Project 083 NO_x Cruise/Climb Metric System Development

Massachusetts Institute of Technology

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Massachusetts Institute of Technology (MIT)
- P.I.: Dr. Raymond L. Speth
- FAA Award Number: 13-C-AJFE-MIT, Amendment Nos. 103, 115, 117, 133, 137, and 143
- Period of Performance: September 19, 2022, to August 31, 2027 (reporting here with the exception of funding level and cost-sharing only for the period October 1, 2024, to September 30, 2025)
- Tasks:
  1. Evaluation of cruise nitrogen oxides (NO_x) dependence on pressure ratio
  2. Assessment of Boeing Fuel Flow Method 2's accuracy for modern engines

Project Funding Level
The Federal Aviation Administration (FAA) provided $900,000 in funding and $900,000 in matching funds were received. Sources of matching funds are approximately $129,500 from MIT, plus third-party in-kind contributions of $250,000 from NuFuels LLC, and $520,500 from Earth Force Technologies.

Investigation Team
Dr. Raymond L. Speth (P.I.), All Tasks
Sarah Reider (graduate student), Task 1
Wyatt Giroux (graduate student), Task 2

Project Overview
The International Civil Aviation Organization (ICAO) is responsible for setting emissions standards for aircraft engines to limit the environmental impacts of these emissions. To limit the impacts of aviation emissions, the FAA's Office of Environment and Energy is working with the ICAO Committee on Aviation Environmental Protection (CAEP) to consider updated emissions standards for aircraft engines by using metrics relevant to the full-flight emissions of these species, rather than only those emissions occurring during a standard landing and takeoff (LTO) cycle. Emissions standards set by ICAO will influence the development of future engine technologies, thus resulting in a reduction of emissions from future aircraft engines, and consequently improved human health and reduced environmental impacts. To this end, the FAA needs to understand and quantify how current and future standards may impact aviation emissions in the United States and worldwide, and how changes in these emissions may affect the environment and human health.

The objective of this project is to provide support for FAA decision-making related to potential certification standards that control emissions during cruise and climb, in addition to the current standards for LTO. The project includes analyses important for understanding the costs and benefits of both current standards and policies that may be proposed in the future. By providing a rational, scientific basis for decisions regarding the implementation of emissions standards, this project contributes to an efficient implementation process and provides industry with regulatory certainty. The analyses provided in this project will allow the FAA to identify policy proposals that serve the national interest and advocate for those policies within the ICAO.

Task 1 – Evaluation of Cruise NO_x Dependence on Pressure Ratio

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Objective

The objective of this task was to assess the uncertainty associated with marginal social costs of NO_x and carbon dioxide (CO_2) and their implications for a potential cruise NO_x standard.

Research Approach

The basis of this task involved developing a modelling framework for estimating uncertainty in monetized environmental cost for full-flight missions. The Transport Aircraft System OPTimization (TASOPT) aircraft design tool (Prashanth et al., 2025) was used to estimate aircraft/engine performance on a mission level for representative narrow-body (NB), wide-body (WB), and regional jets (RJ) at a range of engine overall pressure ratio (OPR) values. This was combined with NO_x emissions characteristic curves derived from Engine Emissions Databank (EEDB) (ICAO, 2024) to obtain the average mission nitrogen oxide emission index (EI(NO_x)). Conventional Jet-A fuel was assumed to be used, resulting in constant EI(CO_2). The Aviation Climate and Air Quality Impacts (ACAI) framework (Kim, 2023) was used to estimate marginal cost distributions for NO_x and CO_2 based on a 2019 global aviation emissions inventory generated by the Aviation Emissions Inventory Code (AEIC) (Simone et al., 2013) with Official Airline Guide (OAG) data. The impulse-normalized cost for each species given sampled marginal costs was then estimated using the marginal costs, thrust specific fuel consumption, and emissions indices for each species.

