

SC02 Deliverable 6:

Refining Methodologies for Estimating Non-Volatile Particulate Matter Emissions from Smoke Number for Regulated and Unregulated Aircraft Turbine Engines

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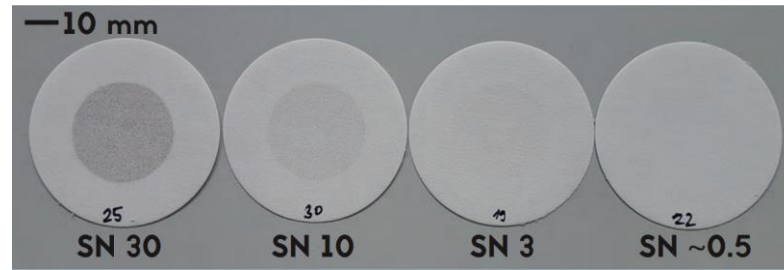


Objectives

- Review the current methodology for estimating nvPM mass and number EIs using nvPM and SN data collected using standardized sampling and measurement systems
- Evaluate the applicability of the SN-nvPM methodology for unregulated turbofan engines <26.7 kN rated thrust
- Propose improvements to the standardized SN-nvPM methodology
- Explore direct correlations between SN and emission indices of nvPM mass and number

- Emission tests with the Swiss and European nvPM reference (and gaseous and smoke) systems done between 2017 and 2023
- 380 SN – nvPM pairs (loss-corrected nvPM mass and number concentration and EIs)
- 12 turbofan engine types (rich-burn), including 3 engines <26.7 kN
- Jet A-1 fuel with SBC (HEFA-SPK) up to 50% blend ratio

