# Project 037 CLEEN II System-level Assessment

## Georgia Institute of Technology

## Project Lead Investigator

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## University Participants

**Georgia Institute of Technology (Georgia Tech)**

- P.I.s: Prof. Dimitri Mavris, Dr. Jimmy Tai
- FAA Award Number: 13-C-AJFE-GIT-055
- Period of Performance: October 1, 2024, to December 31, 2025
- Tasks:
  1. Finalizing Continuous Lower Energy, Emissions, and Noise (CLEEN) Fleet Benefit Assessment Assumptions
  2. Continuation of CLEEN III Modeling of Aircraft Technologies and Advanced Configurations
  3. Emissions Assessment Options
  4. Host CLEEN Consortium

## Project Funding Level

The Federal Aviation Administration (FAA) provided $425,000 in funding to Georgia Tech. Georgia Tech has agreed to a total of $425,000 in matching funds. This total includes salaries for the project director and research engineers, as well as funding for computing, financial, and administrative support, including meeting arrangements. Georgia Tech has also agreed to provide tuition remission for students, paid from state funds.

## Investigation Team

Prof. Dimitri Mavris, (P.I.)
Dr. Jimmy Tai, (co-P.I.)
Brennan Stewart, program management/noise modeling
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Supporting Engineers: Zhimin Liu, Carl Johnson, and Barbara Sampaio Felix
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## Project Overview

The objective of this research project is to support the FAA by independently modeling and assessing the technologies that are being developed under the CLEEN II and CLEEN III programs. This will involve direct coordination and data sharing with CLEEN-funded companies to accurately model the environmental benefits of these technologies at vehicle and fleet levels.

Georgia Tech was previously selected to perform all system-level assessments for the CLEEN program under Partnership for Air Transportation Noise and Emission Reduction (PARTNER) Project 036 and ASCENT Project 010. As a result, Georgia Tech is in a unique position from both the technical and programmatic standpoints to continue the system-level assessments for CLEEN II. From a technical perspective, Georgia Tech has significantly enhanced the Environmental Design

Space (EDS) to incorporate advanced, adaptive, and operational technologies targeting fuel burn, noise, and emissions. EDS has been successfully applied to all CLEEN I contractor technologies including the following: General Electric® (GE) open rotor, twin annular premixing swirler (TAPS) II combustor, Flight Management System (FMS)-Engine, and FMS-Airframe; Pratt & Whitney® geared fan; Boeing® adaptive trailing edge and ceramic matrix composite (CMC) nozzle; Honeywell® hot section cooling and materials; and Rolls-Royce® turbine cooling technologies. In 2024, Georgia Tech stated that all CLEEN II Technology modeling had been completed as well and delivered results to the FAA quantifying the impacts of the CLEEN I and II programs in the areas of fuel burn reduction/cost savings, nitrogen oxides ($NO_x$) reduction, and noise reduction.

Georgia Tech has also gained extensive experience in communicating system-level modeling requirements to industry engineers and translating the impacts to fleet-level fuel burn, noise, and emissions assessments. This broad technical knowledge base covering detailed aircraft and engine design, as well as high-level benefits assessments, places Georgia Tech in a unique position to assess CLEEN III technologies.

Because the goal of this work is to conduct fleet-level assessments for aircraft representative of future “in-service” systems, Georgia Tech will need to create system-level EDS models using a combination of both CLEEN II/III and other public domain N+1 and N+2 technologies. The outcomes of the technology and fleet assumptions-setting workshops conducted under ASCENT Project 010 are used for this effort. Non-CLEEN technologies for consideration, along with potential future fleet scenarios, will help to bound the impact of CLEEN II/III on future fleet fuel burn, emissions, and noise.

Work conducted during this period of performance examined the impact of updates to some of the CLEEN Fleet assessment assumptions. Phase II of the CLEEN program, made the decisions to use the same assumptions as phase I of the CLEEN program. These assumptions were finalized in approximately 2015. There have been significant changes to the aviation market since the assumptions were originally set. CLEEN III plans to update the fleet assumptions to better align with current trends in the aviation industry. This year of work examined the impact of some of these assumption changes on the CLEEN III Fleet as compared to CLEEN II. Georgia Tech also continued the modeling of CLEEN III technologies while working with CLEEN Contractors. This work is being conducted under a non-disclosure agreement (NDA) due to its proprietary nature, so only minimal updates can be provided publicly.

Georgia Tech also worked on creating alternative emission assessment capabilities inside of EDS. Currently, $NO_x$ is predicted according to the landing and takeoff (LTO) cycle, which utilizes an assumption for how long the engine is at various power levels. Georgia Tech added functionality to EDS to compute $NO_x$ emissions along notional takeoff trajectories predicted by EDS. This will provide an estimate of $NO_x$ tied to the takeoff performance of each aircraft, rather than solely being tied to engine performance. Additionally, Georgia Tech explored methods of implementing non-volatile particulate matter (nvPM) Emissions inside of EDS. These metrics will not be utilized by the current phase of CLEEN program, but there is increased interest in tracking or regulating these metrics in the wider aerospace community, so Georgia Tech explored these metrics should they be required for future analysis under the CLEEN program.

Georgia Tech had been planning to host the Spring 2025 CLEEN consortium, (a series of meetings where CLEEN contractors report progress updates to the FAA twice a year), on campus in Atlanta, Georgia. However, restrictions on non-essential government travel in early 2025, as a part of wider cost savings and governmental efficiency pushes, necessitated that the spring 2025 consortium was ultimately held remotely.

Next year’s work will focus on implementing CLEEN III technologies into EDS as test data become available, finalizing a baseline fleet performance scenario, and conducting a preliminary fleet assessment provided a sufficient number of technology modeling tasks are completed.

## Milestones

The major milestones which were planned for this performance period and their planned due dates are listed below, (the major accomplishment section will discuss which were achieved).

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| Task No. | Milestone | Planned Due Date |
|---|---|---|
| 1 | Finalizing CLEEN Fleet Benefit Assessment Assumptions | December 31, 2025 |
| 2 | Continuation of CLEEN III Modeling of Aircraft Technologies and Advanced Configurations | December 31, 2025 |
| 3 | Development of Alternative Emissions Assessment Options within EDS | September 30, 2025 |
| 4 | Host CLEEN Consortium | May 30, 2025 |

## Major Accomplishments

- Analyzed the impact of fleet assumptions updates on CLEEN III Fleet Assessment.
- Continued modeling progress of CLEEN III Technologies.
- Included alternative $NO_x$ emission assessment options in EDS and accessed nvPM prediction options.

# Task 1 - CLEEN Fleet Benefit Assessment Assumptions

**Georgia Institute of Technology**

## Objectives

The objective of this task is to finalize the CLEEN Fleet Benefit Assessment assumptions. During this period of performance, Georgia Tech implemented updated assumptions in the Fleet Assessment Environment and began to analyze their impact.

## Research Approach

The reports *Project 037 CLEEN II System-level Assessment* (Mavris et al., 2023 and Mavris et al., 2024) for the previous periods of performance details the initial updates to the Fleet Assessment Assumption from CLEEN II. This period of performance focused on implementing those assumptions and evaluating the impact on the fleet study. This is being done ahead of the CLEEN III fleet study to examine some of the key changes and evaluate if the results are reasonable.

