation (NPSS) model and International Civil Aviation Organization (ICAO) data from the Emissions Databank (EDB) for the CFM56-7B using the common core.

An analysis of a derivative engine based on this core was started and work is currently ongoing. Simultaneously, a model of a clean-sheet engine is being developed.

## Publications

N/A

## Outreach Efforts

Dr. Jayant Sabnis gave a presentation titled “Noise and emission characteristics of commercial supersonic aircraft propulsion systems” at the Aviation Noise and Emissions Symposium on March 5, 2019.

## Awards

None.

## Student Involvement

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

## Plans for Next Period

Various degrees of derivative engine models are to be developed, ranging from an “off-the-shelf” repurposing of an entire engine to using only the core of an existing engine (expected completion: May 2020).

A clean-sheet approach that ranges from redesigning a core with existing technology (e.g., metallurgy, cooling technology) to using new technology (e.g., advanced materials) and adaptive cycles to meet contrasting requirements at supersonic cruise and sea-level take-off (expected completion: December 2020).

## References

EASA (2019). ICAO Aircraft Engine Emissions Databank, version 26A. Online: https://www.easa.europa.eu/easa-and-you/environment/icao-aircraft-engine-emissions-databank

Gunston, B. (1996). Jane's aero-engines. Jane's Information Group, Print.

# Task 3 - Assess Environmental Footprint Of An Engine For A Supersonic Transport Aircraft

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## Objective

The objective of this task is to develop models to assess the environmental footprint of a supersonic transport aircraft. Models for both the noise footprint and the emissions footprint will be developed.

## Research Approach

### Emissions modeling

The outline of our approach to modeling the emissions from the engines designed is shown in Figure 8. The aircraft configuration and mission profile determine the propulsion system requirements that need to be met. Once the engine is sized based on these requirements, temperatures and pressures in the flow path can be determined. The temperature and pressure at the inlet to the combustor ($T_3$, $P_3$) along with the mass flow rate of the fuel and air are used in a combustor model to estimate the emissions of $NO_x$. The emissions of $NO_x$ are particularly sensitive to the inlet temperature and residence time in the combustor.

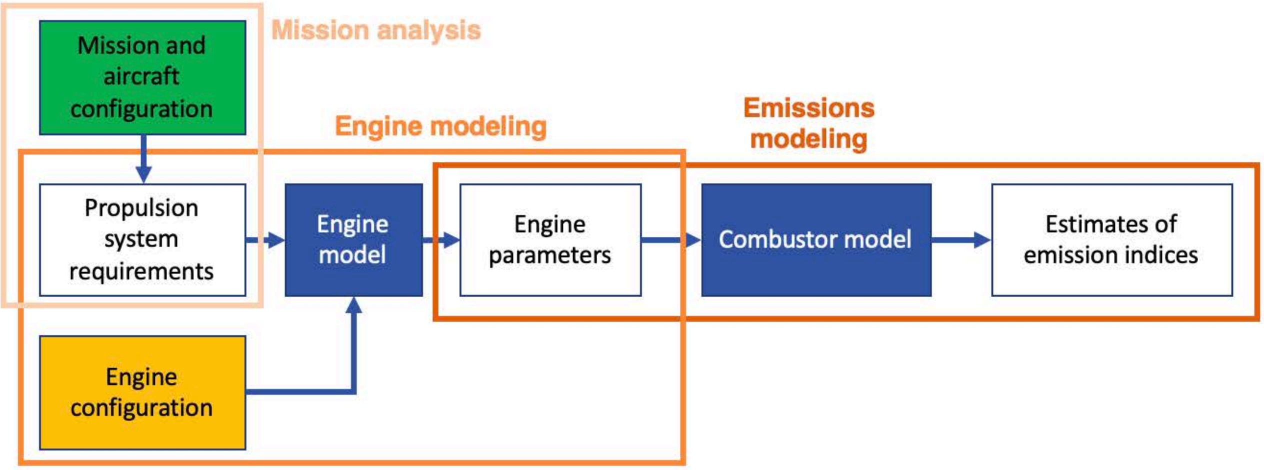

**Figure 8.** Overview of the emissions modeling framework.

The following values are calculated using the NPSS engine model at the combustor inlet:

- Air mass flow rate
- Fuel mass flow rate
- Temperature
- Pressure

These values are used in a reactor network model as shown in Figure 9.

