# Project 048 Analysis to Support the Development of an Engine nvPM Emissions Standard

## Massachusetts Institute of Technology

## Project Lead Investigator

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## University Participants

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- P.I.: Prof. Steven Barrett
- Co-PI: Dr. Raymond Speth
- FAA Award Number: 13-C-AJFE-MIT, Amendment Nos. 027 and 036
- Period of Performance: July 8, 2016 to Aug. 31, 2018 (Reporting here with the exception of funding level and cost share only for the period October 1, 2016 to September 30, 2017).
- Tasks:
    - Task 1: Write a detailed scientific background of the APMT-I tools suite
    - Task 2: Map emissions from a short-list of representative engines to all engine/airframe combinations
    - Task 3: Evaluate metrics from the CAEP/WG3/PMTG for evaluating an engine's nvPM performance
    - Task 4: Verify technology response provided by engine manufacturers
    - Task 5: Evaluate proposed fuel sensitivity corrections and ambient conditions corrections
    - Task 6: Evaluate the current nvPM modeling approaches available to CAEP and assess uncertainty contributions

## Project Funding Level

$350,000 FAA funding and $350,000 matching funds. Sources of match are approximately $105,000 from MIT, plus 3rd party in-kind contributions of $87,000 from University College London and $158,000 from Oliver Wyman Group.

## Investigation Team

Principal Investigator: Prof. Steven Barrett
Co-Principal Investigator: Dr. Raymond Speth
Co-Investigators: Dr. Jayant Sabnis
Graduate Students: Akshat Agarwal

## Project Overview

This projects aims to provide support to the FAA Office of Environment and Energy (AEE) in developing an emissions standard for non-volatile Particulate Matter (nvPM). The analyses will be further used to inform the International Civil Aviation Organization's Committee on Aviation Environmental Protection (ICAO-CAEP) in developing a global standard for nvPM emissions. The analyses will cover both US NAS-wide and global bases covering the costs and benefits from an economic and environmental (air quality, climate and noise) perspective. The main goals for this project include:

- Writing a scientific overview of the Aviation environmental Portfolio Management Tool's Impact (APMT-I) suite of analysis tools.
- Mapping emissions from a short-list of representative engines to a broader list of engine/airframe combinations.
- Evaluating metrics developed by CAEP Working Group 3 PM Task Group (CAEP/WG3/PMTG) important for evaluating an engine/airframe's nvPM emissions performance.
- Using the initial metrics and stringency options, independently verify the technology response provided by engine manufacturers.
- Evaluating proposed fuel sensitivity corrections and ambient conditions corrections.
- Evaluating the current nvPM modeling approaches available to CAEP, as well as investigating the potential of using number emissions to estimate health impacts. The tools will be further developed to incorporate a number of uncertainties relevant to the nvPM modeling approach.

# Task #1: Write a Detailed Scientific Background of the APMT-I Tools Suite

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## Objective(s)

This task involves writing a detailed overview of the scientific background and uncertainty estimations used in the noise, air quality and climate models within the APMT-I tools suite. These papers are intended for presentation to the CAEP Modeling and Databases Group (MDG) to inform the decision to add cost-benefit analysis to the CAEP modeling procedure, which only considers cost-effectiveness analysis at this stage.

## Research Approach

The APMT-I tools suite consists of models to analyze the noise, air quality and climate impacts of aviation emissions. Each model moves from estimated emissions or noise sources to monetized impacts in order to compare and contrast the various costs and environmental benefits of a particular policy. The papers are written to provide a detailed resource for understanding the scientific background, modeling assumptions and uncertainty analyses used within the APMT-I models. The papers will be written in 4 sections covering each of the APMT-I models (air quality, climate and noise) and an additional section on the advantages of using cost-benefit analyses on top of cost-effectiveness.

## Milestone(s)

All documentation (three model papers and one on cost-benefit analysis) have been completed, refined by FAA project managers, and presented to MDG.

