FAA CENTER OF EXCELLENCE FOR ALTERNATIVE JET FUELS & ENVIRONMENT

Analysis to Support the Development of an Engine nvPM Emissions Standards

Project 48

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Introduction

Motivation

- Aircraft nonvolatile particulate matter (nvPM) emissions have negative environmental impacts
- Visibility-based smoke number (SN) limit not designed to target emissions from landing & takeoff (LTO) operations
- New techniques provide more accurate measurements of nvPM mass and particle number emissions

Goal

- Aid FAA & ICAO with data and modeling to provide a scientific basis for establishing an nvPM emissions standard

Approach

- Estimate current and potential future nvPM emissions
- Conduct a cost-benefit analysis using the APMT-Impacts tools

Approach

1 Estimate aircraft engine emissions

- Direct nvPM measurements available for selected engines
- Develop a method to predict emissions from other engines

2 Predict future emissions

- Use nvPM emissions model to estimate future emissions
- Model change in emissions due to candidate regulations

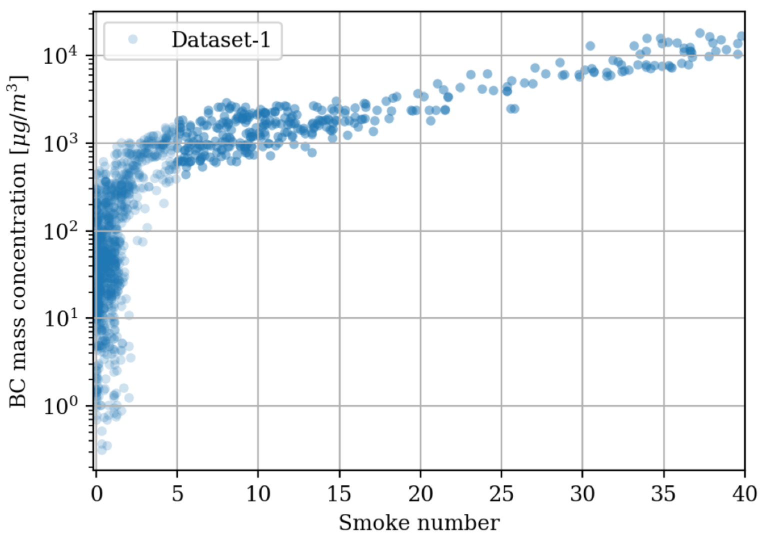
3 Quantify monetized environmental impacts

- Calculate future air quality and climate impacts
- Compare to industry costs of reducing emissions

Estimating nvPM mass and number emissions using SN

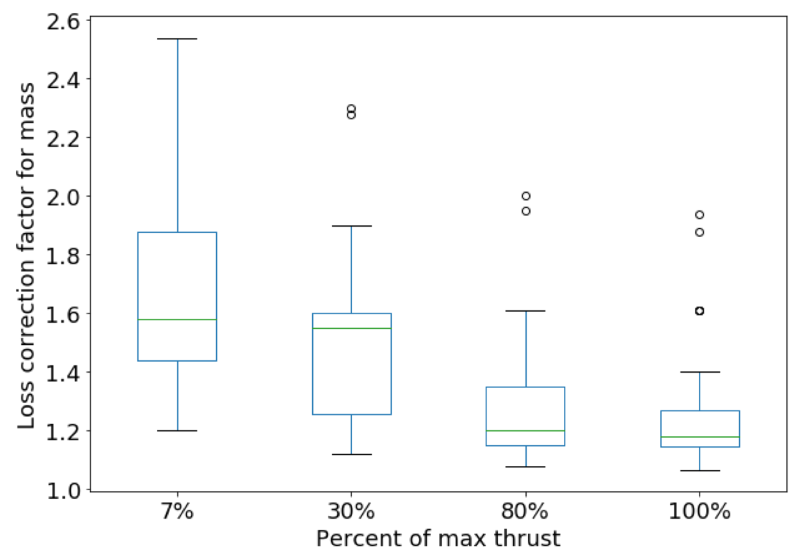
Dataset 1

- Concurrent SN and nvPM mass measurements
- Standardized, certification compliant measurements