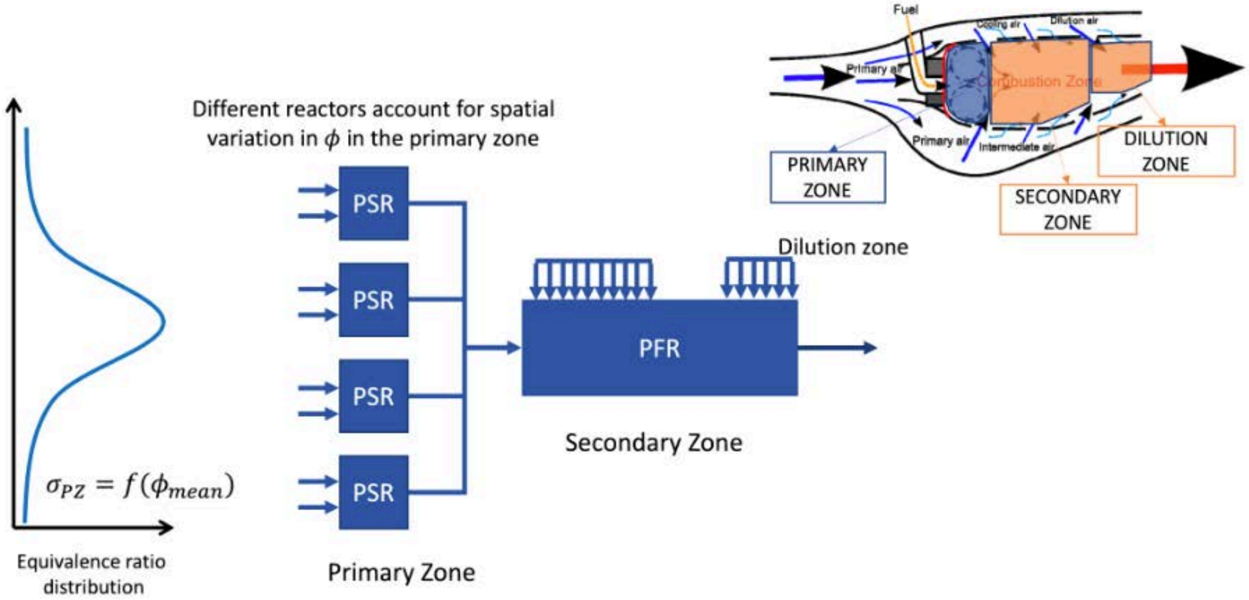

**Figure 9.** Schematic of the reactor network model to estimate emissions from the combustor. PSR, perfectly stirred reactors; PFR, plug flow reactor; PZ, primary zone; $\sigma$, standard deviation; $\phi$, equivalence ratio.

The reactor network model consists of an interconnected network of perfectly stirred reactors (PSR) to represent the primary zone and plug flow reactors (PFR) to represent the secondary and dilution zones. The reactor net model is implemented using the Cantera package (Goodwin et al., 2018) in Python. The model parameters are calibrated to the emissions data published in the EDB.

**Noise footprint**

A flow chart for the noise footprint assessment is given in Figure 10.