The fleet assessment introduces new vehicles by replacing older retiring aircraft and ordering new aircraft to meet increased demand. The replacement matrix, as shown in Figure 1, informs the fleet study which vehicles would comprise the new introductions for each vehicle class for any year. These new introductions would be from either replacing retiring vehicles or vehicles purchased to meet increased demand. An assumption is made that it takes about four years to transition to delivering solely the next generation of vehicles. An example of how to read the replacement matrix is that in the year 2028, 75% of regional jet replacements will consist of N1 generation of vehicles while the other 25% will consist of N2 generation of vehicles.

The assumptions used in CLEEN I/II was that the baseline best-in-class vehicles (which would be infused with technologies to create notional vehicles) were based on what was available in 2015. Between 2015 and 2020, a new generation of vehicles would come into services comprising the N1 generation of vehicles, which would feature CLEEN I technologies, (some, but not all CLEEN I technologies made it into service comprising this generation of vehicles). These dates were chosen to roughly correspond to introductions of actual aircraft such as the Boeing B737-8, Embraer® E190-E2, and Boeing B787-10. Before these introductions, the 2015 best-in-class is used for new deliveries.

In CLEEN I/II, it was assumed there would be N2 generation of vehicles coming into service in the 2020s which would be used for the introduction of CLEEN II technologies. However, the trend in the aviation industry that occurred is that the 2020s has not seen the introduction of new vehicles (outside of the delayed 777x). Therefore, CLEEN III will be updating the assumption regarding when CLEEN II technologies will be introduced on a new generation of vehicles to the mid-2030s, which will likely correspond with the introduction of CLEEN III technologies. Figure 2 shows the effect difference delaying the introduction of a new generation of vehicles from the mid-2020s to the mid-2030s. Relative to the assumptions in CLEEN I/II, in 2050 under the CLEEN III assumptions, the N1 generation is predicted to have approximately 70% increased annual operations, while the N2 generation is predicted to have approximately 37% less annual operations.

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These assumptions are reflected by current trends in the aviation industry. As of December 31, 2025, Boeing has 4,869 unfilled orders for the 737 and 1,076 unfilled orders for the 787 (Boeing, 2025). As of December 31, 2025, Airbus® has 1,793 outstanding orders for the A320neo and 5,348 outstanding orders for the A321neo (Airbus, 2025). Embraer Air as of quarter (Q)2 2025 has 190 outstanding firm orders for the E195-E2 in their backlog (Embraer, 2025). These backlog of orders align well with Georgia Tech's fleet analysis assumptions which has delivery of this generation of vehicles continuing for the foreseeable future.

What this means for the CLEEN fleet assessment is that technologies which made it into service on the N1 generation of vehicles will be in operation on a larger percentage of the overall fleet, while CLEEN II technologies, which will be now be introduced in a 2035 generation of vehicles, will be in operation on a smaller percentage of the overall fleet by 2050. The potential fleet benefit of technologies is influenced by how many vehicles are in the fleet in which the technology is present. These statements are meant not to quantify the impact of these changes, as a full fleet assessment with the CLEEN III assumptions has not been performed. Additionally, a later introduction of these technologies might enable these technologies to express further benefits beyond 2050, and these technologies will be introduced on more technologically advanced vehicles. These factors should be considered when analyzing the impact of CLEEN technologies on the CLEEN III fleet assessment when examining the results.

| Vehicle | Timeframe | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032 | 2033 | 2034 | 2035 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RJ | N+1 | 0 | 0 | 0 | 25 | 50 | 75 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 75 | 50 | 25 | 0 | 0 | 0 | 0 | 0 |
| RJ | N+2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 25 | 50 | 75 | 100 | 100 | 100 | 100 | 100 |
| LSA | N+1 | 0 | 25 | 50 | 75 | 100 | 100 | 100 | 100 | 100 | 100 | 75 | 50 | 25 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| LSA | N+2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 25 | 50 | 75 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| STA | N+1 | 0 | 0 | 0 | 25 | 50 | 75 | 100 | 100 | 100 | 75 | 50 | 25 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| STA | N+2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 25 | 50 | 75 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| LTA | N+1 | 0 | 0 | 0 | 25 | 50 | 75 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 75 | 50 | 25 | 0 | 0 | 0 |
| LTA | N+2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 25 | 50 | 75 | 100 | 100 | 100 |
| VLA | N+1 | 0 | 0 | 0 | 0 | 0 | 25 | 50 | 75 | 100 | 100 | 100 | 100 | 75 | 50 | 25 | 0 | 0 | 0 | 0 | 0 | 0 |
| VLA | N+2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 25 | 50 | 75 | 100 | 100 | 100 | 100 | 100 | 100 |

**Figure 1.** CLEEN I/II fleet replacement matrix assumptions.

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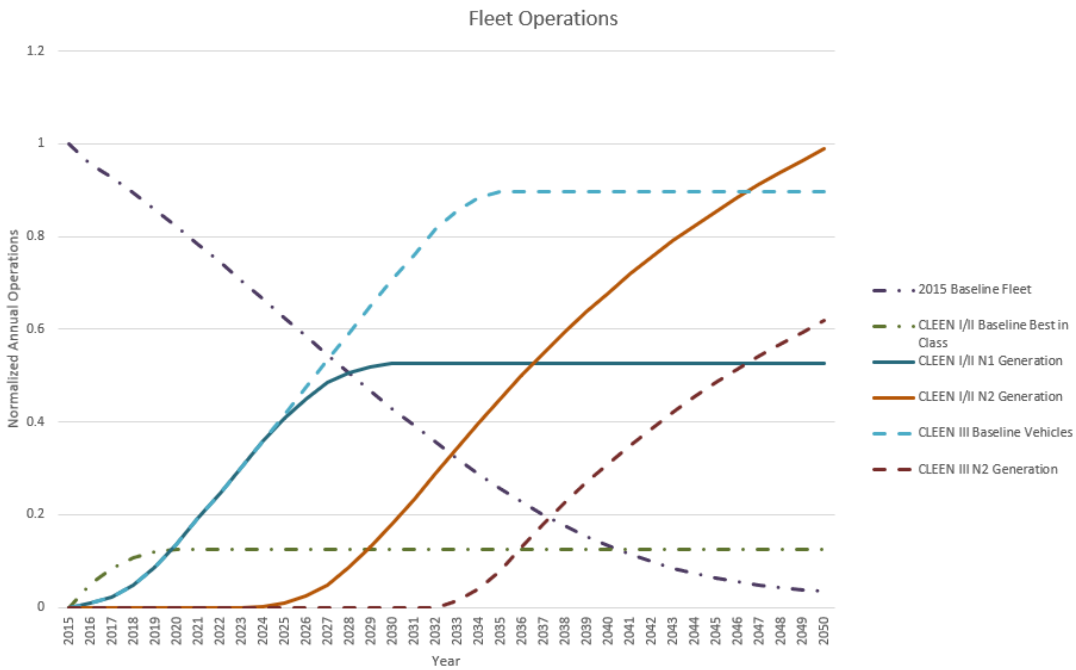


**Figure 2.** Projected fleet assessment operations of different vehicle generations. CLEEN: Continuous Lower Energy, Emissions, and Noise.