Getting from SN to EI number



Step 1: SN – nvPM mass correlation

nvPM mass concentration at EEP

Step 2

AFR, Q

EI mass

Step 3

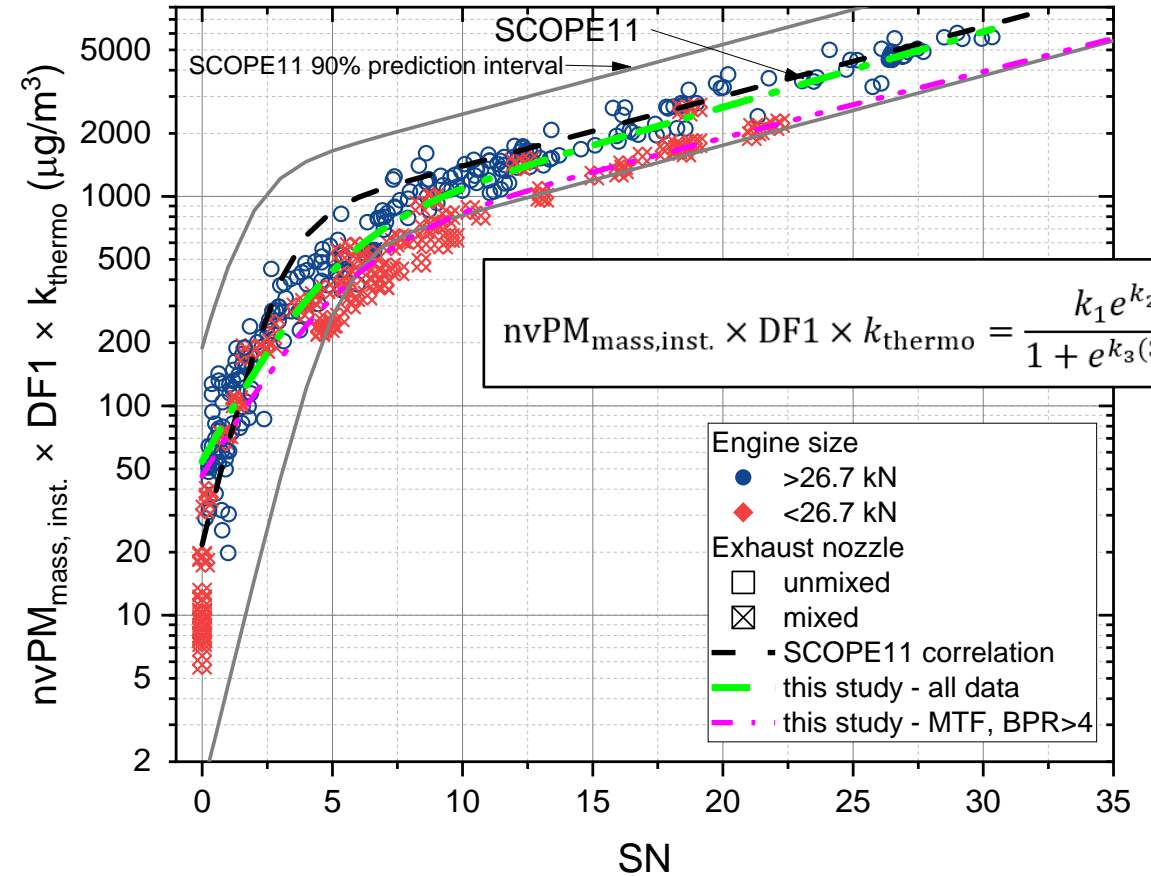
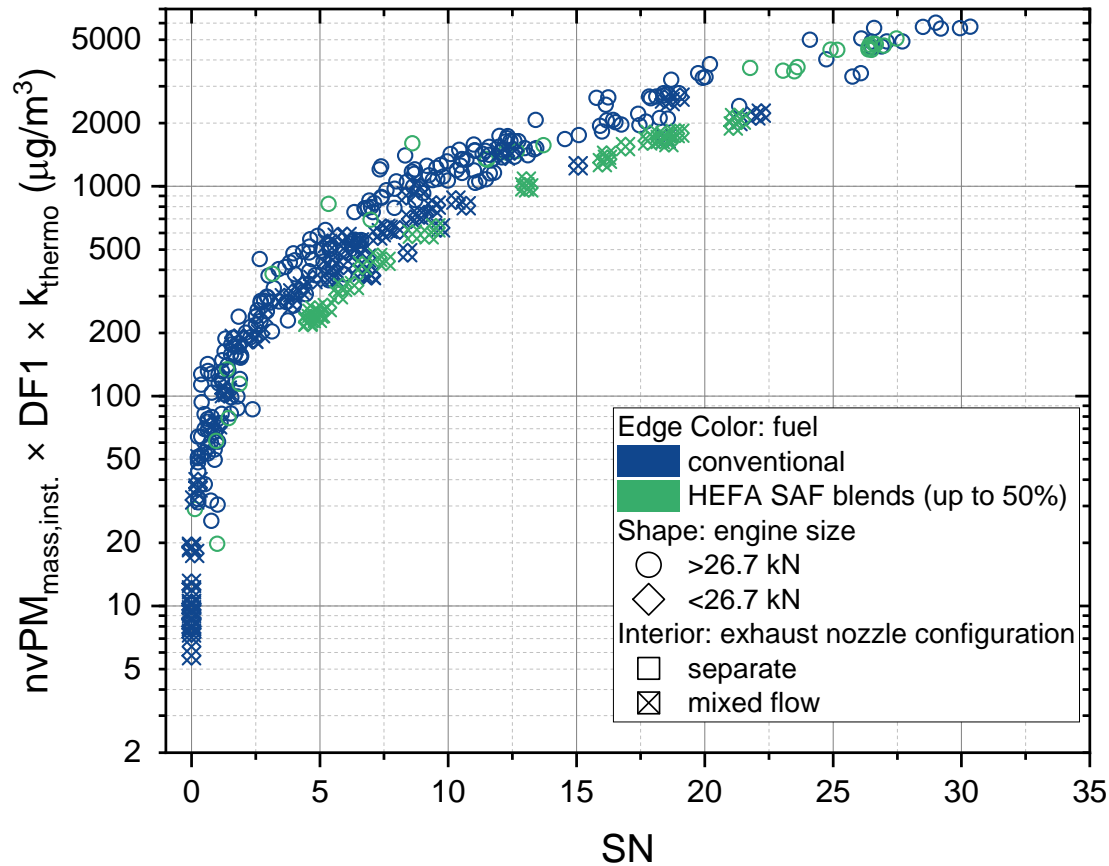
lognormal PSD parameters:
GMD, GSD, Rho