## Major Accomplishments

Task complete.

## Outreach Efforts

Regular presentations were made to MDG's ad-hoc group on cost-benefit analysis, highlighting the scientific methods, assumptions and benefits of using the APMT-Impacts tool suite and the associated cost-benefit analysis architecture.

## Student Involvement

Graduate student Akshat Agarwal was primarily responsible for writing the reviews and presenting them to MDG.

## Plans for Next Period

Task complete.

# Task #2: Map Emissions from a Short-List of Representative Engines to All Engine/Airframe Combinations

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## Objective(s)

The objective of this task is to develop mappings between a short-list of representative engines that were analyzed during the measurement campaign and engine/airframe combinations currently in operation. This mapping will be used to develop an nvPM emissions inventory and identify the engine/aircraft combinations that may fail a particular stringency option.

## Research Approach

A major improvement from historic smoke/PM standards developed by CAEP is the use of a new measurement method to more precisely estimate nvPM emissions from aircraft engines. The measurement campaign will focus on a subset of all available aircraft engines. However, to model the effect of an emissions standard on the current fleet of aircraft, it is crucial to have estimates of nvPM emissions from the full range of engines currently in use. This requires a mapping between measured and available engines.

The mapping has required regular iteration with engine manufacturers communicating their own mappings and MIT has been responsible for ensuring this mapping is reasonable, providing scientific and data-driven justifications. This mapping has now been completed, verified by both OEMs, MIT and the FAA. The final step in this process is calculating the nvPM emissions (mass and number) for each of the “modeled” engines and ensure that they lie in the range that is expected. This process will allow for the use of these engines in understanding OEM responses to stringency options.

## Milestone(s)

The mapping process has been completed and agreed upon by all parties involved.

## Major Accomplishments

The mapping process has been completed and agreed upon by OEMs and the FAA. We have estimated the nvPM emissions from the mapped engines and are submitting information papers to WG3 to verify the emissions levels and associated uncertainties.

## Publications

We will be presenting a paper at the CAEP11 WG3 meeting in Paris this November, which will cover the methods used to estimate nvPM emissions from the fleet of mapped engines and a finalized database of values that can be used by modelers.

## Student Involvement

Graduate student Akshat Agarwal is primarily responsible for conducting the mappings.

## Plans for Next Period

Present information paper to WG3. Expected to be completed by November 30, 2017.

# Task #3: Evaluate Metrics from the CAEP/WG3/PMTG for Evaluating an Engine's Nvpm Performance

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## Objective(s)

The objective of the third task involves independently evaluating the metrics developed by the Particulate Matter Task Group of CAEP Working Group 3 (CAEP/WG3/PMTG). The aim is to identify the key issues relevant to describing nvPM emissions performance.

## Research Approach

Throughout the winter, WG3 was tasked with selecting an appropriate metric that can be used to regulate nvPM mass and number emissions. The aim was to identify parameters that would define any trends found in the experimentally data submitted by OEMs, while maintaining similar parameters for both mass and number emissions. An array of options was presented by the MIT team as well as other groups within WG3. Our focus was in trying to identify trends in the datasets and use this to develop the metric options. This is the analogous approach to $NO_x$ emissions, where OPR is used as an explanatory variable since it is a fundamental parameter that leads to higher combustor temperatures and thus higher $NO_x$ formation rates. For nvPM mass and number emissions, this exercise was found to be challenging and no engine-level parameters (e.g. $F_{00}$ or OPR) were found to explain the trends seen in the received data. This is because nvPM emissions are dependent not only on temperatures and pressures, but also the internal design of the combustor, which can vary substantially between manufacturers and engine size.

After numerous analyses and discussions, the metric system was accepted by the group. On top of deciding the correct metric values, WG3 also had to decide on which correction factors to apply. When measuring nvPM emissions, numerous particles can be absorbed by the flow lines that bring the exhaust emissions to the measurement equipment, so-called system losses. In addition, variations in ambient conditions and fuel properties can alter the measured emissions. It was thus necessary to study which corrections were appropriate to include and the MIT team approached this by studying the effect on uncertainties, and the extent to which system losses increased the uncertainty of the metric value was demonstrated. This work was presented at the WG3 meeting in Tokyo, Japan in May, aiding the group to achieve consensus.