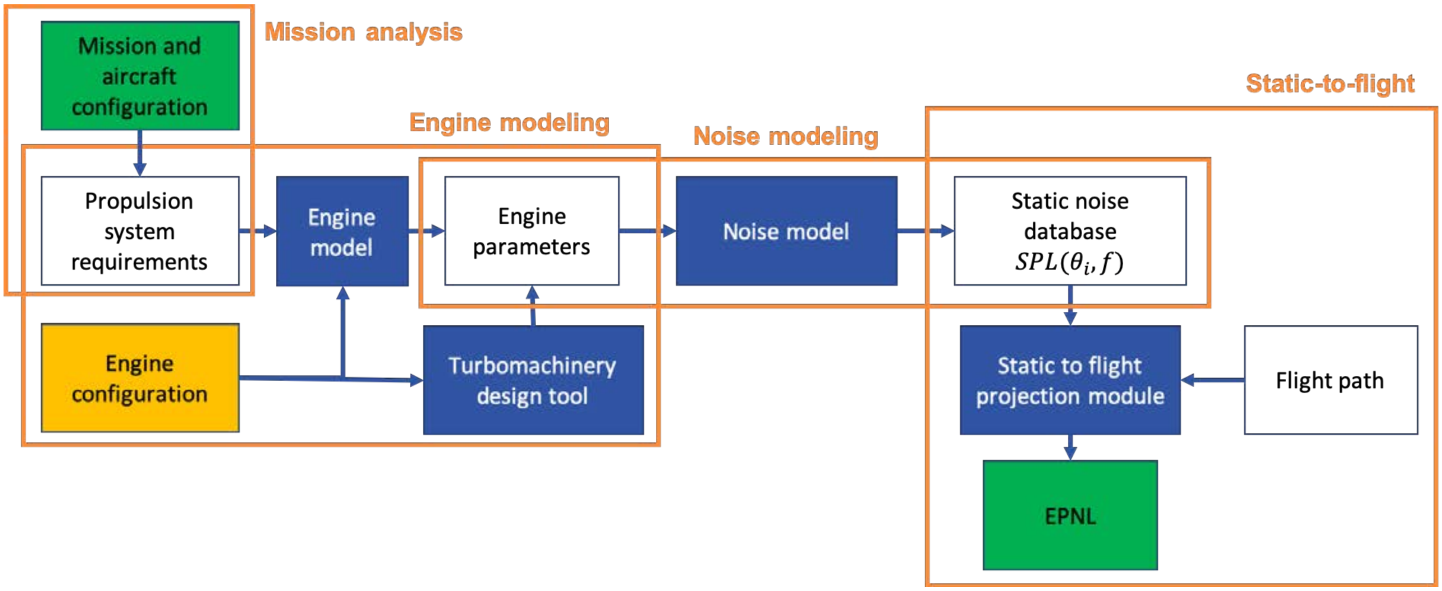

**Figure 10.** Overview of noise footprint assessment. SPL, sound pressure level; EPNL, effective perceived noise level.

The driving parameter used in the noise certification of aircraft is the EPNL, as defined by ICAO in Annex 16 Environmental Protection Volume I Aircraft Noise (ICAO, 2008). As can be seen from Figure 10, four modules need to be developed to define the link between an aircraft configuration flying a given mission and the resulting EPNL during landing and take-off.

As can be seen in Figure 10, the first module is the mission analysis tool. The objective of the mission analysis tool is to derive the propulsion system requirements for an aircraft configuration flying a specific mission. The mission analysis tool is described in Task 1.

Second, an engine modeling tool has to be developed. The objective of the engine modeling tool is to define the link between the propulsion system requirements and the engine parameters relevant for the noise model. The relevant engine parameters are both thermodynamic (e.g., temperatures, pressures, mass flow rates inside the engine) and geometric (e.g., fan diameter, turbomachinery rotor-stator spacing). The thermodynamic parameters are determined using the NPSS engine cycle deck, as described in Task 2. The geometric parameters are determined using a preliminary turbomachinery design tool. The engine modeling tool depends primarily on a specific engine configuration (e.g., a derived engine, a clean-sheet engine).

Third, a noise modeling tool needs to be developed. The objective of the noise modeling tool is to define the link between relevant engine parameters and a static noise database (i.e., SPL as a function of frequency, polar and azimuthal projection angle). The static noise database is generated by addressing by estimating the SPL from two main different noise sources: the airframe and the engine noise source. Although this work focuses on the engine noise footprint, the airframe will be important when effects such as shielding are considered. The engine noise source is divided into several modules, based on the different components in the engine. The following noise modules are developed, based on the Aircraft Noise Prediction Program (ANOPP) theoretical manual (Zorumski, 1981):

- Jet noise module based on the SAE ARP876 method (Society of Automotive Engineers, 1978)
- Jet noise module based on the Stone method (Stone, 1974; Stone & Montegani, 1980)
- Fan noise module based on the Heidmann method (Heidmann, 1975)
- Turbine noise module based on a method developed by GE (Matta et al., 1977)
- Airframe noise module based on the Fink method (Fink, 1977)

As an example, Figure 11 shows the directivity of the overall SPL and the spectral distribution of the jet mixing SPL using the SAE ARP876 module. The input parameters for the jet mixing noise module are given in Table 1 and are taken from the STCA

Release Package Noise Assessment at t = 0.0 s. The outputs of the model are compared with the outputs of the STCA Release Package in Figure 11.