PSD

Step 4

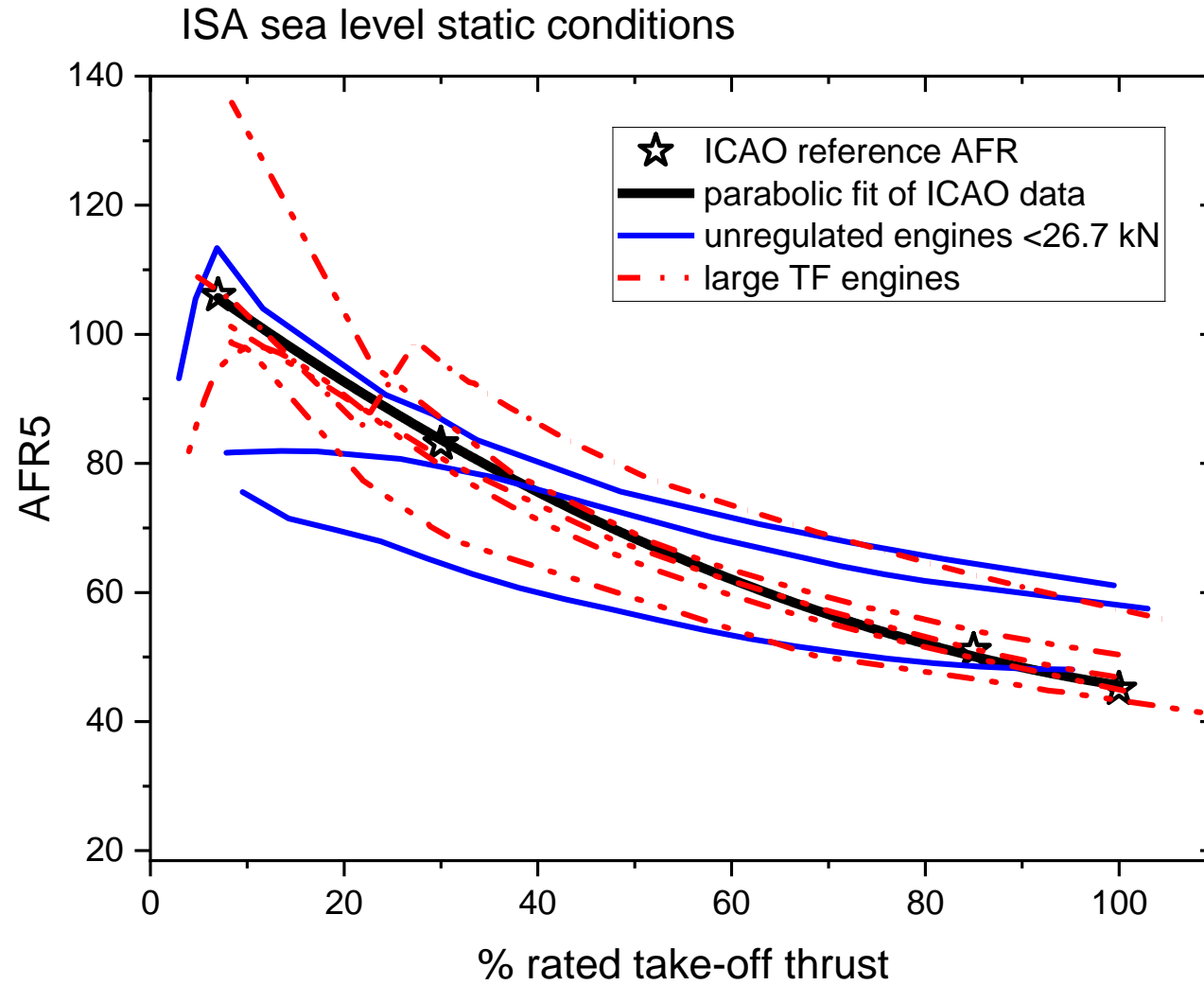
EI number

Step 1: SN-nvPM mass correlation



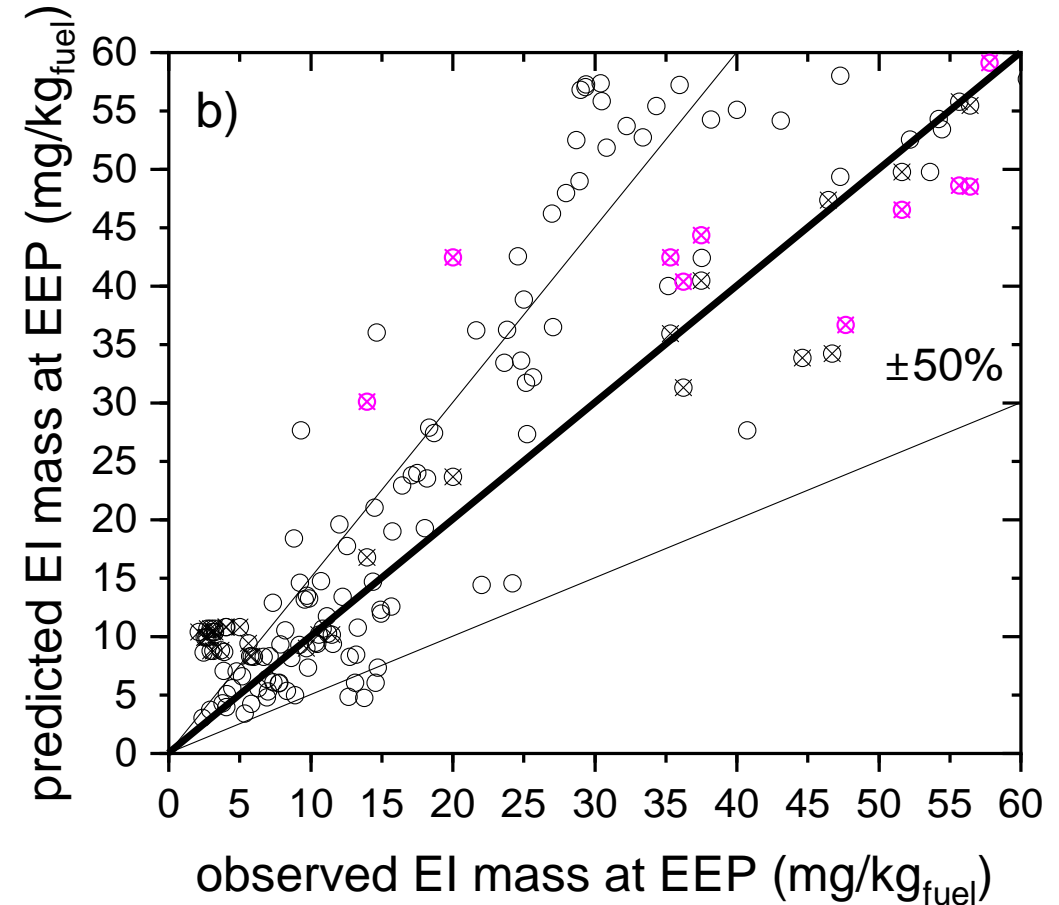
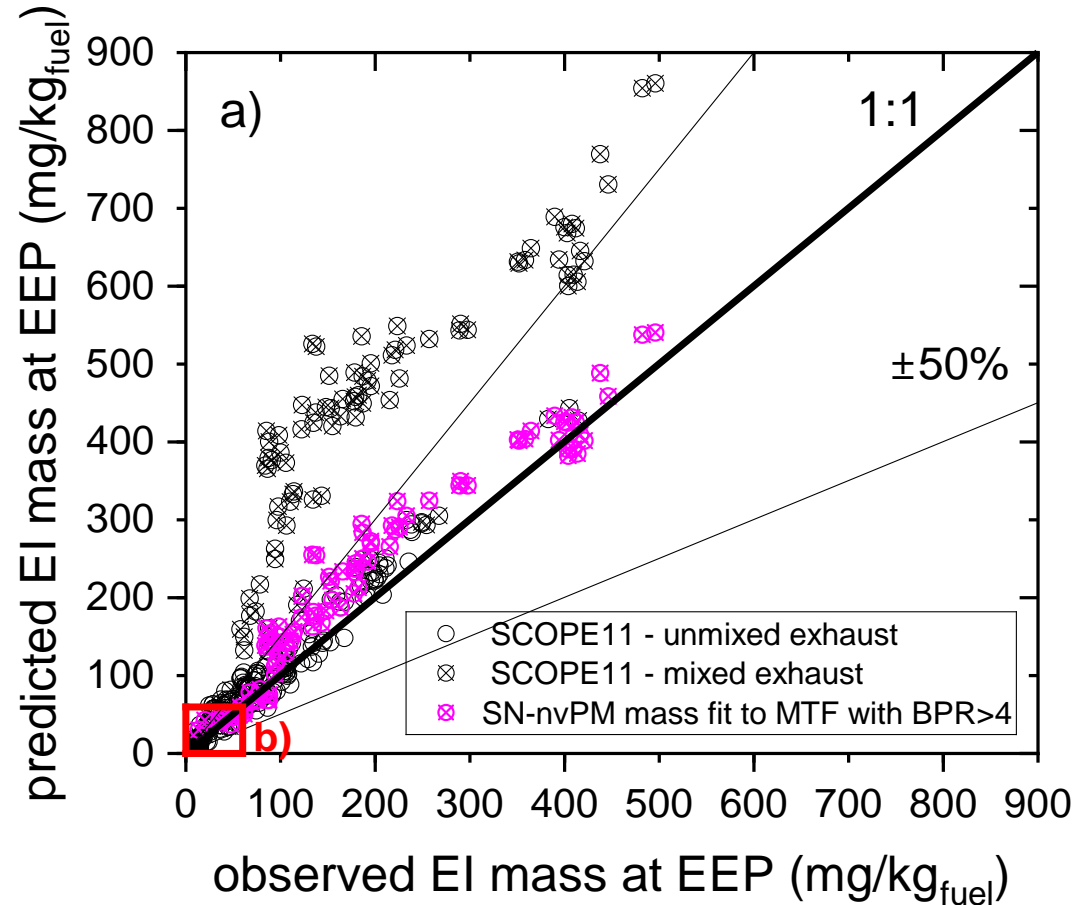
- Fuel composition did not significantly affect the nvPM mass-SN correlation for a given engine
- All core flow samples within the 90% prediction band of SCOPE11 correlation
- MTF engines with high BPR on average higher SN at a given nvPM mass – GMD effect? (see report for details)

