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

Massachusetts Institute of Technology

Project Lead Investigator

Steven Barrett
Associate Professor
Department of Aeronautics & Astronautics
Massachusetts Institute of Technology
77 Massachusetts Ave
Building 33-316
Cambridge, MA 02139
617-452-2550
sbarrett@mit.edu

University Participants

Massachusetts Institute of Technology

- PI(s): Prof. Steven Barrett
- Co-PI: Dr. Raymond Speth
- FAA Award Number: 13-C-AJFE-MIT, Amendment Nos. 027, 036, 045, and 054
- Period of Performance: July 8, 2016 to May 31, 2020 (reporting here with the exception of funding level and cost share only for the period October 1, 2018 to September 30, 2019)
- Tasks:
    1. Cost-benefit analysis of non-volatile particulate matter (nvPM) standard options
    2. SCOPE11 method to predict aircraft engine nvPM emissions
    3. Evaluating the retirement of the smoke number (SN) limit

Project Funding Level

$550,000 FAA funding and $550,000 matching funds. Sources of match are approximately $149,000 from Massachusetts Institute of Technology (MIT), plus third-party, in-kind contributions of $87,000 from University College London, $158,000 from Oliver Wyman Group, and $156,000 from Byogy Renewables Inc.

Investigation Team

- Prof. Steven Barrett (MIT) serves as PI for the A48 project 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 the A48 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 A48 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.
- 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 establish 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. A reduction in nvPM emitted by aircraft engines will lead to improved human health and climate impacts of aviation. To this end, the FAA needs to understand and quantify how an nvPM standard might impact the total nvPM emissions for the National Air Space (NAS) as well as the globe, including overall system-wide environmental and monetary costs and benefits.

The objective of this project is to provide support for FAA decision-making related to the nvPM certification standard by analyzing scenarios involving different emission metrics, policy options, and assumptions about technology and fleet evolution. The analyses being conducted include economic, climate, air quality, and noise impact assessments on both global and NAS-wide bases. Activities executed for this project year focus on identifying and evaluating nvPM metrics and policy options, analyzing and developing methods to correct measurements based on fuel properties and ambient conditions, developing emissions inventories based on estimated technological responses to proposed regulations, and conducting cost-benefit analyses of proposed regulations. This research is also contributing to the understanding of how an nvPM standard may influence future engine development, fleet evolution, and associated fleet-wide nvPM emissions.

Task 1 - Cost-Benefit Analysis of non-volatile Particulate Matter (nvPM) Standard Options

Massachusetts Institute of Technology

Objective(s)

The objectives for this task involve estimating the climate and health impacts of the emissions, and the associated uncertainties, caused by each policy option. Results are shared with FAA project managers.

Research Approach

To calculate and monetize the environmental effects of a policy option, we use the APMT-Impacts Climate model, developed under ASCENT Project 21, and the APMT-Impacts Air Quality tool, developed under ASCENT Project 20. The climate model has been continuously improved upon since Marais et al. (2008), with the latest developments described by Grobler et al. (2019). The model allows rapid estimation of the climate impacts due to aviation and can quantify the associated uncertainty. It has previously been used in the Committee on Aviation Environmental Protection (CAEP)/8, CAEP/9, and CAEP/10 cycles. The air quality model uses a computationally efficient adjoint approach to estimate air quality impacts due to a set of emissions, requiring only multiplication of the pre-computed sensitivities with three-dimensional emissions (latitude × longitude × altitude). In all estimates, we quantify the uncertainty attributable to the concentration response functions that relate a change in concentration to a change in premature mortalities. In addition, for full-flight emissions, we estimate the uncertainty due to ammonia emissions. Finally, high-resolution adjoint sensitivities have also been calculated for certain regions (North America and Asia-Pacific), and we use these sensitivities to estimate regional air quality impacts in addition to the global results. Both the climate and global air quality models are able not only to compute the physical impacts (temperature change and premature mortalities, respectively), but also to monetize these impacts for use in a cost-benefit analysis. This aggregate global environmental impact can be combined with estimates of the industry costs to give a net cost-benefit result. If the benefits are greater than the costs, then the regulation is cost-beneficial and vice versa if the costs outweigh the benefits.