## Milestone(s)

Metric value analysis completed and presented to WG3.

## Major Accomplishments

Task Complete.

## Publications

CAEP11-WG3-PMTG05-IP01, Effect of correction and uncertainty, May 2017, WG3 Tokyo.

## Outreach Efforts

Regular presentations were made to the metrics ad-hoc group with the aim of helping the group come to consensus on the best metric values to use. These presentations were made regularly from January to March of 2017. A final presentation on uncertainties was made in May in Tokyo.

## Student Involvement

Graduate student Akshat Agarwal was primarily responsible for studying the OEM data and identifying a range of parameters to use. He also led the presentation in Tokyo to understand the effects of various corrections and uncertainties in the data.

## Plans for Next Period

Task Complete.

# Task #4: Verify Technology Response Provided by Engine Manufacturers

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## Objective(s)

The objective of this task is to independently verify the technology response provided by the engine manufacturers and assist the FAA in developing consensus.

## Research Approach

OEMs have supplied technology responses to WG3 in October 2017. The technology responses identify the predicted cost to OEMs of reducing nvPM mass or number by a pre-determined amount and also present potential emissions' trade-offs with other species. For example, RQL engines are expected to trade-off $NO_x$ emissions with nvPM mass. Our role is to use our expertise to understand whether these responses are justified and provide feedback to the FAA on how to improve these responses. In addition to consulting in-house experts, we are also approaching the problem using the range of data available in the ICAO emissions data bank (EDB). Historic $NO_x$ standards have led to combustor technologies gradually reducing $NO_x$ emissions while maintaining high fuel performance. The EDB also collects smoke number (SN) information, which has been shown to be well correlated with nvPM mass emissions. Thus, we can identify changes in SN due to improvements in combustor technology that lead to a reduction in $NO_x$ emissions. We are currently processing this dataset and understanding some of the trends presented.

## Milestone(s)

EDB data has been processed and we are aiming to present to the FAA in early November.

## Outreach Efforts

Initial discussions with FAA have begun and we will continue this process to assist the group in coming to consensus on the technology responses.

## Student Involvement

Akshat Agarwal is primarily responsible for analyzing the EDB data and will lead the effort to presenting first to the FAA and then to WG3.

## Plans for Next Period

This task is expected to be completed following the November WG3 meeting.

# Task #5: Evaluate Proposed Fuel Sensitivity Corrections and Ambient Conditions Corrections

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## Objective(s)

The fifth task for this project involves conducting an independent evaluation of the proposed fuel sensitivity corrections and ambient conditions corrections.

## Research Approach

While metric values were being agreed upon in WG3, it was also necessary to develop models that could correct variations in nvPM emissions measurements due to changes in fuel composition. The group had already been accustomed to various approaches to this correction using fuel hydrogen content as the proxy. We began this process using in-house expertise (Speth et al. 2015), with presentations to WG3 in May in Tokyo of an alternative approach that used fuel aromatics content. We have since worked with other members of WG3, led by Dr Prem Lobo, to reconcile the different approaches. This collaborative work led to an additional modeling approach developed by Raymond Speth and presented to WG3 in July in Ann Arbor. After receiving feedback from WG3 on this approach, we will continue to work with Dr Lobo to identify an approach for treating fuel sensitivity that can achieve consensus within WG3.

## Milestone(s)
Presented the potential use of fuel aromatics content instead of fuel hydrogen content in Tokyo. Collaborated with Dr Prem Lobo to develop an alternative modeling approach using fuel hydrogen content and presented this approach in Ann Arbor.