Dataset 2

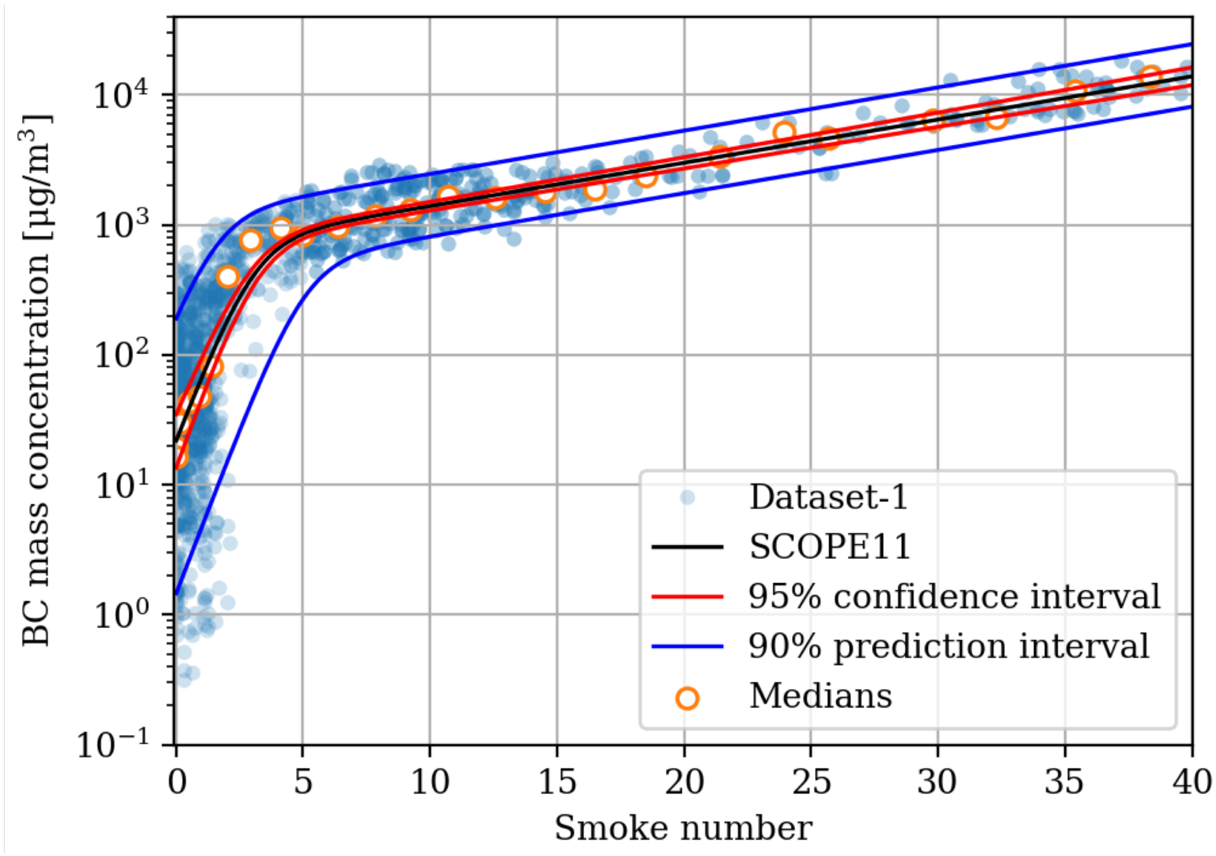
- nvPM mass and particle number measurements
- Estimate of particle losses in measurement system



Estimating nvPM mass and number emissions using SN

Use dataset 1 to predict mass emissions

Result



Observations

- Estimates instrument measurement

$$C_{BC,i} = \frac{648.8e^{0.0766 \cdot SN}}{1 + e^{-1.098 \cdot (SN - 3.064)}}$$

- Predicts steeper trend at low SN than at high SN
- Confidence & prediction intervals grow at low SN due to data spread
- Intervals are propagated through emissions code to estimate uncertainty

Estimating nvPM mass and number emissions using SN

Use dataset 2 to predict exit plane mass emissions

Approach

- Measured emissions are affected by losses in the measurement system:

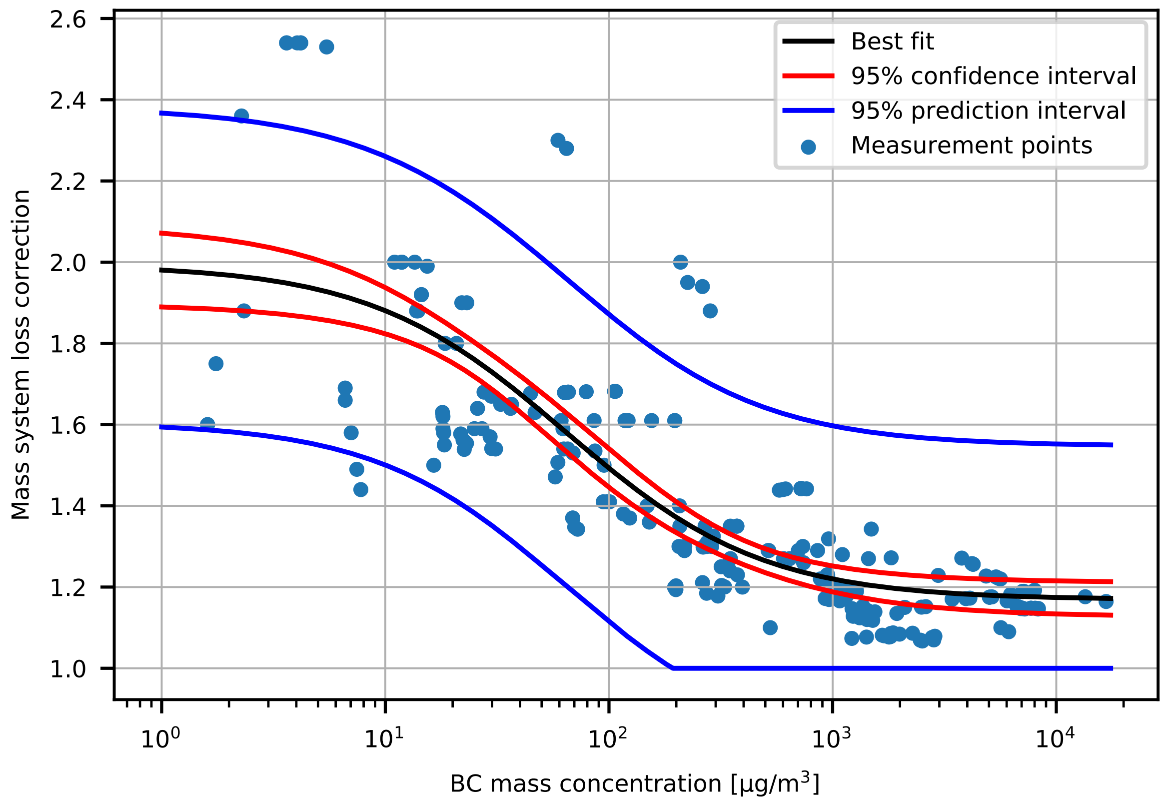
$$C_{BC,e} = k_{slm} \cdot C_{BC,i}$$

- Losses vary by particle size
- Larger particles carry more mass so mass concentration is a proxy for particle size

$$k_{slm} = \ln\left(\frac{3.219 \cdot C_{BC,i} + 312.5}{C_{BC,i} + 42.6}\right)$$

- Corrects emissions to engine exit plane

Correlation



Estimating nvPM mass and number emissions using SN

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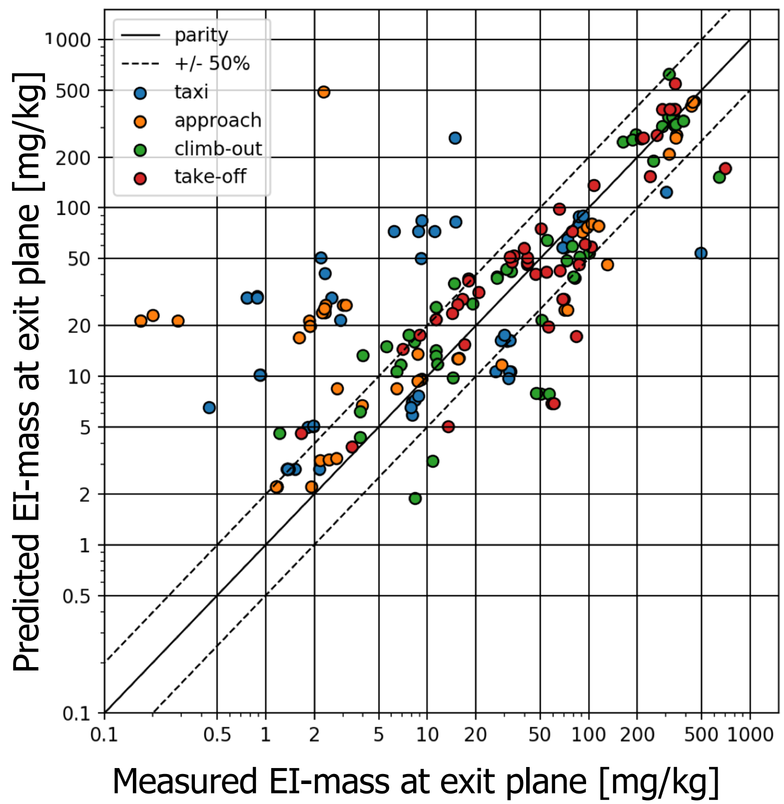


