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

Massachusetts Institute of Technology

Project Lead Investigator

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- FAA Award Number: 13-C-AJFE-MIT, Amendment Nos. 027, 036, 045, 054, 065, and 069
- Period of Performance: July 8, 2016 to August 10, 2021 (reporting here with the exception of funding level and cost share only for the period October 1, 2019 to September 30, 2020)
- Tasks:
    1. Developing a no-change criterion for engine remeasurement.
    2. Comparing approaches to estimate non-volatile particulate matter (nvPM) particle number emissions.
    3. Extending the nvPM fuel correction method for blended fuels.

Project Funding Level

FAA provided $750,000 in funding. A total of $750,000 of matching funds are contributed by approximately $196,000 from the Massachusetts Institute of Technology (MIT), and third-party in-kind contributions of $87,000 from University College London, $158,000 from Oliver Wyman Group, $156,000 from Byogy Renewables, Inc., and $153,000 from NuFuels LLC.

Investigation Team

- Prof. Steven Barrett (MIT) serves as PI for ASCENT Project 48 as head of 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-PI for Project 48. 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 Project 48. 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.
- Akshat Agarwal (MIT) is a graduate student in the Laboratory for Aviation and the Environment. He is responsible for conducting the cost-benefit analysis of the nvPM emissions standard and developing methods for estimating nvPM emissions based on smoke number measurements.

Project Overview

The FAA's Office of Environment and Energy (FAA-AEE) is working with the international community to implement an international aircraft engine nvPM standard for engines of rated thrust greater than 26.7 kN. The proposed nvPM standard will influence the development of future engine technologies, resulting in reduction of nvPM emissions from aircraft engines, and thus lead to improved human health and climate impacts of aviation. During the Committee on Aviation Environmental Protection (CAEP)/11 cycle, the FAA, alongside other national aviation authorities, developed an nvPM emissions standard for the mass and particle number emitted by aircraft engines. During the current cycle (CAEP/12), the FAA needs support to provide a technical basis for the implementation of the nvPM emissions standards.

The objective of this project is to provide support for FAA decision-making related to the implementation of the nvPM certification standard. The first task focuses on developing a method to define the conditions in which an engine needs to re-certified for emissions after small changes are made to it—so-called no-change criteria. Second, we aided the CAEP and FAA decision-making process for choosing the best method to estimate particle number emissions to include in the airports air quality manual (Doc 9889). Finally, we extended the nvPM certification fuel correction approach for use with blended biofuels, so that the CAEP modeling and database group (MDG) is able to quantify reductions in emissions for using blended fuels.

Task 1 – Developing a No-change Criterion for Engine Remeasurement

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Objective

The objective of this task was to identify when an engine, after small changes are made to it, needs its emissions remeasured.

Research Approach

The landing and takeoff (LTO) nvPM mass and number standards were developed and agreed upon during CAEP/11. This process identified the total emissions per unit rated thrust that an engine can emit during the LTO procedure as the quantity to be evaluated. For gaseous emissions and the CAEP/10 maximum mass concentration standard, allowances are made for small changes to the engine design that do not require emissions re-certification. In this task, we developed no-change criteria for the CAEP/11 LTO nvPM mass and number standards by basing it on the uncertainty of the nvPM mass and number measurement system. If an engine's nvPM mass or number metric value (D_p/F_{00}) is estimated to change by more than the combined uncertainty of the underlying measurements, then an engine should be re-tested. This is because there is statistical certainty that the emissions of an engine have changed.

In order to quantify the uncertainty of a metric value, we first introduce the approach to estimate it. It is calculated as

$$\mathrm{MV} = \frac{D_p}{F_{00}} = \frac{\sum_{i=1}^{4} \mathrm{EI}_i \dot{m}_{f,i}}{F_{00}}$$

where D_p is the total LTO emissions, F_{00} is the engine rated thrust, EI_i is the emissions index at International Civil Aviation Organization (ICAO) mode of operation i, and $\dot{m}_f$ is the fuel flow rate. To calculate each EI_i, we use

$$EI_m \left[\frac{\mathrm{mg}}{\mathrm{kg_f}}\right] = \frac{22.4 \times 10^{-3} \mathrm{nvPM}_m \, k_t k_f}{\left([CO_2]_{dil} + \frac{1}{\mathrm{DF}_1}([CO] - [CO_2]_b + [HC])\right)(M_C + \alpha M_H)}$$

where $\mathrm{nvPM_m}$ is the mass concentration, k_t is the thermophoretic correction, k_f is the fuel correction, $[\mathrm{X}]$ is the diluted mass concentration of species X, DF_1 is dilution factor 1, $\mathrm{M_C} = 12.0$ g/mol, $\mathrm{M_H} = 1.0$ g/mol and α is the ratio of moles of hydrogen to moles of carbon in the fuel. The subscripts b and dil represent the background and post-dilution concentrations of a species. The derivation of this equation can be found in AIR6241 (2013). A similar form of the equation is used for number emissions.