Steps for completion of the fleet study include the steps listed below. These will guide work for the next period of performance.

- Selected updated best-in-class reference vehicles and new fleet analysis assumptions (previously completed).
- Create and calibrate best-in-class reference vehicles (previously completed).
- Implement updated fleet replacement assumptions (completed this period).
- Implement updated base year fleet makeup.
- Implement updated demand growth forecasts.
- Run fleet study for non-CLEEN technology Infused vehicles using public tech Technology Impact Matrix (TIM).
- Run fleet study for CLEEN technology infused vehicles (completion is dependent on Task 2).
- Compare CLEEN and non-CLEEN fleet study results to establish CLEEN III program benefits.

# Task 2 - Continuation of CLEEN III Modeling of Aircraft Technologies and Advanced Configurations

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## Objectives

The objective of this task is to estimate the impacts of CLEEN relevant technologies at the vehicle system-level, each of these technologies must be modeled regarding their impacts to aircraft fuel burn, noise, and emissions using EDS.

## Research Approach

Georgia Tech was previously selected to perform all system-level assessments for the CLEEN program under ASCENT Project 010. Because the ultimate goal of this work is to conduct fleet-level assessments for aircraft representative of future “in-service” systems, Georgia Tech will need to create system-level EDS models using a combination of both CLEEN (Phases I, II, and III) and other public domain near-term and midterm Entry into Service (EIS) technologies. Vehicle system-level modeling for all relevant CLEEN technologies will be performed using EDS.

Table 1 presents a list of CLEEN technologies funded under Phase III of the program which as suitable for the Fleet Assessment. The efforts related to sustainable aviation fuel (SAF) funded under CLEEN III are excluded from this list as they are outside the scope of Georgia Tech's fleet assessment. Mavris et al. (2024) noted that the CLEEN II technology modeling process had been completed, as well as noting which areas of the primary fleet analysis metrics each technology affects. Due to the proprietary nature of the modeling work, as Georgia Tech works directly with each CLEEN contractor under an NDA, specific details of the modeling efforts cannot be provided. However, with Phase III of the CLEEN Program publicly slated to concluded in 2026 as noted in Orton (2024), Georgia Tech is engaged with all contractors with the goal of delivering fleet assessment results after all contractor modeling has concluded, and data have been integrated into Georgia Tech's modeling environment.

**Table 1.** CLEEN III Technologies and Impact Area.

| Contractor | Technology/Model Impact Area | Fuel Burn | $NO_x$ | Noise |
|---|---|---|---|---|
| **Boeing** | Quiet Landing Gear | | | X |
| | Quiet High Lift System | | | X |
| | Advanced Inlet | X | | X |
| | Intelligent Operations | X | | X |
| **Collins** | Large Cell Novel Core Exhaust | | | X |
| **Delta/MDS/America's Phenix** | Fan Leading Edge Protective Coating | X | | |
| **GE** | MESTANG III | X | | |
| | Open Fan | X | | X |
| | Advanced Thermal Management | X | | |
| | Hybrid Electric Integrated Generation | X | | |
| | Combustor Technology | X | X | |
| | Advanced Acoustics | | | X |
| **Honeywell** | High Pressure Core | X | X | X |
| | Highly Efficient Fan | X | | X |
| | Compact low-pressure turbine | X | | |
| **Pratt and Whitney** | Fan Noise Technologies | | | X |
| | Fan Performance Technologies | X | | |
| | Combustor – Swirlers | | | X |
| | Combustor – Cooling Technologies | X | | |
| | Combustor- Low Pattern Factor | X | | |
| | Combustor – $NO_x$ Reduction | | X | |
| **Rolls-Royce** | Centrifugal Compressor | X | | |
| **Safran** | Short Inlet | | | X |

# Task 3 - Emissions Assessment Options

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## Objective

Georgia Tech has provided the $NO_x$ emissions fleet benefit assessments for both of the first two phases of the CLEEN program. As the CLEEN program continues through Phase III, Georgia Tech will work on expanding the assessment capabilities used in delivering this $NO_x$ emissions benefits in addition to assessing if nvPM emissions can be predicted to ensure that ASCENT Project 037 has the capability to be ready for any future shifts in emission metrics modeling.

## Research Approach

$NO_x$ emitted in the LTO cycle has been exclusively considered as LTO emissions for FAA CLEEN program level metric by which to assess fleet benefits. The landing and take-off cycle computes $NO_x$ emissions through a combination of engine performance metrics and an assumed operation cycle (European Environment Agency & EASA, 2016). The LTO cycle uses the times described in Table 2 in the calculation of LTO emissions. The aircraft emission rate per operation conditions is multiplied by the assumed time in each operation mode to get the LTO emissions.

This formulation results in LTO emissions cycle results in $NO_x$ emissions being a function of only the engine performance. By being decoupled from airframe performance, changes to the aerodynamics or weight of the aircraft (which could result in varying thrust levels and time to climb away from the terminal airspace) have no impact on the $NO_x$ as predicted by this cycle. This cycle has benefits in that it allows $NO_x$ to be quantified by entirely public information using the data in the International Civil Aviation Organization (ICAO) Emission Database (ICAO, 2021), as the operational assumptions are fixed and the emissions metrics are all publicly reported by the European Union Aviation Safety Agency (EASA) for engines above 6,000 lbf (26.78 kN). However, this comes at the cost of being decoupled from the aerodynamics and takeoff/landing weight of the aircraft.

Georgia Tech has developed the capability to assess $NO_x$ in a more comprehensive way to ensure Georgia Tech maintains the capability to model any future standards for $NO_x$ metrics. Two additional emissions approaches have been developed for fleet benefit articulation. In the previous period of performance, it was reported that Georgia Tech added the capability to our Flight Optimization System analysis to assess $NO_x$ over the full mission. Full mission $NO_x$ considers $NO_x$ produced by aircraft across the complete mission, not just around the airport. The other metric, terminal mission $NO_x$, considers $NO_x$ produced by aircraft below an altitude of 3,000 ft. This assessment approach, though a less common standard than LTO $NO_x$, considers installation effects, aircraft LTO trajectory, and actual engine operations in this window of the mission. A description for the implementation for each functionality is described in Mavris et al. (2024). Georgia Tech has completed development of the terminal area $NO_x$ capability during this performance period.

Below are examples of Georgia Techs analysis of the $NO_x$ emissions using these metrics as assessed in EDS for a Georgia Tech Notional 787-8 with Notional Engine model of a GEnx-1B70. Table 2 shows the LTO cycle $NO_x$ calculations, (please note numbers have been rounded to the nearest tenth of a decimal). Figure 3 shows the cumulative $NO_x$ build up over the course of a notional mission. Figure 4 shows the cumulative $NO_x$ over course of a notional takeoff.