To use the climate and air quality tools, the effect of each policy option on emissions is estimated using the Aviation Environmental Design Tool (AEDT). Twelve policy options were modeled, and each option was considered with and without trade-offs with other emissions species (e.g., reducing nvPM could increase NO_x emissions). The change in full-flight nvPM mass and nvPM number emissions relative to baseline business-as-usual emissions for a 2024 policy implementation date are shown in Figure 1. Policy options 7, 8, and 9 are indistinguishable, as are options 10, 11, and 12, so each set is grouped together for the remainder of this section. As expected, nvPM mass emissions decrease for all policy options, with the reduction ranging between 1.5% and 44.8% in 2032 and 1.0% and 74.0% in 2042. Similarly, nvPM number emissions decrease by between 0.35% and 20.9% in 2032 and between 0.32% and 41.6% in 2042. The change in emissions tends to increase over time as engines that meet the standard replace those in the baseline. In addition, the percentage reduction in nvPM mass is consistently greater than the reduction in nvPM number.

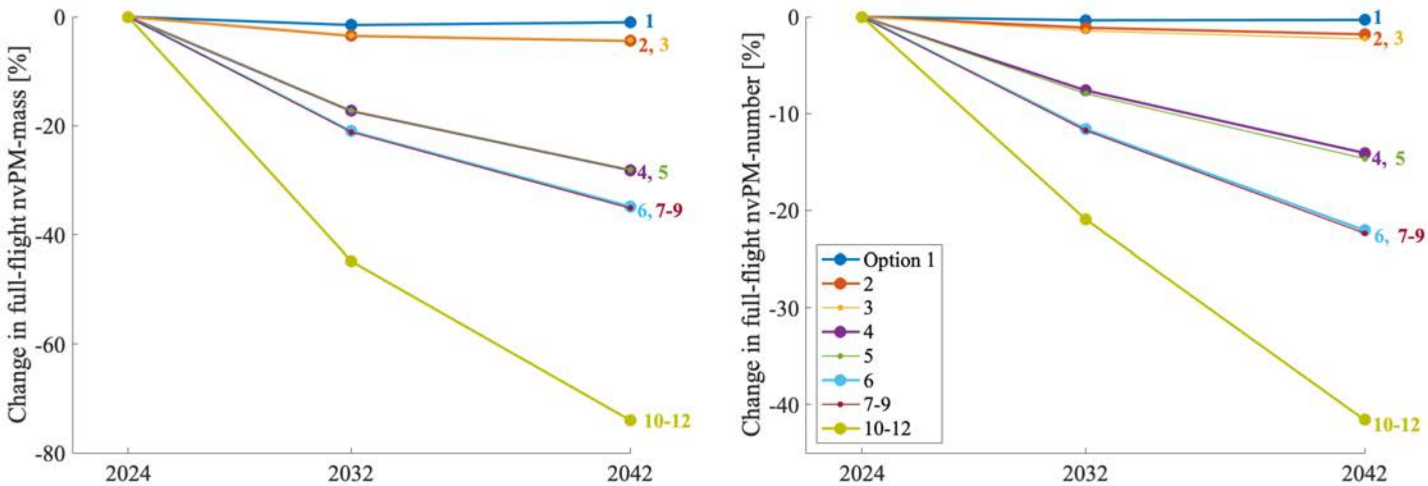

Figure 1. Percentage change in non-volatile particulate matter (nvPM) mass (left) and nvPM number (right) emissions relative to the baseline business-as-usual scenario for full-flight aviation activity, assuming a 2024 implementation date.

Figure 2 uses full-flight emissions to estimate the monetized impact of each policy option when using scenarios with no trade-offs. The air quality model has also been used to estimate monetized health impacts for landing and take-off (LTO) emissions; however, these results are not presented below. In policy options 1 through 9, the climate damages outweigh the air quality health impacts. In addition, industry costs outweigh the combined environmental benefits, leading to a net societal cost. The reverse is true for policy options 10–12, where the air quality impacts outweigh the industry costs, leading to a net societal benefit. Given the large required reduction in nvPM emissions to pass these policy options, certain engines are assumed unable to respond. These engines are substituted with others that have lower NO_x emissions, leading to a reduction in air quality emissions and thus a net societal benefit. Results for scenarios with trade-offs were also considered in this task.