To calculate the uncertainty in the metric value, we must combine the uncertainties of each emissions index measurement together. For this task, we assume that $\dot{m}_{f,i}$ and F_{00} have negligible uncertainty. The uncertainty in each value required for estimating the emissions index is defined by the SAE E31 team and the key values are included in Table 1.

Table 1. Uncertainty of each component of the nvPM mass and number measurement system. (Reproduced from CAEP/11-WG3-PMTG/10-WP/12)

	Mass	**Number**
Instrument $\left(\frac{u(\text{nvPM}_m)}{\text{nvPM}_m}\right)$	30 $\mu g/m^3$ + 13%	6×10^4 /cm^3 + 7%
Dilution factor 1 $\left(\frac{u(DF_1)}{DF_1}\right)$	4%	4%
CO_2 concentrations $\left(\frac{u([CO_2]_{dil})}{[CO_2]_{dil}}, \left(\frac{u([CO_2]_b)}{[CO_2]_b}\right)\right)$	4%	4%
Dilution factor 2 $\left(\frac{u(DF_2)}{DF_2}\right)$		10%
Thermophoretic losses $\left(\frac{u(k_t)}{k_t}\right)$	2%	2%
Fuel correction $\left(\frac{u(k_f)}{k_f}\right)$	8%	10%

We assume that all uncertain components follow a Gaussian distribution and are statistically independent. This allows us to combine uncertainties in quadrature. To calculate the relative uncertainties of each emissions index, $u_{r,c}(\mathrm{EI})$, quadrature is performed as

$$u_{\mathrm{r,c}}(\mathrm{EI}) = \frac{1}{\mathrm{EI}}\sqrt{\begin{array}{c}\left(\frac{\partial \mathrm{EI}}{\partial \mathrm{nvPM_m}} u_{\mathrm{r}}(\mathrm{nvPM})\right)^2 + \left(\frac{\partial \mathrm{EI}}{\partial k_t} u_{\mathrm{r}}(k_t)\right)^2 + \left(\frac{\partial \mathrm{EI}}{\partial k_f} u_{\mathrm{r}}(k_f)\right)^2 + \\ \left(\frac{\partial \mathrm{EI}}{\partial [\mathrm{CO_2}]_{\mathrm{dil}}} u_{\mathrm{r}}([\mathrm{CO_2}]_{\mathrm{dil}})\right)^2 + \left(\frac{\partial \mathrm{EI}}{\partial \mathrm{DF_1}} u_{\mathrm{r}}(\mathrm{DF_1})\right)^2 + \left(\frac{\partial \mathrm{EI}}{\partial [\mathrm{CO_2}]_{\mathrm{b}}} u_{\mathrm{r}}([\mathrm{CO_2}]_{\mathrm{b}})\right)^2\end{array}}$$

where $u_r(X)$ is the relative uncertainty of component X as defined in Table 1. Finally, to get the uncertainty in the metric value, we again use quadrature, assuming that the uncertainty at each mode of operation is independent and follows a Gaussian distribution.

To identify potential options for the no-change criteria, we estimate the uncertainty of emissions indices and metric values for engines with reported data. Emissions are converted to concentrations by estimating the volumetric flow rate through the engine. The approach for this is described in detail in Agarwal et al. (2019). We can then propagate uncertainties using the previous set of equations. This is conducted for all engines with reported data.

Figure 1 and Figure 2 show the relative uncertainty in nvPM mass and number metric value ($\mathrm{D_p/F_{00}}$). The uncertainty in the metric value increases as the metric value decreases. This is caused by the limit of detection, which adds an absolute uncertainty of $30\ \mu\mathrm{g/m^3}$ for mass and 6×10^4 particles/cm^3. This trend can be modeled using an inverse proportional function as shown in each figure. The scatter in this relationship is caused by the differing contribution of each mode of operation to the overall Dp value. The relationships show that the uncertainty tends towards 9.6% for mass and 6.0% for number.

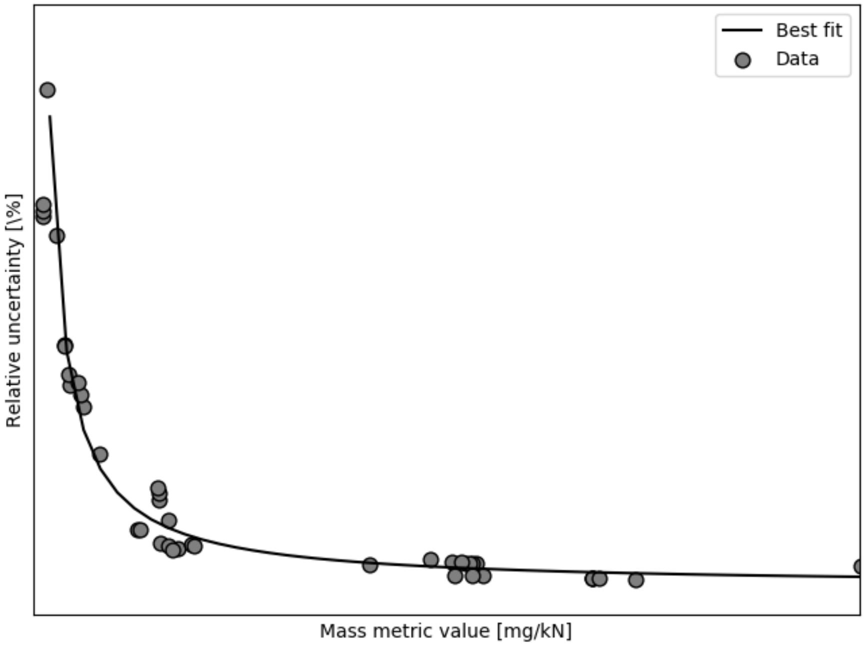

Figure 1. Relative uncertainty in mass metric value.