Step 2: EI mass - AFR



- Assumed reference AFR in good agreement with calculated values of AFR5

Step 2: EI mass



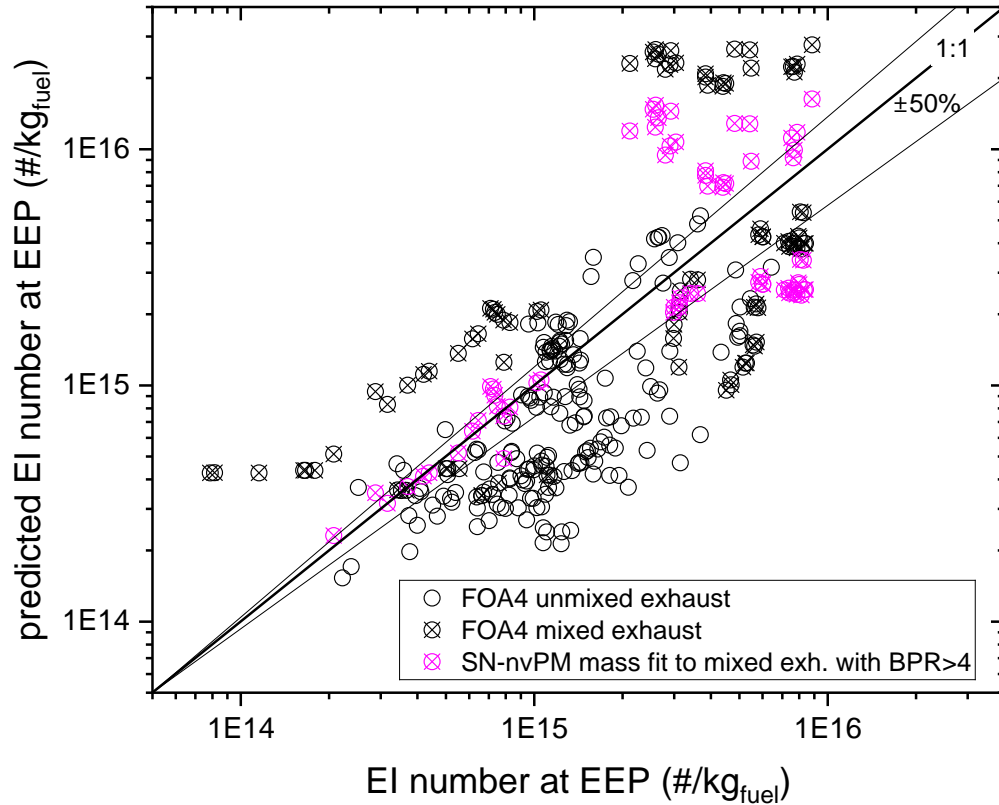
- Overprediction for MTF engines using default SCOPE11 correlation, good agreement using updated fit parameters