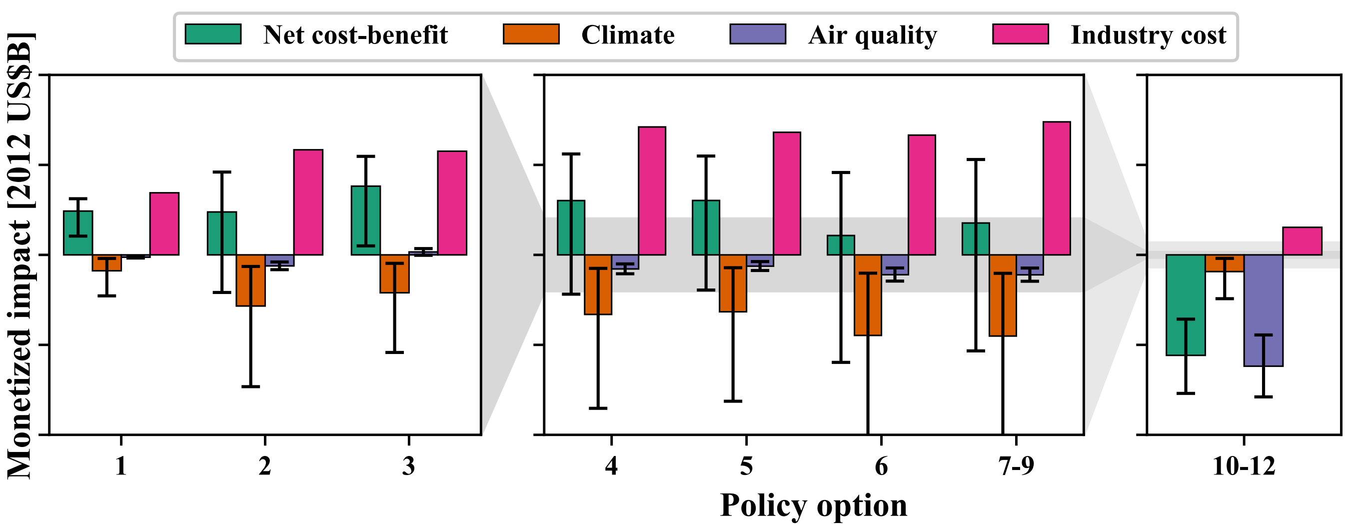

Figure 2. Cost-benefit analysis for the “no trade-offs” scenario using full-flight emissions for air quality impacts. The left panel, showing policy options 1–3, uses a zoomed-in scale equivalent to the gray shaded area of the middle panel. Likewise, the middle panel, showing policy options 4–9, uses a zoomed-in scale equivalent to the gray shaded area of the right panel. Analysis was conducted using the mid environmental lens and a 3% discount rate.

Milestone
The completed cost-benefit analysis was presented to the FAA in a detailed report and presentation in order to inform decision-making related to the CAEP/11 standard.

Major Accomplishments
This work has been completed and the results shared in a series of presentations to FAA-AEE. A detailed report on the results was written and shared with the FAA as well.

Publications
N/A

Outreach Efforts
Our results have been communicated to the FAA in a detailed report and presentation.

Awards
None.

Student Involvement
Graduate student Akshat Agarwal used the APMT-Impacts component models to evaluate climate and air quality costs for each policy option, and developed visualizations to help decision-makers understand the results of the cost-benefit analysis.

Plans for Next Period
N/A

References
Grobler, C., Wolfe, P.J., Dasadhikari, K., Dedoussi, I.C., Allroggen, F., Speth, R.L., Eastham, S.D., Agarwal, A., Staples, M.D., Sabnis, J., & Barrett, S.R.H. (2019). Marginal climate and air quality costs of aviation emissions. Environmental Research Letters 14 (11): 114031. https://doi.org/10.1088/1748-9326/ab4942

Marais, K., Lukachko, S.P., Jun, M., Mahashabde, A., & Waitz, I.A. (2008). Assessing the impact of aviation on climate. Meteorologische Zeitschrift 17 (2): 157–72. https://doi.org/10.1127/0941-2948/2008/0274

Task 2 - SCOPE11 Method To Predict Aircraft Engine nvPM Emissions
Massachusetts Institute of Technology

Objective
The objective for this task was to develop an approach to estimate aircraft engine nvPM-mass and particle number emissions using SN measurements.