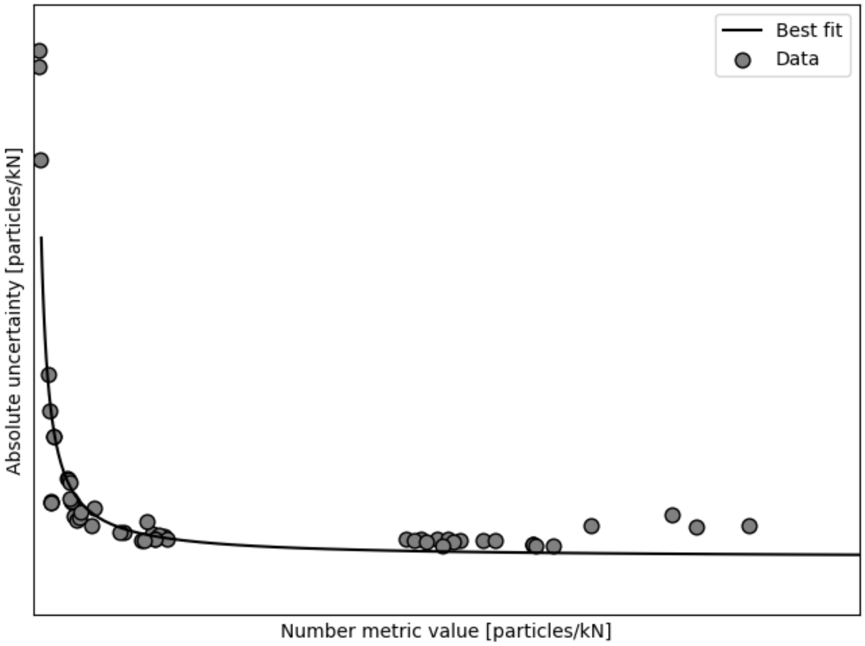

Figure 2. Relative uncertainty in number metric value.

Using the best fit lines, we can define a no-change criterion as a piecewise, continuous function. Below a threshold metric value, we use the absolute uncertainty to determine the no-change criteria. Above this threshold, we use the relative uncertainty. To define the values of the absolute and relative uncertainties in each region, we use the best-fit relationships found in Figure 1 and Figure 2. First, we select the threshold metric value and identify the relative uncertainty according to the best fit relationships. This also defines the absolute uncertainty, which is calculated by multiplying the relative uncertainty with the metric value. This is used to determine the no-change criteria below the threshold metric value.

Three sample no-change criteria are shown in Figure 3 and Figure 4. This approach allows the no-change criteria to balance the increase in uncertainty at low emissions as well as the approximately constant uncertainty at higher emissions. It also accounts for the scatter in the relative uncertainty that is especially prevalent when the emissions are below approximately 200 mg/kN for mass and 2×10^{15} particles/kN for number. orange case. Mass (lower green case) and number (central orange case) provide sufficient balance between low and high emissions.

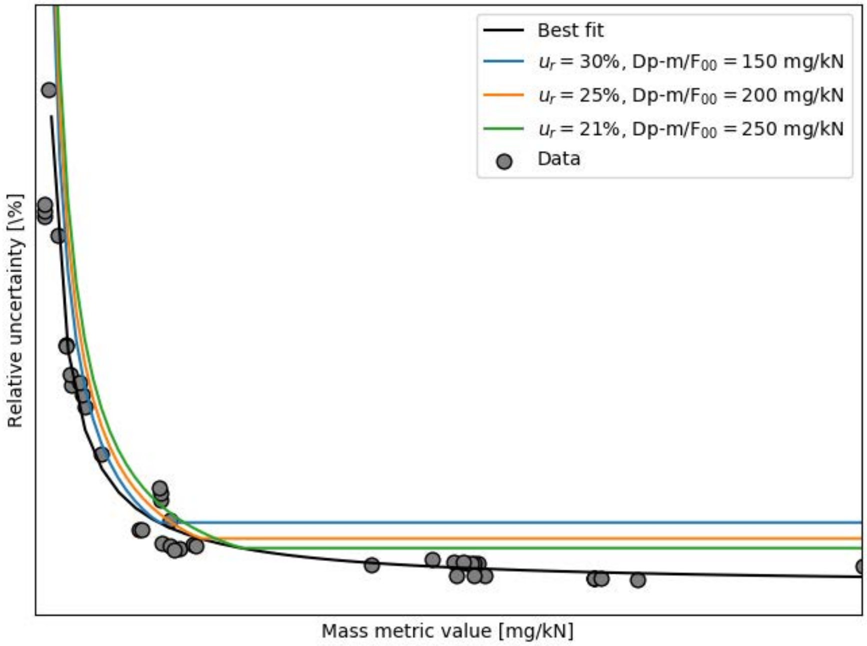

Figure 3. As in Figure 1, but including three options for the mass no-change criterion.