**Table 1.** Parameters of the jet mixing noise module.

| Variable | Value | Variable | Value |
|---|---|---|---|
| Ambient speed of sound $c_O$ | 346.16 m/s | Jet density $\rho_{jet}^{*} = \rho_{jet} / \rho_0$ | 0.68421 |
| Ambient density $\rho_0$ | 1.183 kg/m³ | Jet velocity $V_{jet}^{*} = V_{jet} / c_0$ | 1.1859 |
| Number of engines $N_e$ | 1 | Jet total temperature $T_{jet}^{*} = T_{jet} / T_0$ | 1.7352 |
| Flight Mach number $M_0$ | 0 | Jet area $A_{jet}^{*} = A_{jet} / A_{ref}$ | 0.60647 |
| Distance between source and pseudo-observer $r_S$ | 0.311 m | | |
| Engine reference area $A_e$ | 0.96 m² | | |

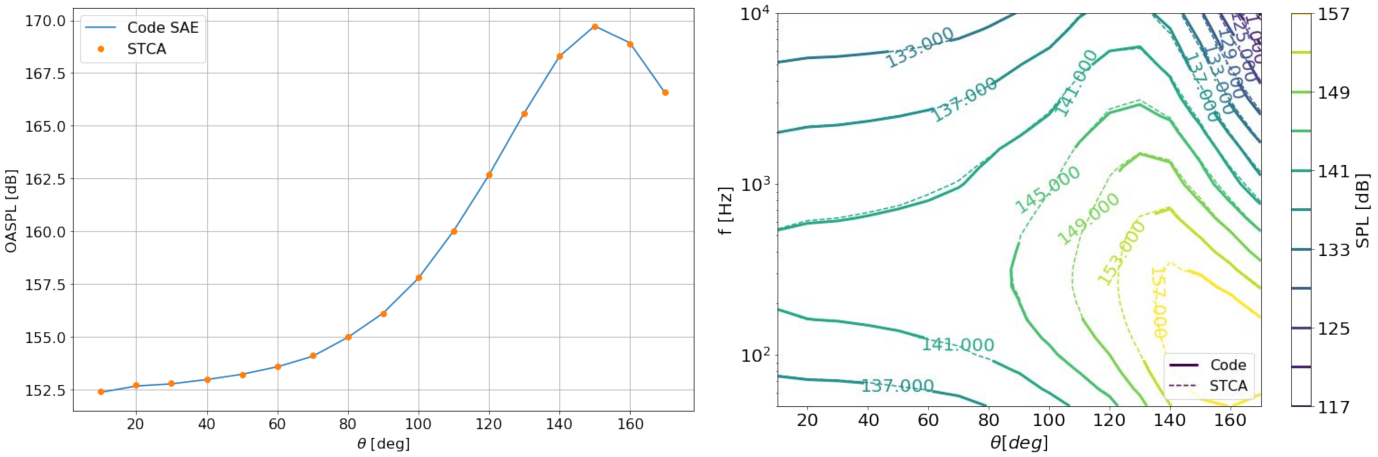

**Figure 11.** Directivity of overall sound pressure level (OASPL) of the SAE ARP 876 jet mixing module (left), and spectral distribution of the SPL of the SAE ARP 876 jet mixing module (right).

Finally, a static-to-flight projection tool needs to be developed. The objective of the static-to-flight projection tool is to derive the EPNL from the static noise database. A standard take-off procedure, as defined under ICAO Annex 16 (1) Section 3.6.2., and a standard approach procedure, as defined under ICAO Annex 16 (1) Section 3.6.3, will be used to calculate the EPNL. The take-off procedure is given in Figure 12. The static-to-flight projection tool has not been developed yet.

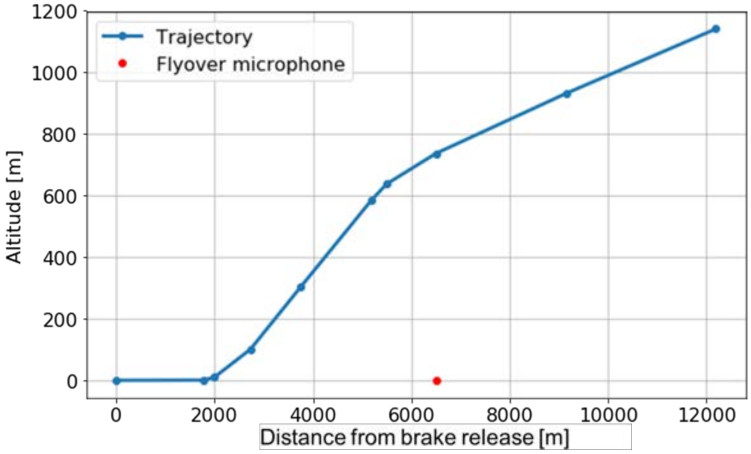

**Figure 12.** Standard take-off trajectory of the 55-tonne STCA used in the static-to-flight projection. The flyover microphone is indicated at 6500 m after brake release.