Research Approach
The SN has been found to be correlated with nvPM mass concentration over a range of SN values (Stettler et al., 2013; Wayson et al., 2009); however, these approaches either used measurements not taken at the same time and with the same engine or used non-aircraft engine sources of nvPM emissions. In addition, they did not develop approaches to estimate nvPM particle number emissions, which is a crucial emission that can affect the climate impact of contrails (Burkhardt et al., 2018). In addition, the systems used to measure nvPM emissions lead to particle losses that can affect the measurements of mass and particle number (AIR6504, 2017). This work focuses on improving the estimates of nvPM mass emissions using an updated aircraft engine emissions dataset, develops an approach to account for particle losses, and finally develops a method to estimate particle number emissions.

To develop each correlation, we use two complementary datasets. Dataset 1 consists of 1,407 paired instrument-measured nvPM mass concentrations and SN measurements. This is used to develop the correlation between SN and mass concentration. The form of the equation, best-fit values, and the 95% confidence intervals are:

$$C_{\mathrm{nvPM},i} = \frac{k_1 e^{k_2 \mathrm{SN}}}{1 + e^{k_3(\mathrm{SN}+k_4)}}$$
$$k_1 = 648.4 \pm 44.9\ \mathrm{\mu g/m^3}$$
$$k_2 = 0.0766 \pm 0.0038$$
$$k_3 = -1.098 \pm 0.120$$
$$k_4 = -3.064 \pm 0.277$$

where k_i are constants to be fitted and $C_{\mathrm{nvPM},i}$ is the instrument-measured nvPM mass concentration. Dataset 2 consists of 264 simultaneous nvPM mass and particle number emissions measurements. These measurements all used the same certification-compliant measurement system as dataset 1 and also included estimates of particle losses. This dataset was used to estimate measurement losses for nvPM mass emissions using the form, best-fit values, and 95% confidence intervals shown below:

$$k_{slm} = \ln\left(\frac{a_1 \cdot C_{\mathrm{nvPM},i}(1+\beta_{\mathrm{mix}}) + a_2}{C_{\mathrm{nvPM},i}(1+\beta_{\mathrm{mix}}) + a_3}\right)$$
$$a_1 = 3.219 \pm 0.135$$
$$a_2 = 312.5 \pm 119.1\ \mathrm{\mu g/m^3}$$
$$a_3 = 42.6 \pm 19.4\ \mathrm{\mu g/m^3}$$

where a_i are constants to be fitted, β_{mix} is the bypass ratio for mixed engines and 1 otherwise, and k_{slm} is the loss correction for nvPM mass emissions. k_{slm} can be used with the instrument-measured mass concentration to estimate the mass concentration at the exit or exhaust plane of the engine ($C_{\mathrm{nvPM},e}$):

$$C_{\mathrm{nvPM},e} = k_{\mathrm{slm}} \cdot C_{\mathrm{nvPM},i}$$

Finally, to estimate particle number emissions, we assumed emissions to be lognormally distributed. Assuming a geometric standard deviation (GSD) of 1.8 and soot density (ρ) of 1,000 $\mathrm{kg/m^3}$, we can estimate particle number emissions ($C_{N,e}$) using the method of Heintzenberg (1994):

$$C_{N,e} = \frac{6 C_{\mathrm{nvPM},e}}{\pi \rho \mathrm{GMD}^3 e^{4.5(\ln\sigma)^2}}$$

In this equation, the only unknown is the GMD, which represents the geometric mean diameter of the nvPM particles. This can be predicted using an estimate of nvPM mass concentration in the combustor ($C_{\mathrm{nvPM},c}$) as shown below:

$$\mathrm{GMD}\ [\mathrm{nm}] = a\, C_{\mathrm{nvPM},c}{}^{b}$$
$$a = 5.08 \pm 0.55\ \mathrm{nm}$$
$$b = 0.185 \pm 0.015$$

To estimate $C_{\mathrm{nvPM},c}$, we used basic gas turbine theory to estimate conditions at the combustor exit and used this to scale $C_{\mathrm{nvPM},e}$. The full details of the method can be found in Agarwal et al. (2019).