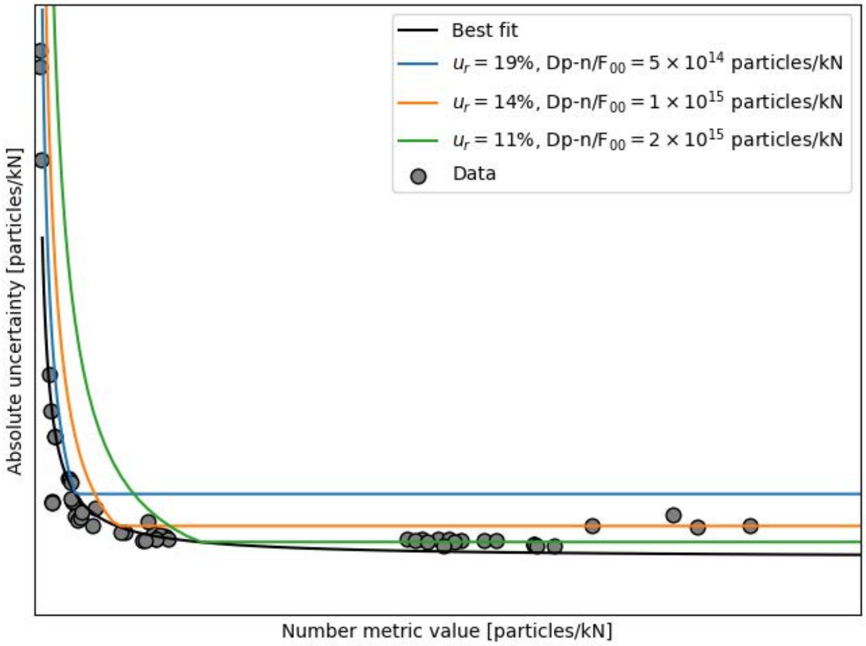

Figure 4. As in Figure 2, but including three options for the number no-change criterion.

Milestone

The complete analysis was presented to the FAA and in a Working Paper for CAEP/12-WG3-ECTG/5.

Major Accomplishments

This work has been presented to CAEP/12-WG3-ECTG/5.

Publications

N/A

Outreach Efforts

Our results have been communicated to the FAA and CAEP-WG3 in a detailed report and presentation.

Awards

None

Student Involvement

Graduate student Akshat Agarwal conducted the analyses and presented the work.

Plans for Next Period

Feedback was received during the CAEP/12-WG3/5 meeting and we aim to refine the method and present updated results at the next meeting.

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Black Carbon Mass and Particle Number Emissions." *Environmental Science & Technology* 53 (3): 1364–73. https://doi.org/10.1021/acs.est.8b04060.

Task 2 – Comparing Approaches to Estimate nvPM Particle Number Emissions

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Objective

This Task aimed to compare three approaches to estimate nvPM particle number emissions developed during CAEP/11, as well as two additional approaches recently published in the literature (Zhang et al. 2019; Teoh et al. 2019).

Research Approach

The Emissions Characterizations Task Group (ECTG) in WG3 has been trying to identify the best approach to estimate particle number emissions given information of nvPM mass emissions. This approach will be implemented in the ICAO airport air quality manual (Doc 9889) and be used by airports to quantify nvPM emissions. The goal of the approach is thus high accuracy without being overly complicated so as to be difficult for airports to implement. Three approaches have been developed by WG3 including:

- SCOPE11 approach (Agarwal et al. 2019).
- Fixed geometric mean diameter (GMD)-20 using 20 nm at idle, 20 nm at approach, 40 nm at climb-out, and 40 nm at takeoff.
- Fixed GMD-25, which is the same as Fixed GMD-20 but uses 25 nm at approach.

In addition, two approaches have been published in the literature that use the fractal aggregates approach to convert from mass to number emissions. These include:

- Zhang et al. (2019)
- Teoh et al. (2019)

We have implemented all five approaches and aim to capture the performance of all methods on estimating particle number emissions indices and the Dp number (mass of any pollutant emitted, expressed in grams) for the LTO cycle for all engines in the nvPM values database (VDB).