A Monte-Carlo simulation was performed using the cost distributions from ACAI to evaluate the cost response of potential cruise NO_x standards. Specifically, scenarios where a single capped value is placed on NO_x was considered. This was performed for each aircraft type for several NO_x characteristic curves representing both rich-quench-lean (RQL) and staged lean burn combustors. The examined caps were specified in terms of EI(NO_x) at the climb out (C/O) LTO point as a surrogate for cruise values. Cap values between 15 g/kg and 34 g/kg were examined. In cases where the total cost did increase, the marginal cost of CO_2 was generally found to be extremely high ($\gtrsim 0.45$ $/kg) and the probability of increased total cost reaches a maximum of around 14% for the most stringent limits considered. The OPR changes required for each engine/aircraft to meet the corresponding cap value are shown in Figure 1.

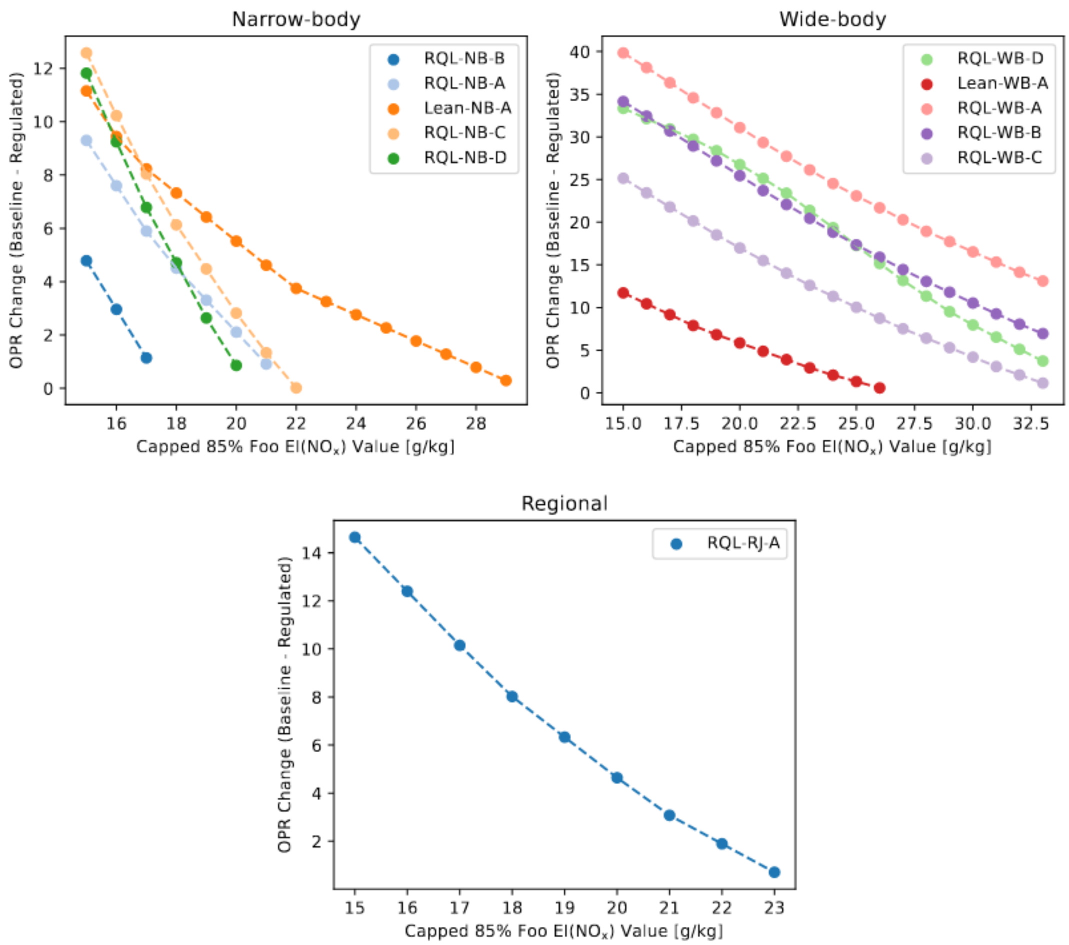

Figure 1. Change in overall pressure ratio (OPR) relative to baseline vs. cap values for each aircraft/engine combination examined. EI (NOx): nitrogen oxide emission index, NB: narrow-body, RJ: regional jet, RQL: rich-quench-lean, WB: wide-body.