Starting with certification SN measurements found in the International Civil Aviation Organization (ICAO) Engine Emissions Data Bank (EDB) (EASA, 2017), we can apply each step of the above method to estimate emissions of nvPM mass at the instrument, mass at the exit plane, and particle number at the exit plane. In Figure 3, we show the prediction compared with measurements from dataset 2. The overall R^2 value in each case is ~0.8, but this value tends to be lower for predictions during taxi operations. This is driven by the wide data spread between SN and mass concentration at low SN.

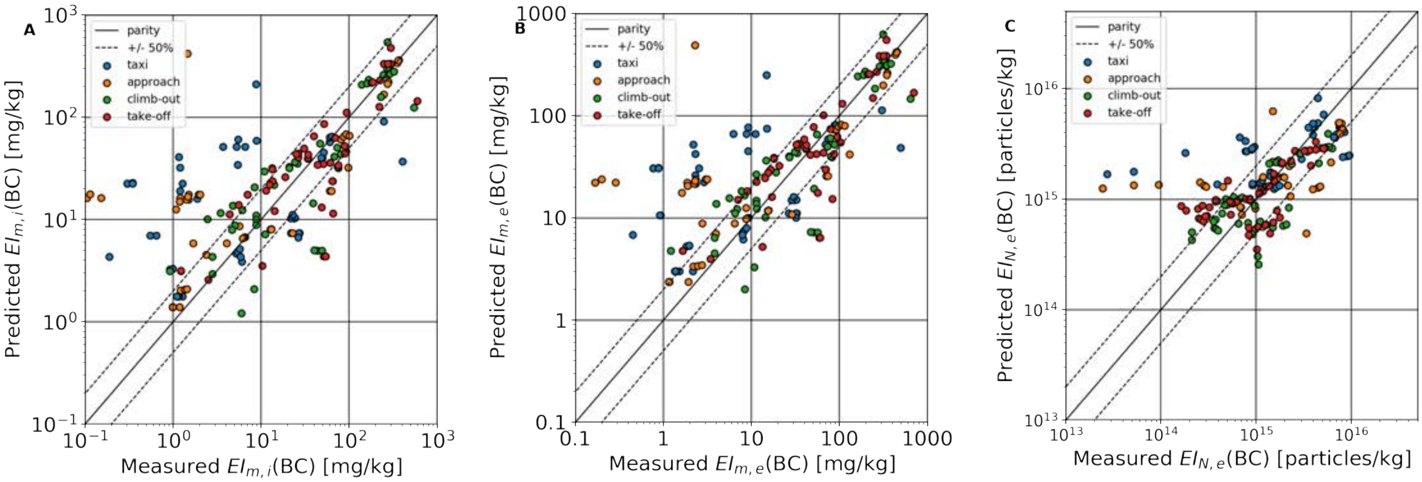

Figure 3. Parity plots of predicted versus measured results for (A) non-volatile particulate matter (nvPM) mass emissions at the instrument, (B) nvPM mass emissions at the exit plane, and (C) nvPM number emissions at the exit plane. $EI_{m,i}(BC)$, black carbon mass emissions index at the instrument; $EI_{m,e}(BC)$, black carbon mass emissions index at the exit plane; $EI_{N,e}(BC)$, black carbon number emissions index at the exit plane.

Milestone
The methods for estimating black carbon mass and number emissions based on smoke number were documented in a white paper which was shared with the FAA and CAEP Working Group 3.

Major Accomplishments
The completion of this work resulted in a peer-reviewed publication in *Environmental Science & Technology* (Agarwal et al., 2019).

Publications
Agarwal, A., Speth, R. L., Fritz, T. M., Jacob, S. D., Rindlisbacher, T., Iovinelli, R., Owen, B., Miake-Lye, R. C., Sabnis, J. S., & Barrett, S. R. H. (2019). SCOPE11 Method for Estimating Aircraft Black Carbon Mass and Particle Number Emissions. Environmental Science & Technology, 53(3), 1364–1373. https://doi.org/10.1021/acs.est.8b04060

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

Awards
None.