The results for estimating the number emissions index are shown in Figure5, which shows the measured versus estimated emissions index using all five methods. The approach developed by Zhang et al. (2019) shows the highest error and bias, overpredicting the emissions index. The bias is highest for taxi emissions at 9.8×10^{17} particles/kg and the results show that there is an emissions-dependent offset with the parity line. The SCOPE11 (top left) and Teoh et al. (2019) (top right) approaches show similar results that are offset from each other. This is because the SCOPE11 mass and GMD approaches are used as input to the Teoh mass-to-number conversion. The bias of the SCOPE11 results is a factor of 1.3–21 lower than that for Teoh et al. Finally, the fixed GMD approach shown in the bottom right shows the highest variance in the results, however, these results seem to have low bias. This is expected since the GMD is a strong function of the engine and emissions level, thus it is difficult to identify optimum values fixed for each mode of operation.

Figure 6 shows the measured versus estimated Dp number emissions using all five methods, as well as the performance metrics on the right side of the figure. These results show that the fixed GMD approaches have the lowest root mean square error (RMSE), which can be up to 20% lower than that for the SCOPE11 method. The results do still show higher spread of the data when compared to the SCOPE11 method. This is evidenced in the bias of the results, which is a factor of 37.5 lower in SCOPE11 than the next-best, fixed-20 approach. For fleet estimates as required by Doc 9889, the bias is considered the best metric to assess performance.

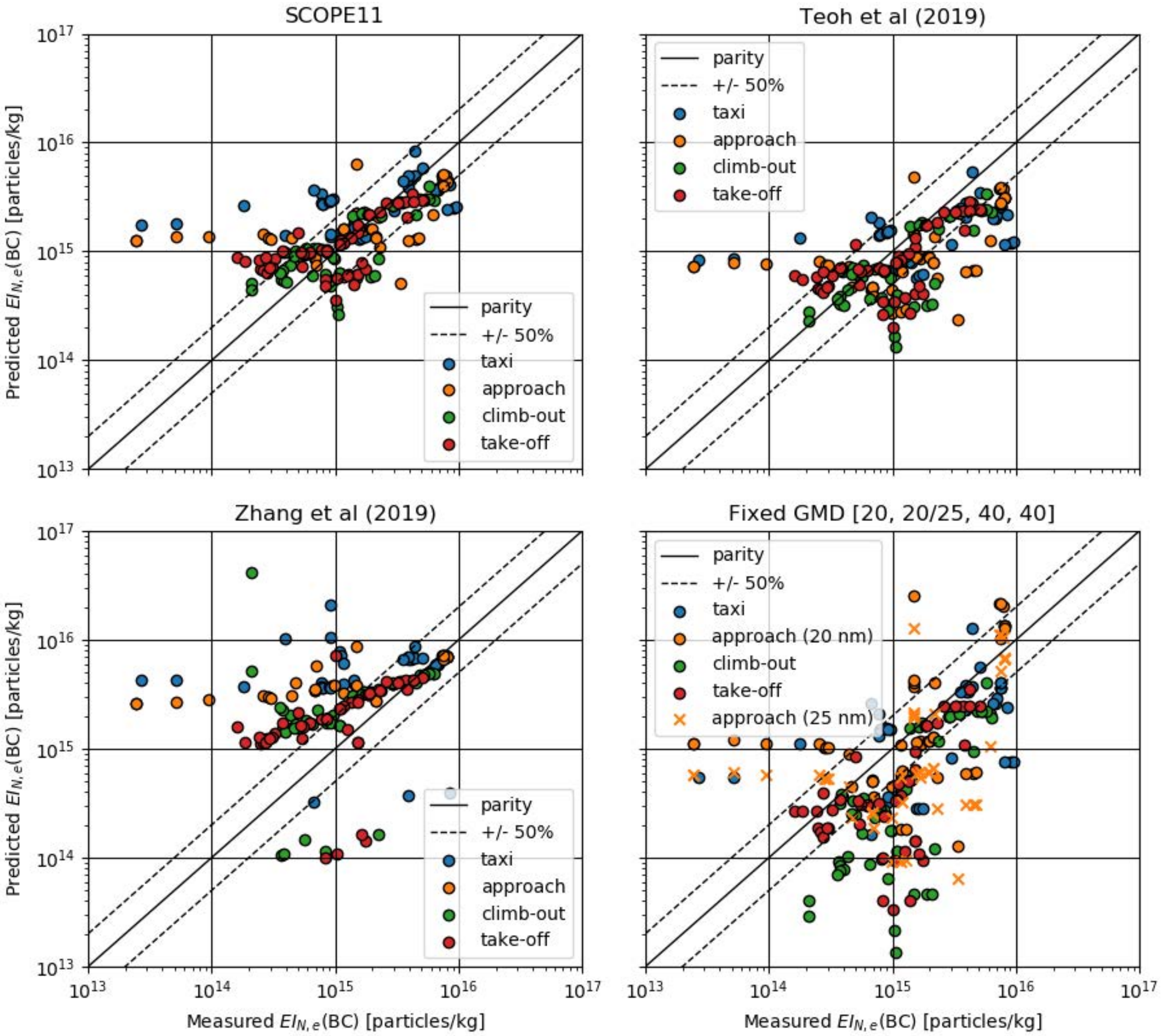
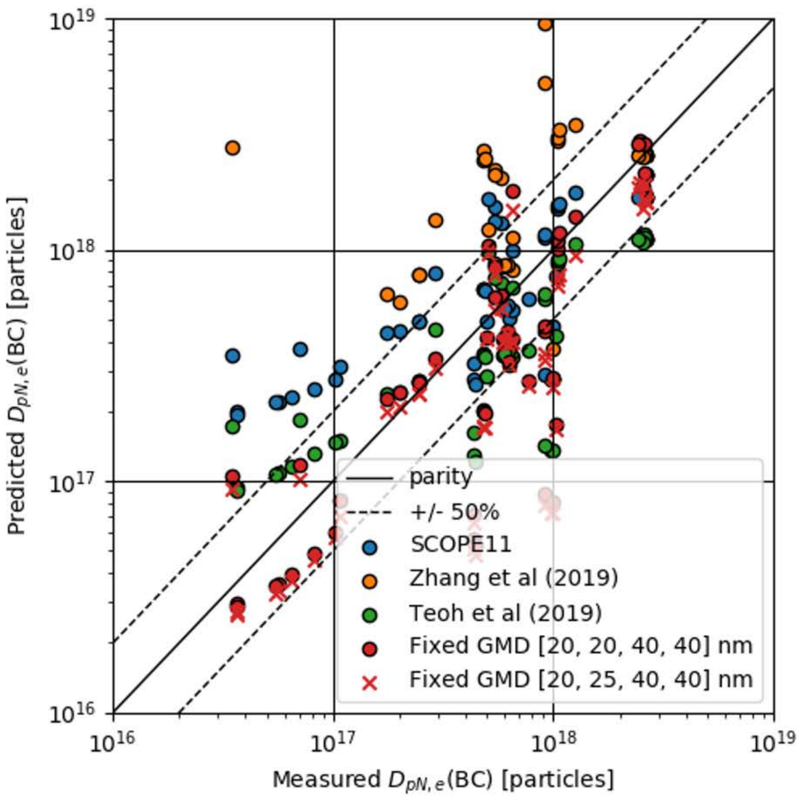