Milestone

Documented the completed analysis in a master's thesis (Reider, 2025).

Major Accomplishments

The analysis demonstrated that even given uncertainty in monetized emissions models, it remains cost effective on an environmental basis to place caps on cruise NO_x. The changes in OPR required to meet aforementioned caps were also determined.

Publications

Reider, S. (2025). *Stochastic Methods for Setting Effective Aviation NO_x Policies* [Master's thesis, Massachusetts Institute of Technology]. MIT Libraries. https://dspace.mit.edu/handle/1721.1/163033

Outreach Efforts

None.

Awards
None.

Student Involvement
Graduate student Sarah Reider conducted the analyses and presented the work to the FAA.

Plans for Next Period
This task is complete.

References
ICAO. (2024). *ICAO Aircraft Engine Emissions Databank* (v30). International Civil Aviation Organization. https://www.easa.europa.eu/domains/environment/icao-aircraft-engine-emissions-databank

Kim, J. (2023). *Sensitivity of the ozone layer, climate, and public health to changes in the location of aviation emissions* [Master's thesis, Massachusetts Institute of Technology]. MIT Libraries. https://dspace.mit.edu/handle/1721.1/150205

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Task 2 – Assessment of Boeing Fuel Flow Method 2's Accuracy for Modern Engines
Massachusetts Institute of Technology

Objective
The objective of this task was to ensure the Boeing® Fuel Flow Method 2 (BFFM2) is continuing to provide accurate estimates of cruise emissions given evolutions in modern engine technology since the method's development in 2006.

Research Approach
During work on cruise/climb NOx stringency assessment, numerous inconsistencies were identified in the derivation of BFFM2 (DuBois & Paynter, 2006). While many were relatively minor, two of the key assumptions of the method were determined to not follow well-understood engine cycle physics. These assumptions are made based on matching combustor inlet conditions between the evaluation point at altitude (alt) and a known point at reference sea-level static (SLS) conditions. Namely, the combustor inlet temperature is assumed to be equal ($T_{t3,alt} = T_{t3,sls}$) to ensure similarity in chemistry conditions. To ensure this, BFFM2 defines the equivalent SLS fuel flow where this condition should be met:

$$\dot{m}_{f,\mathrm{equiv}} = \dot{m}_{f,\mathrm{alt}} \frac{\theta_{\mathrm{amb}}^{3.8}}{\delta_{\mathrm{amb}}} e^{0.2M_0^2} \quad \text{(Eq. 1)}$$

In the derivation of this equivalent fuel flow, the two core assumptions under suspicion are (1) equal combustor exit temperature, $T_{t4,alt} = T_{t4,sls}$, and (2) equal corrected mass flow per unit area at combustor inlet, $D(M_{3,alt}) = D(M_{3,sls})$. The former would require equal fuel-air ratio (FAR) between the two operation points. However, this condition does not generally hold, with FAR varying significantly between sea level and altitude conditions.

The second assumption requires equal corrected flow per unit area at the combustor inlet. Corrected flow per unit area is defined as

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$$\frac{\dot{m}\sqrt{RT_t}}{p_t A\sqrt{\gamma}} = D(M) = M\left(1+\frac{\gamma-1}{2}M^2\right)^{-\frac{\gamma+1}{2(\gamma-1)}} \quad \text{(Eq. 2)}$$

Corrected mass flow per unit area is expressible as a function of only Mach number, another non-dimensional group. As such, it is subject to the same issue identified in the equal exit temperature assumption.