Student Involvement
Graduate student Akshat Agarwal was responsible for developing the method for estimating particle number emissions based on combustor mass concentration and was the lead author of the paper documenting the method.

Plans for Next Period
N/A

References

Agarwal, A., Speth, R.L., Fritz, T.M., Jacob, S.D., Rindlisbacher, T., Lovinelli, R., Owen, B., Miake-Lye, R.C., Sabnis, J.S., & Barrett, S.R.H. (2019). "SCOPE11 method for estimating aircraft black carbon mass and particle number emissions. Environmental Science & Technology 53 (3): 1364–73. https://doi.org/10.1021/acs.est.8b04060

AIR6504. (2017). Procedure for the calculation of non-volatile particulate matter sampling and measurement system penetration functions and system loss correction factors - SAE aerospace information report 6504 (AIR6504)

Burkhardt, U., Bock, L., & Bier, A. (2018). Mitigating the contrail cirrus climate impact by reducing aircraft soot number emissions. Npj Climate and Atmospheric Science 1 (1): 37. https://doi.org/10.1038/s41612-018-0046-4.

EASA. (2017). ICAO Engine Emissions Databank (EDB) V24

Heintzenberg, J. (1994). Properties of the log-normal particle size distribution. Aerosol Science and Technology 21 (1): 46–48. https://doi.org/10.1080/02786829408959695

Stettler, M.E.J., Swanson, J.J., Barrett, S.R.H., & Boies, A.M. (2013). Updated correlation between aircraft smoke number and black carbon concentration. Aerosol Science and Technology 47 (11): 1205–14 https://doi.org/10.1080/02786826.2013.829908

Wayson, R.L., Fleming, G.G., & Lovinelli, R. (2009). Methodology to estimate particulate matter emissions from certified commercial aircraft engines. Journal of the Air & Waste Management Association 59 (1): 91–100, https://doi.org/10.3155/1047-3289.59.1.91

Task 3 - Evaluating The Retirement of the Smoke Number (SN) Limit

Massachusetts Institute of Technology

Objective

This task aimed to understand the effectiveness of the CAEP/10 maximum mass concentration limit in preventing the visibility of aircraft engines. A limit with this feature would allow regulators to retire the SN limit, which was developed with these goals in mind.

Research Approach

The overall method follows a similar approach to how the SN limit was evaluated (Stockham and Betz, 1971; Champagne, 1971; Munt, 1979). Aerosol optical theory following Bond and Bergstrom (2006) was used to relate the transmissivity of light through black carbon aerosol with the mass concentration, as follows:

$$C_{\mathrm{nvPM,e}} = \frac{\rho_{\mathrm{soot}}\,\lambda \log(1/T)}{K_{\mathrm{e}}\,L}$$

where ρ_{soot} is the soot density, λ is the wavelength of light, T is the transmissivity of light through the soot particles, K_e is the mass-normalized absorption coefficient, and L is the path length of the light through the exhaust plume. A transmissivity of 98% was considered the limit below which the plume becomes visible and was used as the baseline throughout the analysis. As a representation of path length, we used the diameter of the exhaust nozzle, which was estimated using gas turbine theory, following Cumpsty and Heyes (2015). We used rated thrust, overall pressure ratio, bypass ratio, and fuel flow rate values at rated thrust from the EDB and assumed a bypass-to-jet velocity ratio of 0.9 for unmixed turbofan engines. For mixed-flow turbofan engines, this ratio was changed and a matching stagnation pressure at the mixing plane was imposed instead.

Results for turbojets, unmixed turbofans, and mixed-flow turbofans for a range of engines are shown in Figure 4. Engines were chosen to span a wide range of rated thrusts and manufacturers, and the analyses were conducted as if engines are turbojet, unmixed turbofans, or mixed-flow turbofans, respectively. The current CAEP/10 limit is included as well as the same limit if it were not shifted upward by 2 standard deviations. This second line is analogous to the SN limit in mass concentration space. These results show that the SN limit is suitable for turbojet engines, which is the type of engine it was originally developed for. The current CAEP/10 limit seems to be sufficient to prevent the visibility of unmixed turbofan engines; however, neither limit would prevent the visibility of mixed-flow turbofan engines.