**Table 2.** Example of landing and takeoff (LTO) nitrogen oxides ($NO_x$) cycle for a notional 787 as calculated by Environmental Design Space (EDS).

| Segment | Time (min) | EI NOx (g NOx/kg Fuel) | Fuel Flow Rate (lbm/s) | NOx per Engine (lbs) |
|---|---|---|---|---|
| **Taxi** | 26 | 4.9 | 0.5 | 3.8 |
| **Approach** | 4 | 11.1 | 1.5 | 4.0 |
| **Takeoff** | 0.7 | 35.3 | 5.4 | 8.0 |
| **Climb** | 2.2 | 20.6 | 4.5 | 12.2 |
| **Total** | N/A | N/A | N/A | 28.1 |

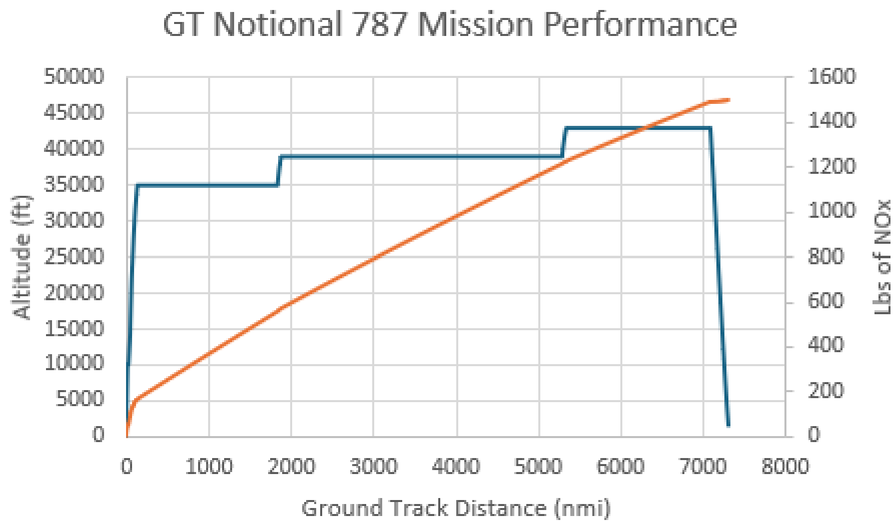


**Figure 3.** Example of full mission nitrogen oxides ($NO_x$) build up for notional 787 in Environmental Design Space (EDS).

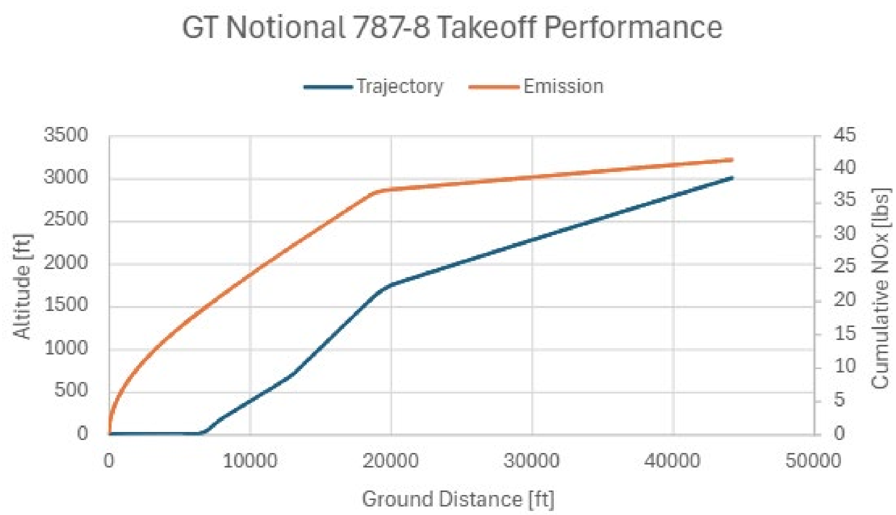


**Figure 4**. Example of Takeoff nitrogen oxides (NOx) build up for notional 787 in Environmental Design Space (EDS).

Although Georgia Tech now has the capability to model alternative $NO_x$ metrics, both Georgia Tech and the FAA agree that LTO $NO_x$ will remain the standard for the CLEEN III program. However, Georgia Tech will continue to develop EDS emission analysis capabilities which might become metrics of interest in future phases of the CLEEN program.

Another metric of interest of growing interest to the aviation industry is nvPM emissions. Georgia Tech does not currently have the capabilities to predict this metric as a part of our EDS analysis. However, this emission is of interest due to its contribution to contrail creation. Georgia Tech explore nvPM predictions through the application of the Mission Emissions Estimation Methodology (MEEM) method as described in Ahrens et al. (2022) as well as exploring if a P3T3 correlation could be created by regressing data in the ICAO Emissions Database (ICAO, 2021). To explore these methods, Georgia Tech attempted to fit nvPM data for PW1100G, GEnx-1B, and the CF6 engine families. Figure 5 to Figure 7 below show the nvPM levels plotted against thrust. These engines were selected to provide two modern and one older engine examples.