## Publications
CAEP11-WG3-PMTG5-IP03, Fuel sensitivity corrections for nvPM measurements, May 2017, WG3 Tokyo.
CAEP11-WG3-PMTG6-WP14, Fuel sensitivity corrections factors for nvPM mass and number, July 2017, WG3 Ann Arbor MI.

## Outreach Efforts
Regular presentations have been made to the FAA and the metrics ad-hoc group within PMTG. These efforts are aimed at disseminating preliminary results, engaging in discussions about the approach and receiving feedback from WG3.

## Student Involvement
Graduate student Akshat Agarwal is collaborating on the data analyses for this task.

## Plans for Next Period
The planned analysis of fuel sensitivity was completed in with the presentations in July 2017. Analysis of refinements to the approach to be used by PMTG will be evaluated on an as-needed basis throughout the duration of the project.

# Task #6: Evaluate the Current Nvpm Modeling Approaches Available to CAEP and Assess Uncertainty Contributions
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## Objective(s)
The objectives for this task involve assessing the modeling capabilities available to CAEP for estimating the environmental impacts of aviation (air quality, climate and noise) and their potential for incorporating additional measurements available from the new nvPM measurement system. In addition, we aim to include additional uncertainties from the new measurement system that have previously not been included.

## Research Approach
In the final task, we not only aim to quantify the environmental impact of an nvPM emissions standard, but also attempt to quantify the various uncertainty contributions due to the new measurement methods. The nvPM emissions tests are conducted at ground level because of their ease in comparison to high-speed, cruise-altitude measurements. However, in order to evaluate the effects of cruise-altitude emissions on other atmospheric processes, e.g., contrail formation, these ground level test data must be mapped to cruise conditions. This has been addressed in historic models such as the FOX model (Stettler et al. 2013)for nvPM emissions, who used a correlation developed by Dopelheuer and Lecht (1998). In this task, we will evaluate the applicability of these models for the new method of measuring nvPM emissions, quantifying the uncertainty of the measurements.

The next part of this task involves ensuring the advanced nvPM measurement capabilities can be used to model the environmental impacts of an nvPM emissions standard. The new nvPM measurement system allows for the estimation of number emissions. These are important for estimating the health impacts of nvPM exposure and will be incorporated in addition to the mass-based exposure response functions that are currently used. We will also study the uncertainties associated with the differential toxicity between the various types of PM species. Finally, we will study the uncertainties in the climate model due to the direct black carbon warming impact and the warming due to contrails.

## Milestone(s)
The cost-benefit analysis requires the generation of emissions datasets in a format that can be run through the APMT-Impacts air quality and climate models. We have received preliminary datasets that represent landing and take-off (LTO) emissions on a global scale from Volpe. The format of this requires us to pre-process the data such that they can seamlessly run through our air quality and climate models. We have developed the processes to automatically pre-process

the datasets and are currently working on running them through our air quality model. Upon receiving the full-flight data, we will be able to run simulations through our climate model as well.

## Outreach Efforts
We have presented our preliminary results to the FAA and will continue to update them as we work through our modeling chain and receive additional data from Volpe.

## Student Involvement
Graduate student Akshat Agarwal is primarily responsible for conducting the analyses.

## Plans for Next Period
We aim to complete this task by August 31, 2018.

## References

Dopelheuer, A., and M. Lecht. 1998. "Influence of Engine Performance on Emission Characteristics." In *Symposium of the Applied Vehicle Technology Pane-Gas Turbine Engine Combustion, Emissions and Alternative Fuels, Lisbon, Portugal*. Citeseer.

Speth, Raymond L., Carolina Rojo, Robert Malina, and Steven R. H. Barrett. 2015. "Black Carbon Emissions Reductions from Combustion of Alternative Jet Fuels." *Atmospheric Environment.*

Stettler, Marc E. J., Adam M. Boies, Andreas Petzold, and Steven R. H. Barrett. 2013. "Global Civil Aviation Black Carbon Emissions." *Environmental Science & Technology* 47 (18):10397–404.