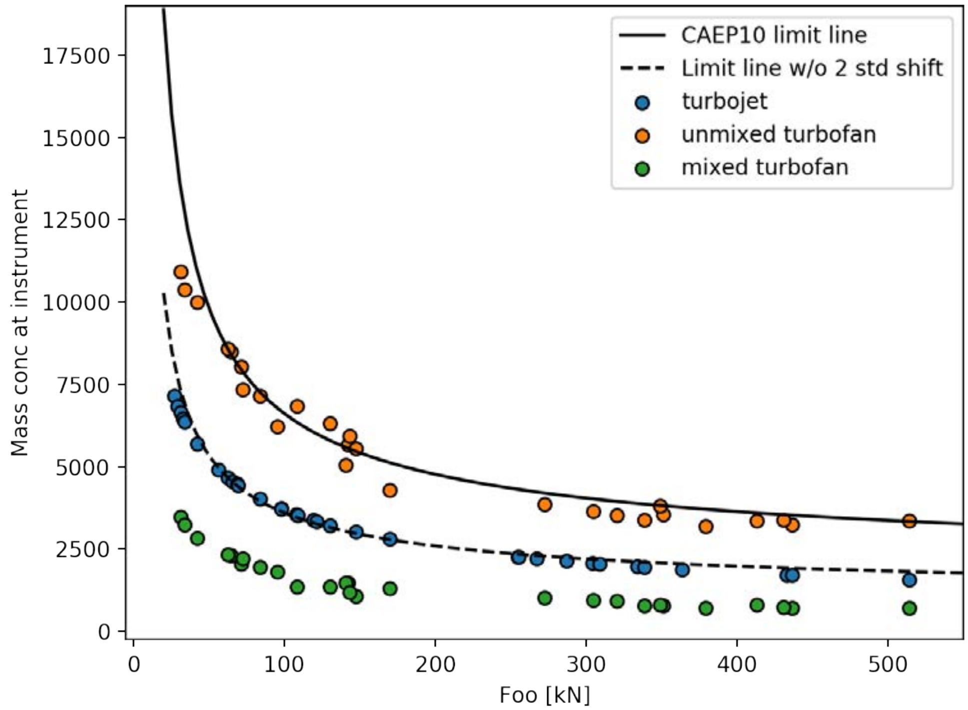

Figure 4. Instrument-measured mass concentration [μg/m³] versus rated thrust [kN] for turbojet (blue), unmixed turbofans (orange), and mixed-flow turbofans (green) at a transmissivity of 98%. Also shown are the CAEP/10 limit and the limit without a shift of 2 standard deviations (2 std).

Milestone

The analysis of the effectiveness of the SN and CAEP/10 standards at preventing plume visibility was completed.

Major Accomplishments

This work was presented to FAA project managers and ICAO-CAEP members in Working Group 3. In addition, the work culminated with a working paper to the CAEP/11-WG3/10 meeting in Montreal.

Publications

N/A

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 investigated approaches to estimating plume visibility that have been applied historically and developed an updated analysis based on engine cycle analysis for modern engines.

Plans for Next Period

N/A

References

Bond, T.C. & Bergstrom, R.W. (2006). Light absorption by carbonaceous particles: An investigative review. Aerosol Science and Technology 40 (1): 27–67. https://doi.org/10.1080/02786820500421521

Champagne, D.L. (1971). Standard measurement of aircraft gas turbine engine exhaust smoke. American Society of Mechanical Engineers Digital Collection. https://doi.org/10.1115/71-GT-88

Cumpsty, N. & Heyes, A. (2015). Jet propulsion. Third edition. Cambridge University Press.

Munt, R.W. (1979). Evaluation of aircraft smoke standards for the criterion of invisibility. EPA-AA_SDSB 79-25

Stockham, J. & Betz, H. (1971). Study of visible exhaust smoke from aircraft jet engines. FAA-RD-71-22