Step 3: PSD parameters in FOA4 and SCOPE11

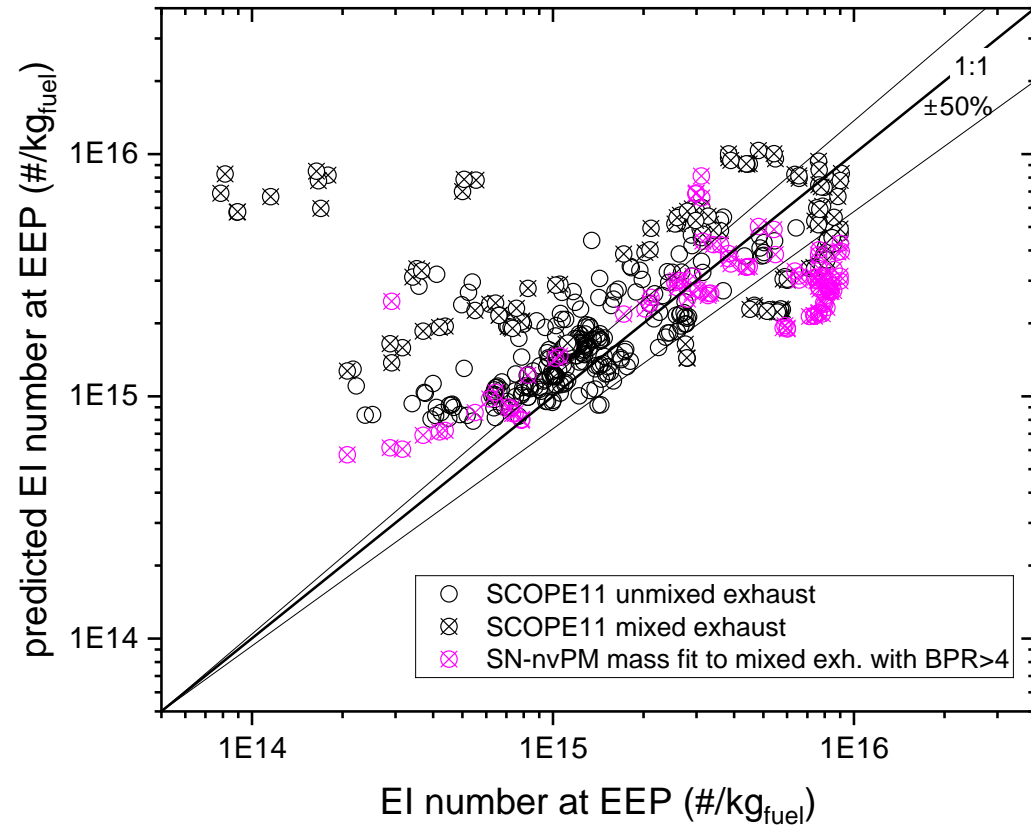
Method	GMD (nm)	GSD	Avg. density (g/cm ³)
FOA4	20 nm at 7% and 30% F _{oo} 40 nm at 85% and 100% F _{oo}	1.8	1
SCOPE11	5.08nvPM _{mass,St.4} ^{0.185}	1.8	1