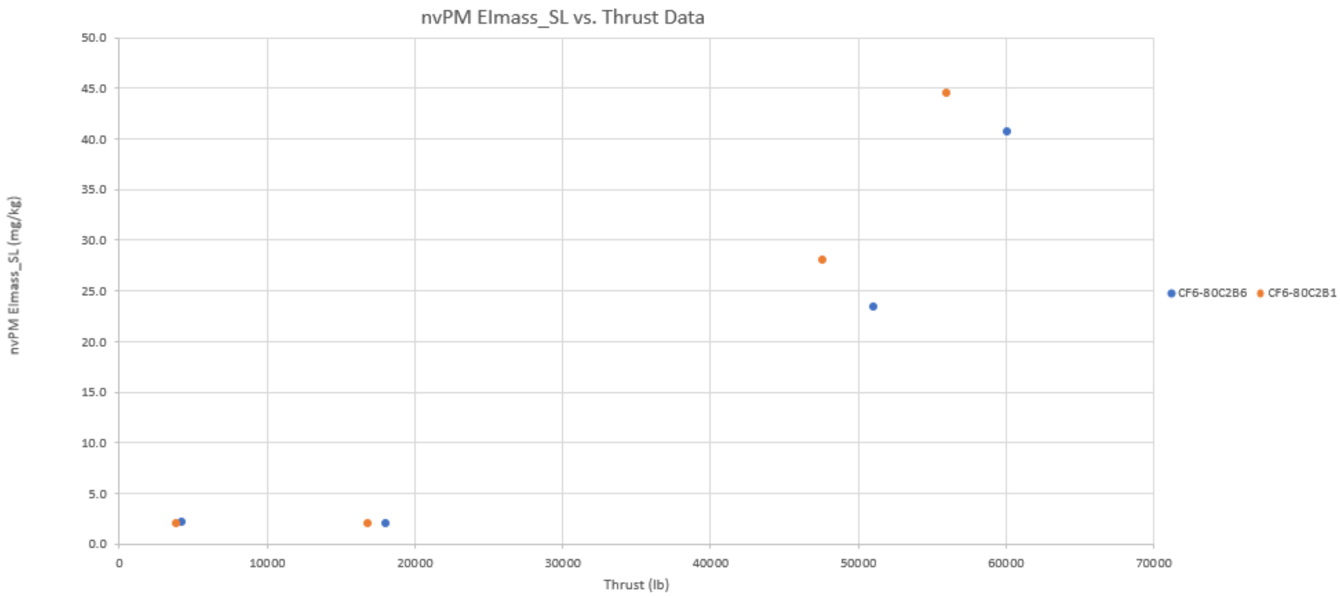


**Figure 5.** CF6 family non-volatile particulate matter (nvPM) emission mass vs. thrust from ICAO Emission Database.

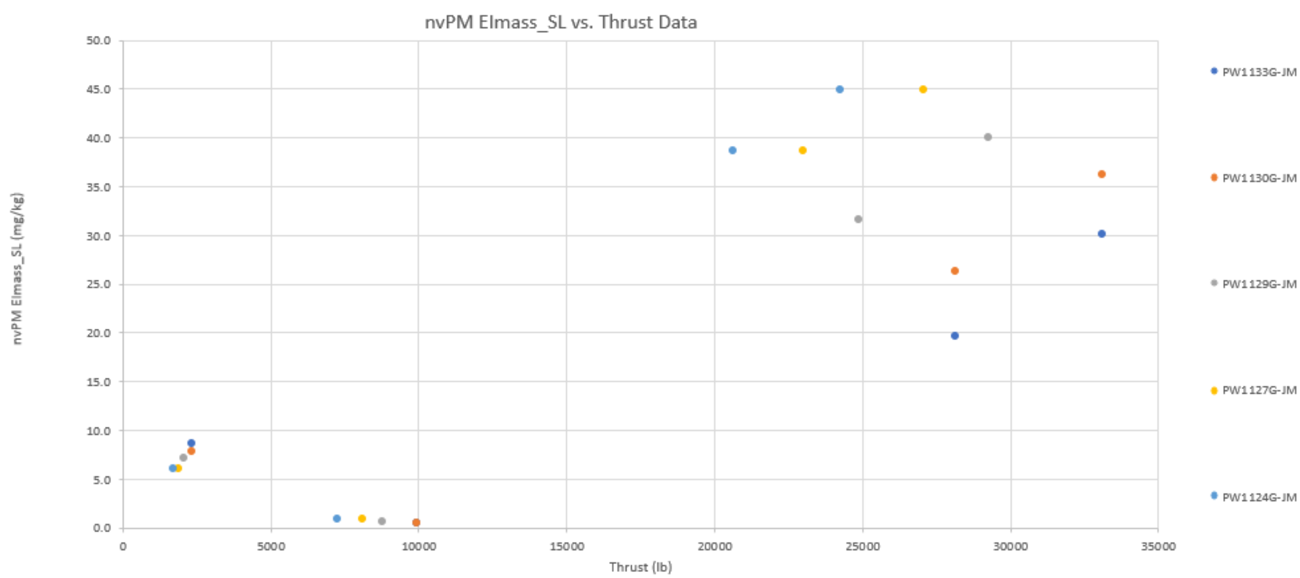


**Figure 6.** PW1100G family non-volatile particulate matter (nvPM) emission mass vs. thrust from ICAO Emission Database.

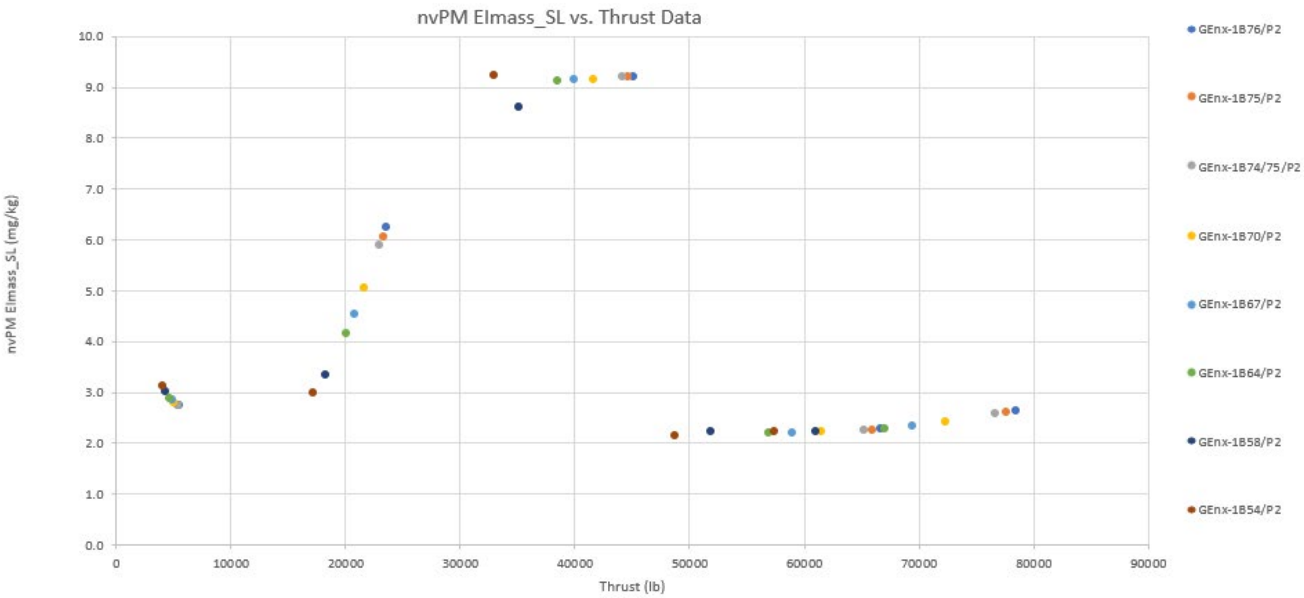


**Figure 7.** GEnx family non-volatile particulate matter (nvPM) emission mass vs. thrust from ICAO Emission Database.

Georgia Tech explored the MEEM method as outlined by Ahrens et al. (2022). The paper by Ahern outlines a four-step procedure to predict nvPM emissions. Figure 8 to Figure 10 show the process described in step 3 of Ahern which is either a four- or five-point linear interpolation fit over the certification data from the ICAO databank. This linear interpolation fits well as it passes through each of the certification points; however, it is only valid for a specific engine and does not provide a basis for extrapolation. Nevertheless, Georgia Tech was able to apply this method to predict operational nvPM by combining these piecewise linear interpolations with the process described in Step 4 of Ahern to correct for nvPM at altitude. This correction uses the ratio of the pressure at the combustor entrance (P3) at the altitude over the pressure at combustor entrance on the ground as shown in Equation 1 below. Steps 1 and 2 of Ahern describe a process of estimating, thrust, temperature, and pressure on the ground and at altitude are needed to apply this proposed method, but these are unnecessary in Georgia Tech's implementation of this method as these values are predicted in the engine model generated by EDS.

$$EI_{mass,Alt} = EI_{mass,GR} \left(\frac{P3_{ALT}}{P3_{GR}}\right)^{1.35} 1.1^{2.5} \quad \text{(Eq. 1)}$$