## Milestone(s)

A model deriving the static noise database from relevant engine parameters was set up. A reactor network–based model was developed and $NO_x$ emissions were calibrated to the EDB data using combustor inlet values obtained from the NPSS model of the CFM56-5B engine.

## Major Accomplishments

### Emissions model

A framework was developed to estimate the $NO_x$ footprint (emissions index) of the baseline engine, given the relevant engine parameters using a reactor network model. A comparison of the model developed and the EDB data is shown in Figure 13.

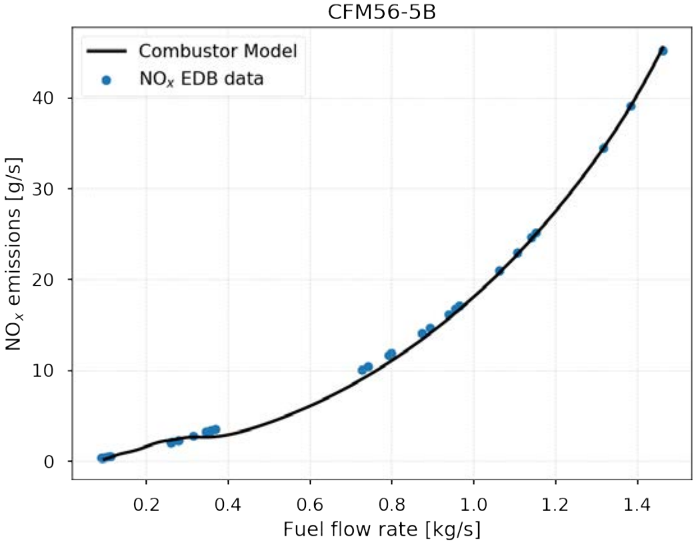

**Figure 13.** Comparison of $NO_x$ emissions [g/s] at different fuel flows between the combustor model and International Civil Aviation Organization (ICAO) data from the Emissions Databank (EDB).

### Noise model

A framework was set up to estimate the noise footprint (SPL) of the engine given the relevant engine parameters using a semi-empirical model.

## Publications

N/A

## Outreach Efforts

Dr. Jayant Sabnis gave a presentation titled “Noise and emission characteristics of commercial supersonic aircraft propulsion systems” at the Aviation Noise and Emissions Symposium on March 5, 2019.

Prof. Steven Barrett gave a presentation titled “Clean-sheet supersonic engine design and performance” at the ASCENT meeting in Atlanta, GA, on April 19, 2019.

Dr. Jayant Sabnis gave a presentation titled “Clean-sheet supersonic engine design and performance” at the ASCENT meeting in Alexandria, VA, on October 22, 2019.

## Awards

None.

## Student Involvement

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

## Plans for Next Period

### Emission footprint

- Continue work on the combustor model for rich-quench-lean (RQL) and staged combustors
- Continue modeling other emissions species such as CO and soot
- Calibrate combustor models to data available on existing engines
- Expected completion: May 2020

### Noise footprint

- Continue the framework development to derive the noise footprint from relevant engine parameters (expected completion: March 2020)
- Start developing a preliminary turbomachinery design tool to derive relevant geometrical engine parameters for an engine configuration (expected completion: August 2020)

## References

Fink, M. (1977). Airframe noise prediction method. FAA-RD-77-29

Goodwin, D.G., Speth, R.L., Moffat, H.K., & Weber, B.W. (2018). Cantera: An object-oriented software toolkit for chemical kinetics, thermodynamics, and transport processes. Version 2.4.0. doi:10.5281/zenodo.1174508

Heidmann, M. (1975). Interim prediction method for fan and compressor source noise. NASA TM X-71763

ICAO (2008). Annex 16 environmental protection volume I: Aircraft noise

Matta, R., Sandusky G., & Doyle, V. (1977). GE core engine noise investigation – Low emission engines. FAA-RD-77-4

Society of Automotive Engineers. (1978). Gas turbine jet exhaust noise prediction. ARP876

Stone, J. (1974). Interim prediction method for jet noise. NASA TM X-71618

Stone, J. & Montegani, F. (1980). An improved prediction method for the noise generated in flight by circular jets. NASA TM-81470

Zorumski, W.E. (1981). Aircraft noise prediction theoretical manual. NASA TM-83199 Parts 1 and 2. Currently maintained at NASA LaRC by the ANOPP team in electronic format and provided upon request