To quantify the error in these assumptions and the overall method, TASOPT (Prashanth et al., 2025) was used to determine an altitude, Mach number, and thrust schedule for a notional narrow-body aircraft. Notional narrow-body engine designs sized at 124 kN thrust were generated using the Numerical Propulsion System Simulation tool (Jones, 2007) for a range of design variables including design altitude, Mach number, and thrust, as well as component efficiencies. Each design was optimized for minimum design-point thrust-specific fuel consumption (TSFC) by varying pressure ratios, fan diameter, and turbine inlet temperature. These engines were then run through the operation schedule determined by TASOPT as well as a sweep of SLS thrust values. Using these two datasets, the point where T_{t3} matches between operation and SLS was found and the altitude and SLS values of T_{t4} and $D(M)$ were obtained. Figure 2 shows the resulting sensitivity of error in the T_{t4} assumption to the design variables, while Figure 3 shows the sensitivity for the corrected mass flow assumption. The error was time-averaged across the mission flown.

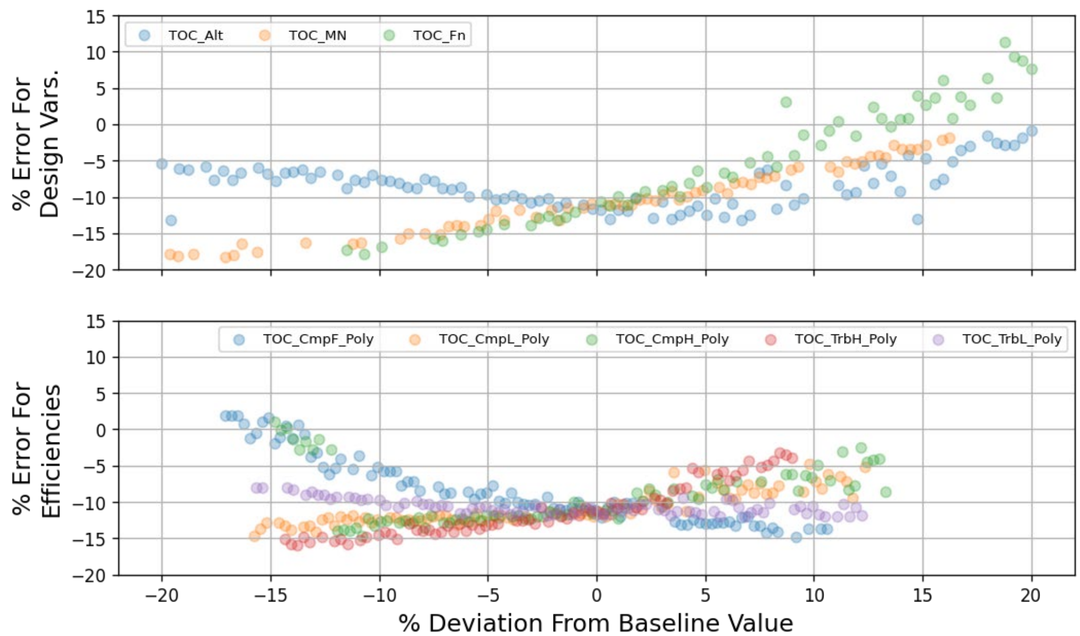

Figure 2. Time-weighted percentage error in the equal T_{t4} assumption as design variables deviate from baseline values. Higher percentage error indicates $T_{t4,alt} > T_{t4,sls}$.