Figure 5. Measured versus predicted number emissions index for SCOPE11 (top left), Teoh et al.(2019) (top right), Zhang et al. (2019) (bottom left), and both fixed GMD approaches (bottom right). To distinguish between 20 nm and 25 nm for the fixed GMD at approach, orange circles or crosses have been used respectively.



	RMSE [#] $\times 10^{17}$	R^2	Bias [#] $\times 10^{17}$
SCOPE11	5.1	0.78	-0.04
Zhang	59.0	-0.10	+20.2
Teoh	6.4	0.82	-3.4
Fix – 20	4.1	0.89	-1.5
Fix – 25	5.0	0.88	-3.0

Figure 6. Measured versus predicted Dp number emissions for the LTO cycle across each method. The key performance metrics are shown on the right side.

Milestone
The results were presented at the CAEP/12-WG3/5 meeting.

Major Accomplishments
The fixed-20 approach was accepted for use in Doc 9889.

Publications
N/A

Outreach Efforts
Our results were regularly communicated to the FAA and ICAO-CAEP in a detailed presentation.

Awards
None

Student Involvement
Graduate student Akshat Agarwal was responsible for completing the analysis.

Plans for Next Period
N/A

References

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Task 3 – Extending the nvPM Fuel Correction Method for Blended Fuels

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Objective

This Task aimed to identify the accuracy of the nvPM fuel correction method for blended fuels and compare the method to other formulations.

Research Approach

Current fuel standards allow aircraft engines to use conventional fuels that are blended with biofuels up to 50% by volume. Biofuels tend to have higher hydrogen content than conventional jet fuels, so blended fuels also tend to have higher hydrogen content than conventional jet fuels. Increasing the hydrogen content of a fuel is expected to decrease nvPM emissions (Moore et al. 2017; Speth et al. 2015). In order to assess the reduction in emissions, the MDG requested WG3 to provide an approach to estimate the decrease in emissions associated with using blended fuels. In this Task, we first assessed the accuracy of using the current certification fuel correction approach developed during CAEP/11. In addition, we developed a different formulation that assumes a quadratic relationship between the change in emissions and the hydrogen content.

To test the performance and fit coefficients of all models, we combined several engine measurement datasets that comprise six different engines for mass emissions and two additional engines for number emission (Bulzan et al. 2010; Beyersdorf et al. 2014; Timko et al. 2011; 2010; Corporan et al. 2013; 2011; Cain et al. 2013; Corporan et al. 2010; Brem et al. 2015). In addition, we include auxiliary power unit (APU) emissions data provided by Prem Lobo, NRC Canada (private communication). Two forms of fits were tested on these datasets. The first follows an exponential trend in hydrogen content (H) and thrust setting (F/F_{00}) as

$$\hat{E} = \exp\big((k_1 + k_2 F/F_{00})(H_0 - H)\big)$$

where $\hat{E}$ is the relative change in emissions, $H_0 = 13.8\%$ is the reference fuel hydrogen content, and k_1 and k_2 are coefficients to be fitted. The second form assumes a quadratic relationship in the hydrogen content as

$$\hat{E} = (1 - \tilde{H})\big[(k_1 + k_2\hat{F})\tilde{H} + 1\big]$$

where $\tilde{H} = \frac{H - H_0}{H_\infty - H_0}$ and H_∞, k_1 and k_2 are coefficients to be fitted. Both forms are fitted to the entire dataset and the coefficients are shown in Table 2 below. This table also includes the coefficients used for the certification fuel corrections approach.