Step 3: EI number FOA4 and SCOPE11

FOA4: GMD=20 nm (7%, 30% Foo) or 40 nm (85%, 100% Foo), GSD = 1.8, $\rho=1.0$

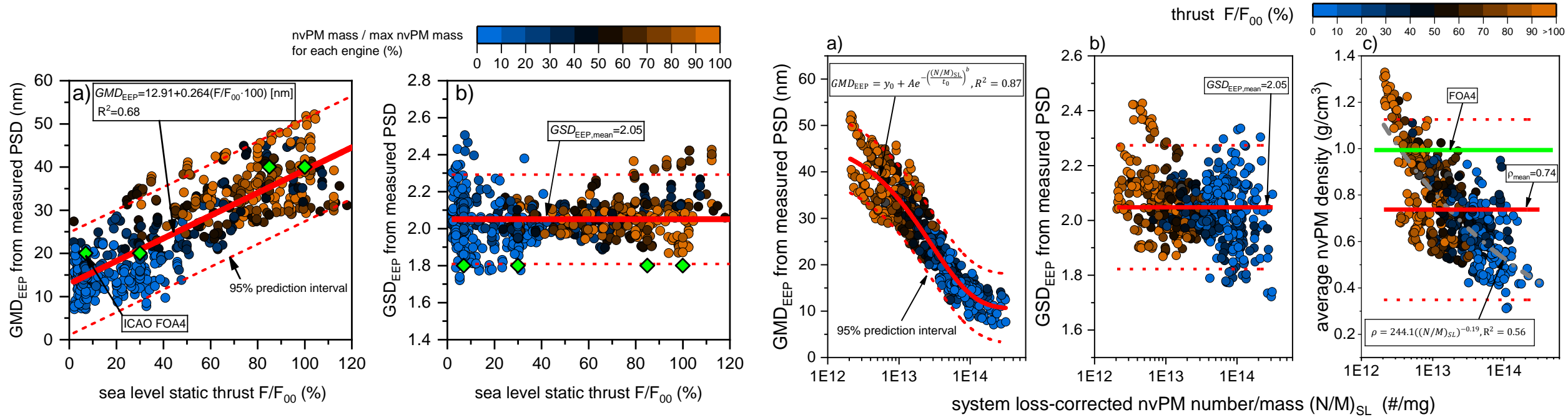


SCOPE11: GMD=f(nvPM mass), GSD = 1.8, $\rho=1.0$



- Overall agreement much worse than for EI mass due to assumptions made in the mass-to-number conversion and high measurement uncertainties of nvPM mass at instrument concentrations $< 10 \text{ ug/m}^3$

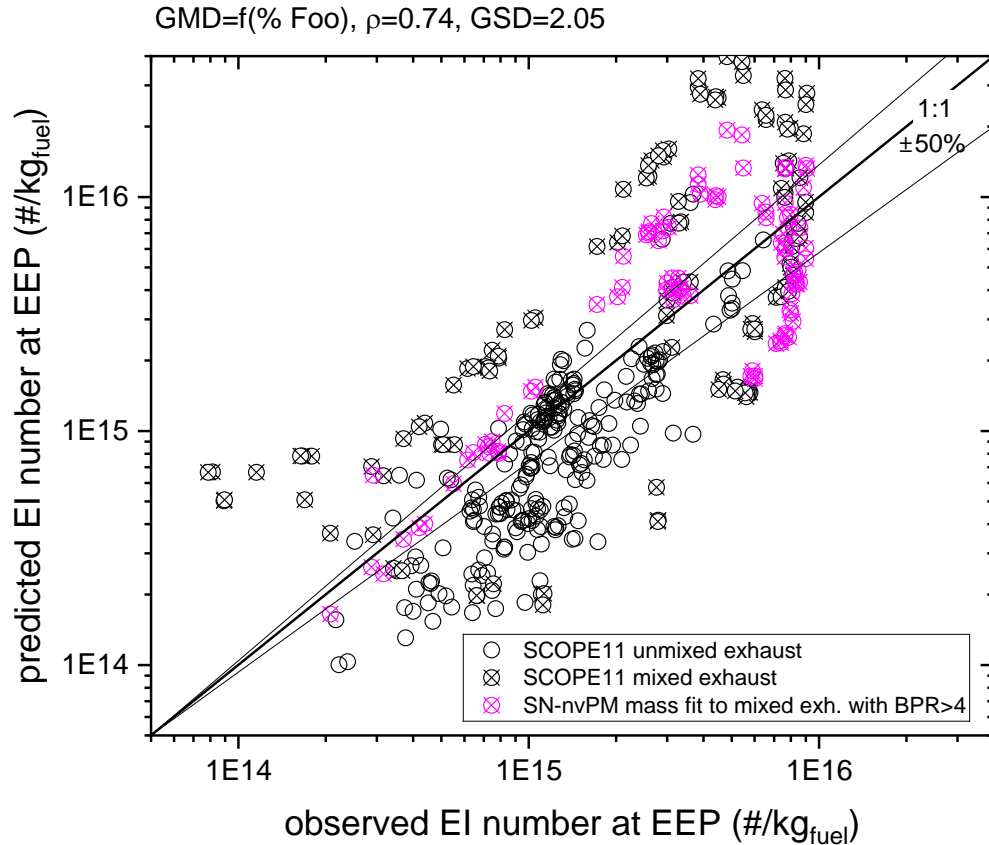
Step 3: empirical PSD properties



[Durdina et al. \(2024\)](https://pubs.acs.org/doi/full/10.1021/acs.est.4c02538)

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Step 3: EI number “improved FOA4”