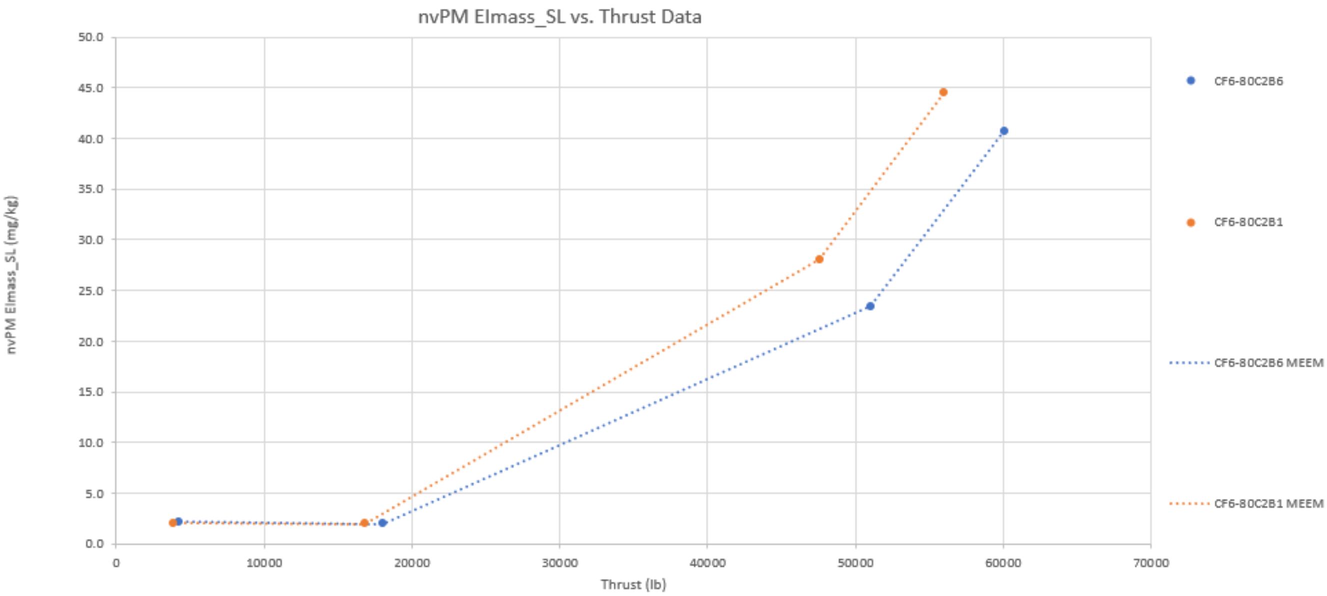


**Figure 8.** Mission Emissions Estimation Methodology (MEEM) interpolation applied to Cf6 family.

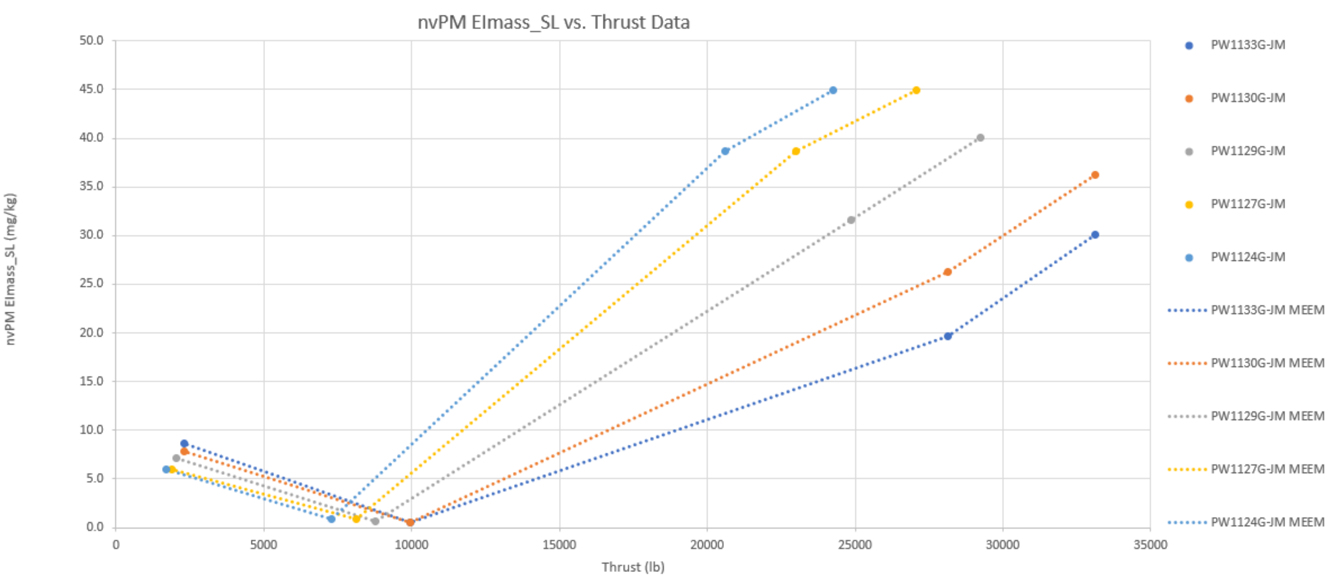


**Figure 9.** Mission Emissions Estimation Methodology (MEEM) interpolation applied to Pw1100g family.

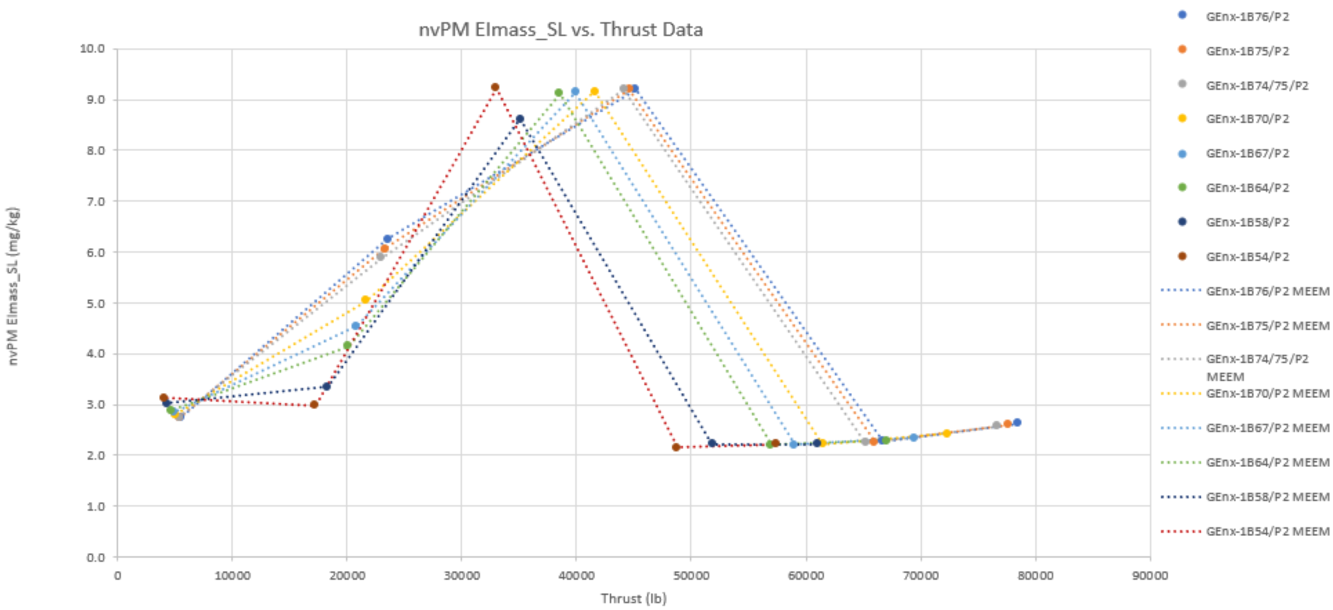


**Figure 10.** Mission Emissions Estimation Methodology (MEEM) method interpolation applied to GEnx family.

Georgia Tech also explored developing a P3T3 correlation to predict nvPM equations. P3T3 correlations are widely used method in industry for predicting certain emission index based on the pressure and temperature at the combustor inlet, (station 3). However, these methods require often proprietary engine performance data. Georgia Tech has a methodology where the proprietary engine performance data are replaced with engine performance data from Notional Flight Optimization System (NPSS) engine models to approximate a P3T3 correlation. Georgia Tech uses this method in $NO_x$ predictions. Georgia Tech attempted to extend this method to nvPM predictions with mixed results which are shown in Figure 11 to Figure 13. It should be noted that without proprietary engine data, the data points in these charts, which correspond to certification thrust levels show on the previous figures, come from Georgia Tech's notional NPSS engine models.

It quickly became apparent that the three engine families had very different $NO_x$ emissions characteristic which would make fitting a regression challenging. The CF6 family showed monotonically increase in nvPM emissions with thrust. The PW1100G family showed that the engines were most efficient at the approach thrust level, and the GEnx engines have the worst emissions at the climb thrust level and the best at the takeoff thrust level. The PW1100g and CF6 engine families also show a variation in the slope of the nvPM emissions with the thrust level among the different ratings in the engine family with the derated engines showing a greater rise in nvPM emissions with thrust. Georgia Tech was unable to create a correction which could account for the differences in the engine rating. So, while this method was able to provide a somewhat acceptable P3T3 correlation for the GEnx and CF6 family, the PW1100G P3T3 correlation performed particularly poorly.