Table 2. Fitted coefficient values for all models tested

	Certification		Exponential re-fitted		Quadratic	
	Mass	Number	Mass	Number	Mass	Number
k_1	1.12	1.05	1.33	1.11	-1.25	-1.30
k_2	-0.95	-0.99	-0.79	-0.69	1.54	1.98
H_∞					15.92	15.93

The performance of the certification, the exponential re-fitted, and the quadratic approach are shown in Figure 6, Figure 7, and Figure 8. The certification approach exhibits low error for relative mass and number emissions above 1.0. This is expected since the model was fitted to this set of CFM56-7 data. Below this range, the performance degrades, and the approach tends to find a bias of -0.10 for mass and -0.09 for number. After re-fitting the coefficients in the certification approach for all the available data (Figure 7), the overall performance improves with the mean absolute error reducing by 20% for mass and 12.5% for number, and the mean error reducing by a factor of 3.2 and 6.0, respectively, for mass and number. The main region where the approach improves for biofuel prediction is for relative emissions below 1.0, which shows lower variance away from the parity line. Above relative emissions of 1.0, the approach does not perform as well as the certification approach and there is high bias in the results. Finally, the results of the quadratic approach are shown in Figure 8. This shows the lowest bias by a factor of 1.9 for mass and factor of 12.5 for number compared with the re-fitted exponential approach. This approach balances the performance at all relative emissions levels (above and below 1.0) better than the exponential form.

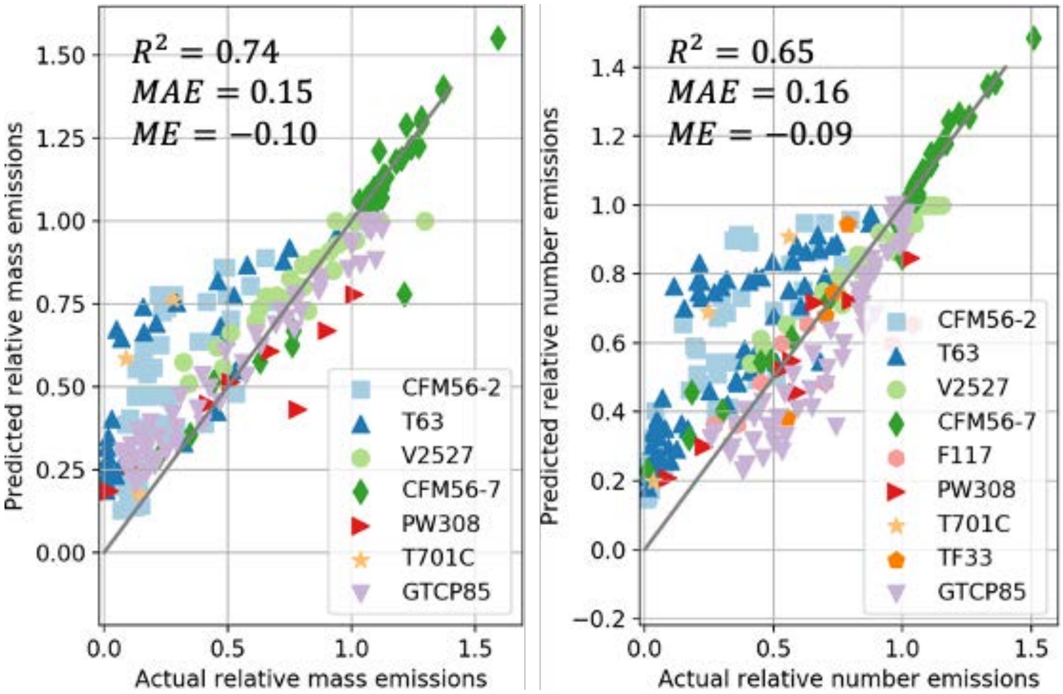

Figure 7. Actual/measured versus predicted relative mass emissions (left) and number emissions (right) using the certification fuel approach.