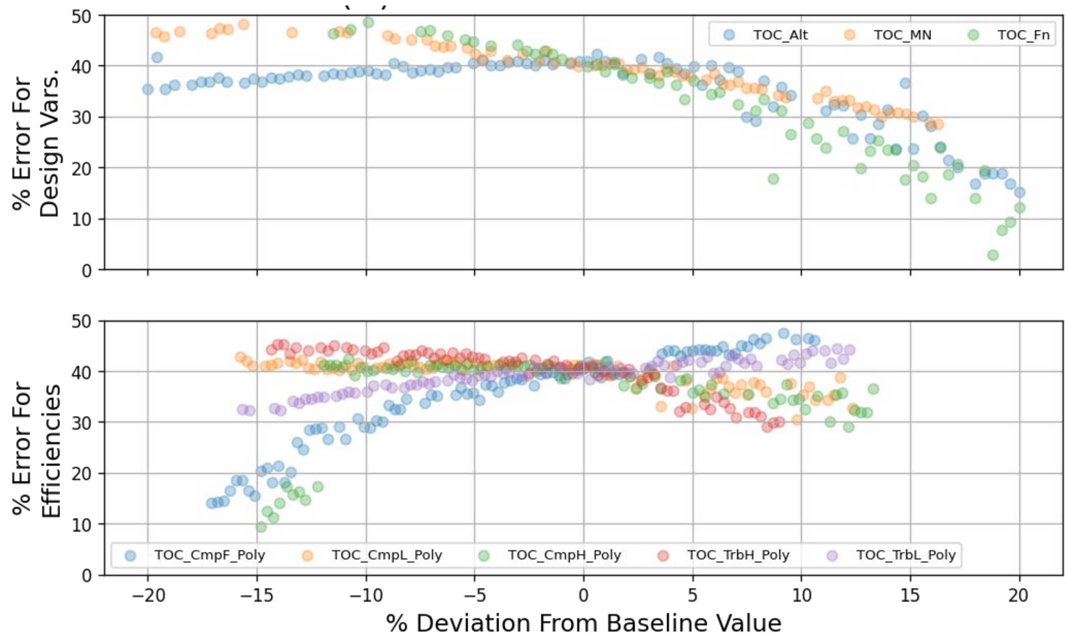

Figure 3. Time-weighted percentage error in the equal $D(M_3)$ assumption as design variables deviate from baseline values. Higher percentage error indicates $D(M_{3,alt}) > D(M_{3,sls})$.

The percentage error in assumptions was found to be consistent across a wide range of design variable values, only approaching zero for extreme cases.

Milestone

Presented the assumption error at the CAEP14-WG3/2 meeting while the analysis of the EI(NO_x) error will be presented at the upcoming CAEP14-WG3/3 meeting.

Major Accomplishments

This work demonstrates that BFFM2 maybe overpredicting cruise NO_x emissions relative to our approximations of proprietary models. This error is derived from the lack of physics-based assumptions in BFFM2's derivation.

Publications

None.

Outreach Efforts

Presented at the CAEP/14-WG3/2-ECTG meeting (June 23-27, 2025).

Awards

None.

Student Involvement

Graduate student, Wyatt Giroux, conducted the analyses and presented the work to the FAA and CAEP WG3.

Plans for Next Period

- Assess the effect of these model assumptions on mission NO_x emissions.
- Formulate a method to replace/improve BFFM2 and test this method against exiting models. The new model will attempt to use principles of non-dimensional analysis to establish a scaling relation between OPR and $\dot{m}_f$ given

publicly reported rated thrust, fuel flow, and OPR. This can then be used to obtain an improved estimate of the SLS fuel flow rate that matches the altitude T_{t3}.

References

DuBois, D., & Paynter, G. C. (2006). “Fuel Flow Method2” for Estimating Aircraft Emissions. *SAE Transactions*, *115*, 1–14. http://www.jstor.org/stable/44657657

Jones, S. M. (2007). An Introduction to Thermodynamic Performance Analysis of Aircraft Gas Turbine Engine Cycles Using the Numerical Propulsion System Simulation Code (NASA/TM-2007-214690). National Aeronautics and Space Administration. https://ntrs.nasa.gov/citations/20070018165

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