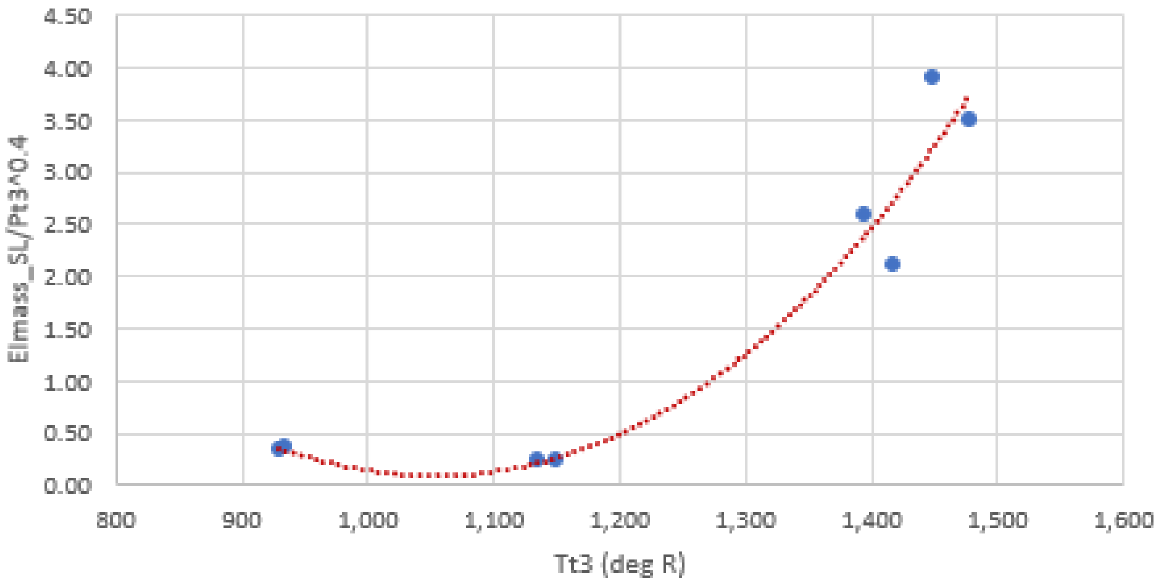


**Figure 11.** Georgia Tech nvPM P3T3 correlation against certification points for notional CF6 engines.

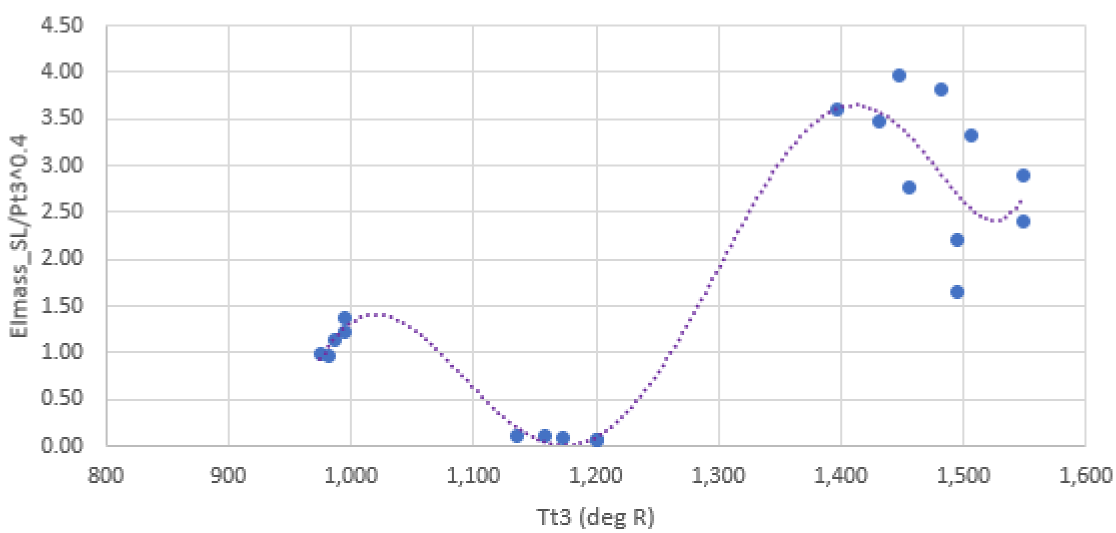


**Figure 12.** Georgia Tech nvPM P3T3 correlation against certification points for notional pw1100g engines.

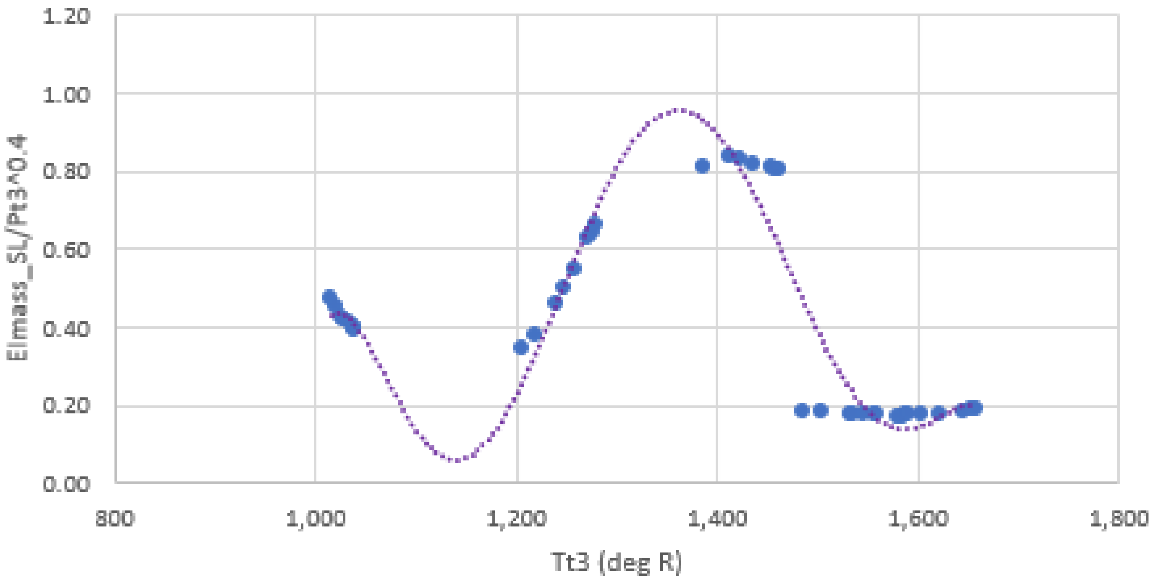


**Figure 13.** Georgia Tech nvPM P3T3 correlation against certification points for notional GEnx engines.

As a result of this task, Georgia Tech has the capabilities of predicting $NO_x$ emissions over the course of the entire mission and for all operations below 3,000 ft. Georgia Tech can also predict nvPM emissions using the two methods described previously. However, the MEEM method is merely an interpolation and will not be suitable for extrapolation, and Georgia Tech attempt at fitting a P3T3 correlation had mixed success for different engine families.

# Task 4 – Host CLEEN Consortium

**Georgia Institute of Technology**

## Objective

Georgia Tech and the FAA had coordinated to host the CLEEN Spring 2025 Consortium on campus at Georgia Tech in Atlanta, Georgia.

## Research Approach

The CLEEN Consortium is a bi-annual event where CLEEN contractors report out progress and updates to the FAA on the current state of their CLEEN programs. This gives the government a chance to ensure that the program remains on track, and allows them to invite other government entities, (such as National Aeronautics and Space Administration representatives), and select academia representation, (Georgia Tech), to participate in these reviews and provide feedback to the FAA. Georgia Tech allocated resources to coordinate with FAA resolving the logistics of hosting a CLEEN Consortium and coordinating with contractors. Georgia Tech also was coordinating with Delta to include a facility tour as a part of the CLEEN Consortium Agenda for government attendees. This coordination continued until late February when it became apparent that restrictions on non-essential travel, such as those in Executive Order 14222 (Exec. Order No. 14,222, 2025) which came as a part of wider governmental cost savings and wider efficiency pushes, would require that the CLEEN Consortium be hosted virtually. Plans for Georgia Tech to host the CLEEN Consortium were cancelled with mutual agreement between the FAA and Georgia Tech.

## Publications

None.

## Outreach Efforts
The Georgia Tech attended the spring and fall CLEEN Consortium in 2025 which included the opportunity for students to observer industry prevent their contributions to the ASCENT program and how professional engineering reviews are conducted.

## Awards
None.