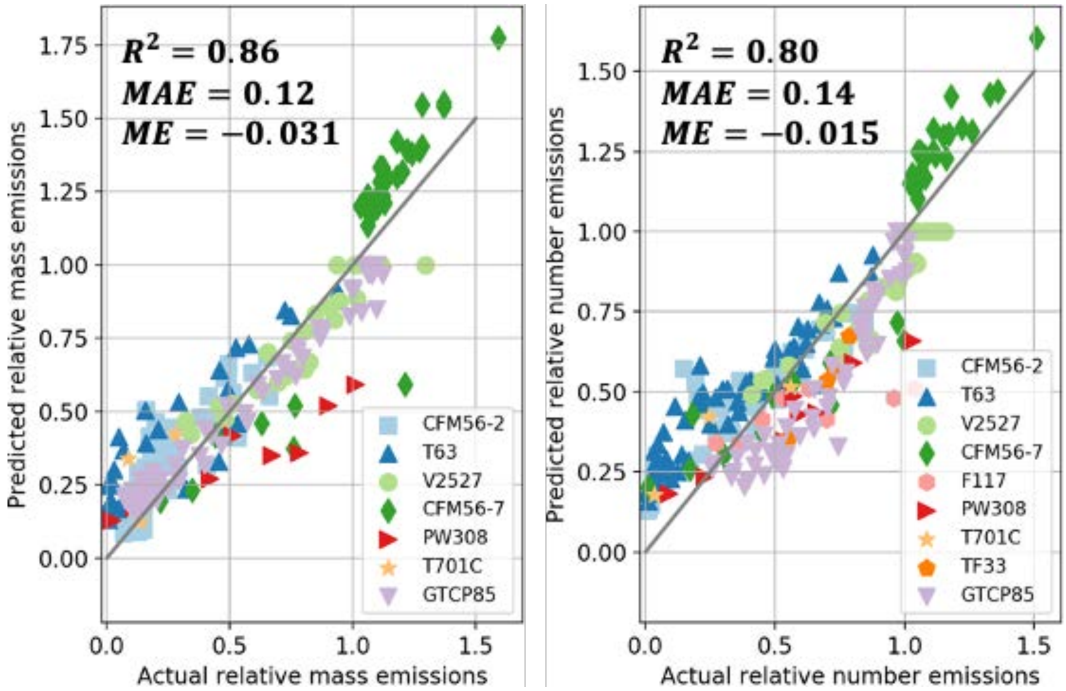

Figure 8. Actual/measured versus predicted relative mass emissions (left) and number emissions (right) using the exponential re-fitted approach.

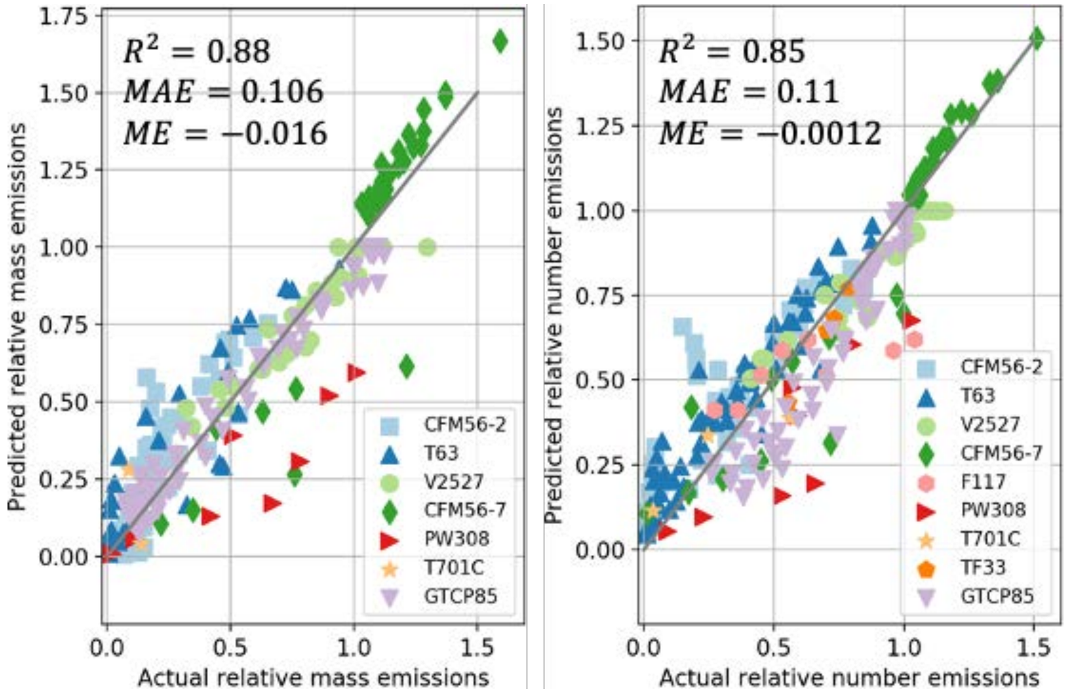

Figure 9. Actual/measured versus predicted relative mass emissions (left) and number emissions (right) using the quadratic approach.

Milestone

The results of this analysis were presented to FAA project managers and to members of the ECTG group under WG3 at the 5th meeting of CAEP/12-WG3.

Major Accomplishments

None

Publications

None

Outreach Efforts

Our results have been communicated to the FAA and ICAO-CAEP in a detailed report and presentation.

Awards

None

Student Involvement

Graduate student Akshat Agarwal conducted the analysis.

Plans for Next Period

This work will be updated based on feedback with MDG and ECTG to complete the analysis by the next WG3 meeting.

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