- Begin with certification SN
- Compare to data from dataset 2
- $R^2 = 0.8$
- RMSE: 82 mg/kg
- Lower accuracy during taxi

Estimating nvPM mass and number emissions using SN

Extend to predict particle number emissions

Approach

- Need particle size to move mass to number

$$C_{\#,e}(BC) = \frac{6C_{m,e}(BC)}{\pi\rho\mathbf{GMD}^3 e^{4.5(ln\sigma)^2}}$$

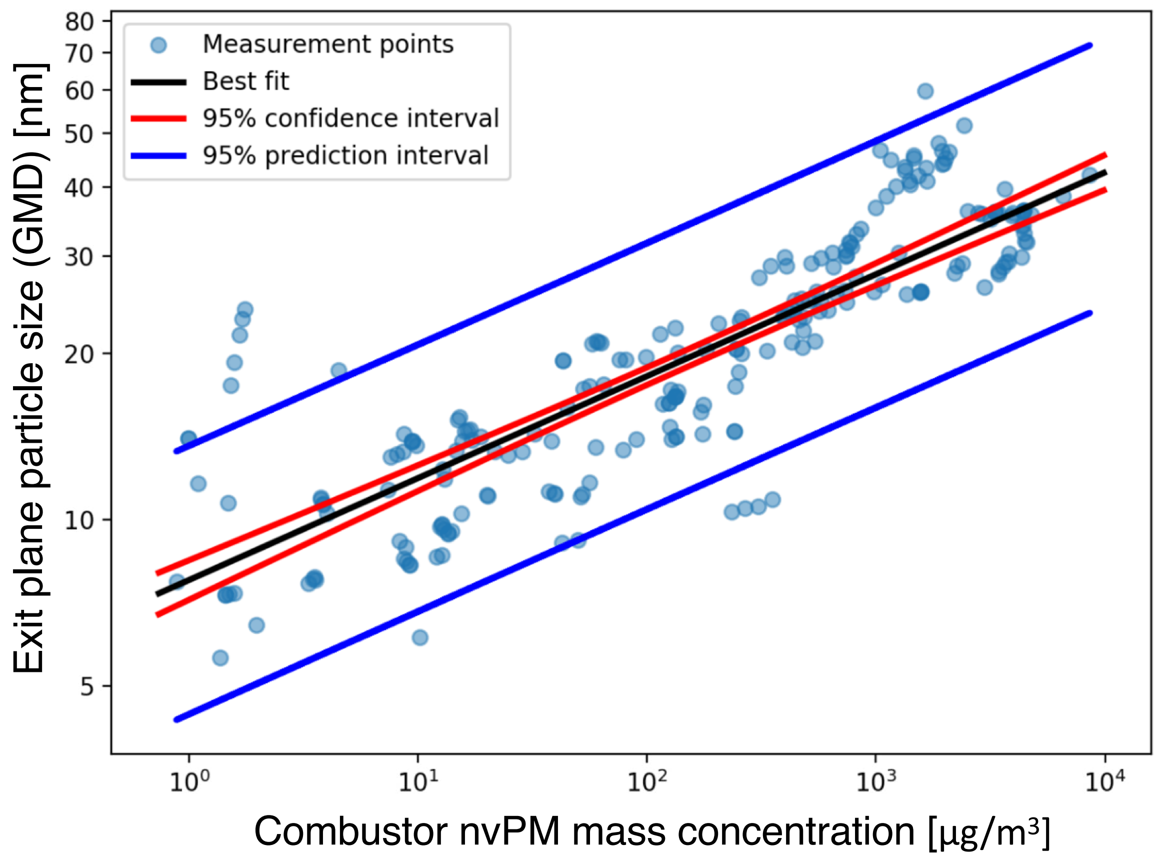
- High mass conc. in combustor drives GMD due to coagulation

$$GMD = 5.08 \cdot C_{BC,c}^{0.185}$$

- Mass balance to get combustor mass conc.