## Student Involvement
Over the course of 2025, 19 different graduate students received funding from this effort. Note that all 19 students were not funded simultaneously. One of the graduate students (Joao De Azevedo) is on a doctoral track, and the other 18 students (Tabitha D'Amato, Dante Cyrus, James Tsangarides, Kayley Lewis, Ballard Huey, Nathaniel Green, Flavius Penescu, Aniela Zaremski, Akash Shiri, Anna Conroy, Vishwa Malaisamy, Samal Siddharth, Anika Chawla, Adi Arora, Nicholas He, Suhanna Bamzai, Ellen Wang, and Thomas Prosser) are on master's degree track. One additional student, Dante Cyrus, supported this project while receiving funding from the U.S. Air Force.

## Plans for Next Period
- Focus on implementing CLEEN III technologies into EDS as data become available.
- Finalize a baseline fleet performance scenario.
- Conduct a preliminary fleet assessment provided that sufficient number of technology modeling tasks are completed.

## References

Airbus. (2025). *Orders and deliveries, Commercial Aircraft*. https://www.airbus.com/en/products-services/commercial-aircraft/orders-and-deliveries

Ahrens, D., Méry, Y., Guénard, A., & Miake-Lye, R. (2022) *A New Approach To Estimate Particulate Matter Emissions From Ground Certification Data: The nvPM Mission Emissions Estimation Methodology (MEEM).* The American Society of American Engineers. https://asmedigitalcollection.asme.org/GT/proceedings/GT2022/85994/V03AT04A035/1148716

Boeing. (2025). *Commercial, Orders & Deliveries.* https://www.boeing.com/commercial

Embraer. (2025). *Orders and deliveries.* https://www.embraer.com/eca/orders-deliveries/en/

European Environment Agency, European Union Aviation Safety Agency. (2016). *European aviation environmental report 2016*. https://op.europa.eu/en/publication-detail/-/publication/796e6041-fc83-11e5-b713-01aa75ed71a1/language-en

Exec. Order No. 14,222. 90 FR 11095 (2025). https://www.federalregister.gov/documents/2025/03/03/2025-03527/implementing-the-presidents-department-of-government-efficiency-cost-efficiency-initiative

ICAO. (2021). ICAO Aircraft Emissions Databank. International Civil Aviation Organization. https://www.easa.europa.eu/en/domains/environment/icao-aircraft-engine-emissions-databank

Mavris, D., & Kirby, M. (2024). *Project 082(A) Integrated Noise and CO2 Standard Setting Analysis*. FAA Center of Excellence for Alternative Jet Fuels & Environment. https://ascent.aero/project/integrated-noise-and-co2-standard-setting-analysis/

Mavris, D., Tai, J., & Brooks, J. (2023). *Project 037 CLEEN II System-level Assessment*. FAA Center of Excellence for Alternative Jet Fuels & Environment. https://s3.wp.wsu.edu/uploads/sites/2479/2024/08/2023-ASCENT-Annual-Report.pdf

Mavris, D., Tai, J., & Brooks, J. (2024). *Project 037 CLEEN II System-level Assessment*. FAA Center of Excellence for Alternative Jet Fuels & Environment. https://s3.wp.wsu.edu/uploads/sites/2479/2025/06/ASCENT-2024-Annual-Report.pdf

Orton, A. (2024). *FAA Office of Environment & Administration Energy Overview and Update.* FAA Center of Excellence for Alternative Jet Fuels & Environment. https://www.faa.gov/sites/faa.gov/files/Nov-2024FAA-Environment-and-Energy-RD-Overview.pdf