$$C_{BC,c} = C_{BC,e}\frac{\rho_{t4}}{\rho_a}$$

Correlation



Estimating nvPM mass and number emissions using SN

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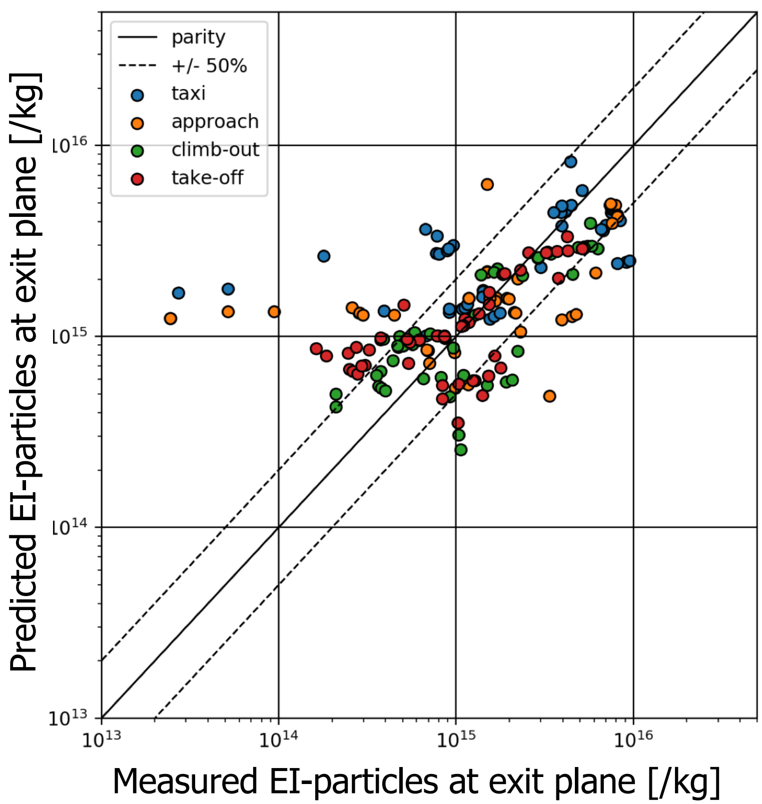

- Use estimated exit plane mass concentration
- Compare to data from dataset 2
- R^2 = 0.82
- RMSE: 1.5×10^{15} particles/kg
- Lower accuracy during taxi/approach

Estimating nvPM mass and number emissions using SN

Application to global LTO emissions in 2015

Method	LTO BC Mass [Gg/yr]	LTO BC Particles [$\times 10^{25}$ particles/yr]
This work[1]	0.74 (95% CI: 0.64, 0.84)	2.85 (95% CI: 1.86, 4.49)
FOA3	0.51	
Stettler et al. (2013)	1.38	
Zhang et al. (2019)	0.72	1.1

[1] A. Agarwal, R. L. Speth, T. M. Fritz, S. D. Jacob, T. Rindlisbacher, R. Iovinelli, B. Owen, R. Miake-Lye, J. S. Sabnis, and S. R. H. Barrett, "SCOPE11 method for estimating aircraft black carbon mass and particle number emissions", *Environmental Science and Technology* **53** (2019), no. 3, 1364–1373.

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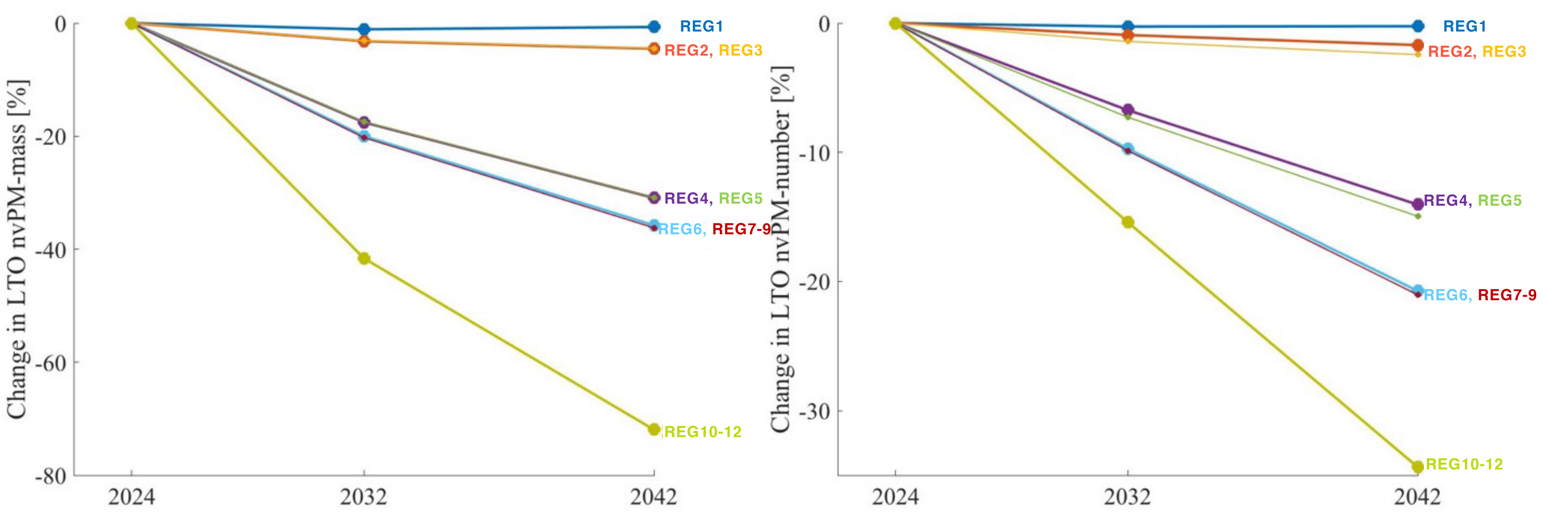
Effect of regulatory options on emissions

- Determine emissions associated with different candidate regulations
- Compare the effect of each candidate regulation on emissions at both LTO and cruise operations to business-as-usual scenario
- Decisions are made considering the resulting cost benefit analysis



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Cost-benefit analysis

- Used the APMT-Impacts tool suite to monetize climate and air quality impacts of emissions reduction
- Modeling tools include:

Climate: Reduced order model that quantifies the physical impacts of CO_2 and non-CO_2 aircraft emissions; monetized using economic damage functions

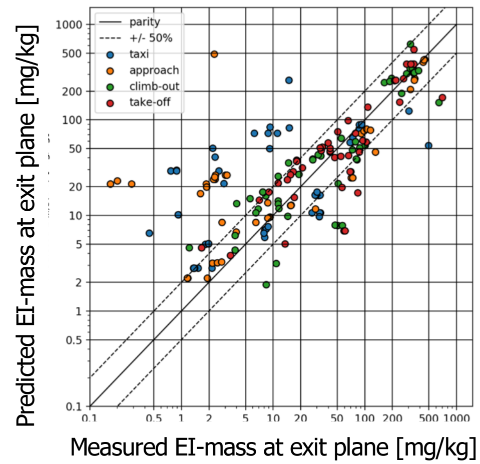
Air quality: Sensitivities calculated using the GEOS-Chem adjoint, a global chemistry transport model, to relate health outcomes to emissions; monetized using value of statistical life

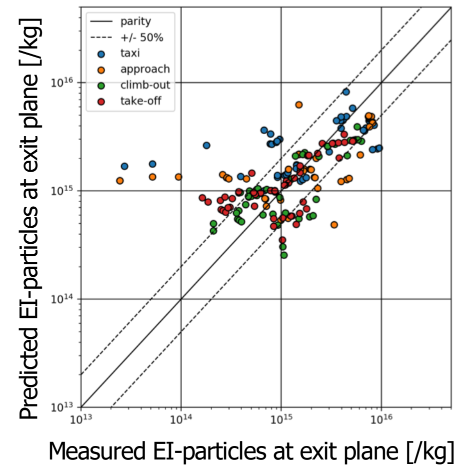
- Uncertainties propagated throughout and compared with industry costs

Summary

1 Estimated aircraft engine emissions

- Developed an approach that uses only SN to estimate nvPM mass and particle number
- Uncertainties included & propagated throughout





2 Predicted future emissions

- nvPM emissions predicted using above approach (SCOPE11)
- Estimated effect of regulations on fleet emissions

3 Quantify monetized environmental impacts

- Evaluated climate and air quality changes using APMT-Impacts
- Environmental uncertainty propagated throughout