GMD (nm)	GSD	Avg. density (g/cm^3)
$12.91+0.264(F/F_{oo})100$	2.05	0.74

- GMD parametrized as a function of thrust (Durdina et al. 2024) and updated GSD and density
- Improved correlation and agreement (lower RMSE) compared to FOA4

Step 3: EI number statistics

FOA4

Method and data	R ² of linear interpolation	RMSE (#/kg fuel)
FOA4 all data	0.15	5.65e15
FOA4 core flow only	0.28	1.35e15
FOA4 MTF with adjusted SN-nvPM mass correlation	0.03	5e15

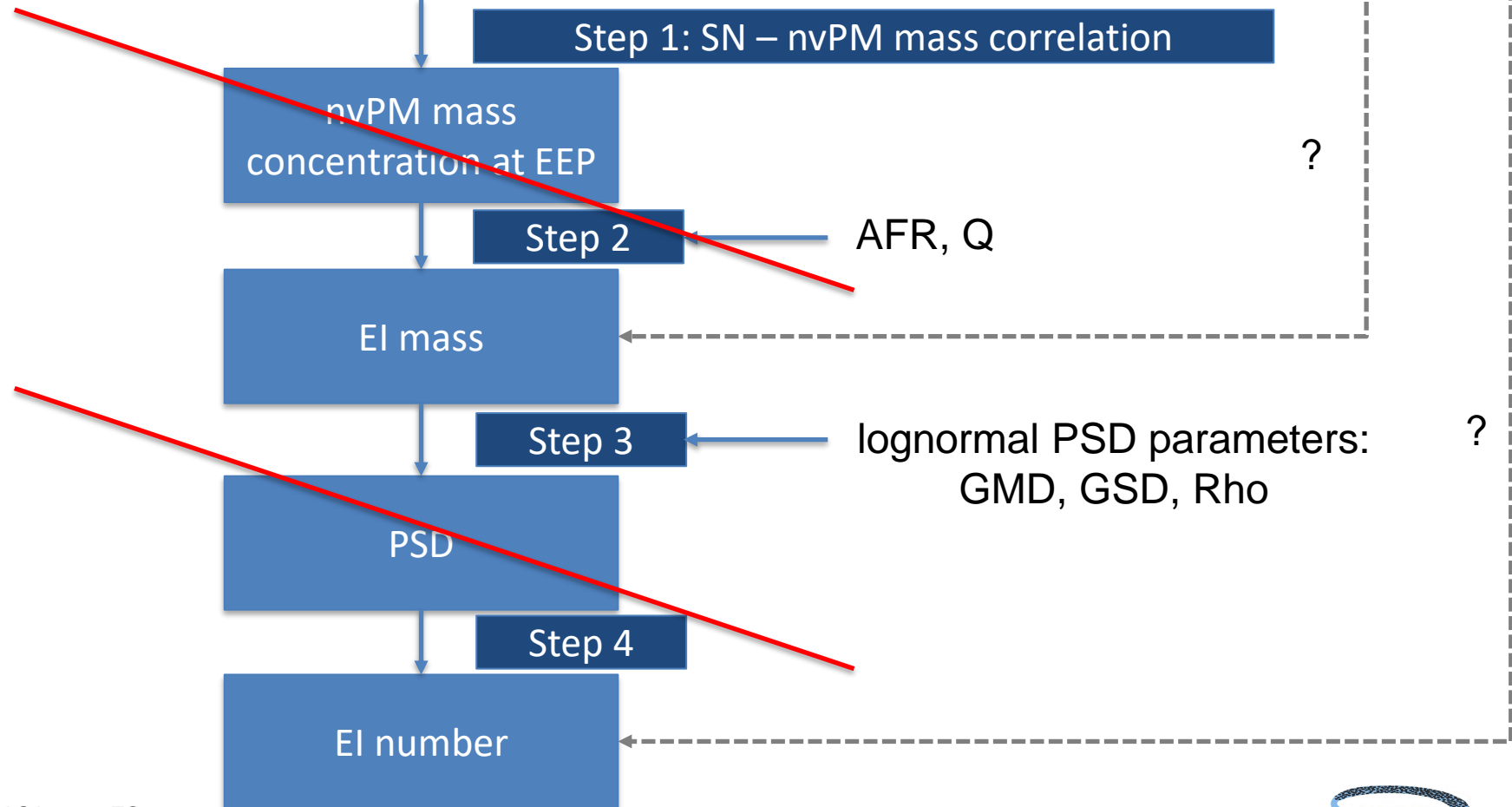
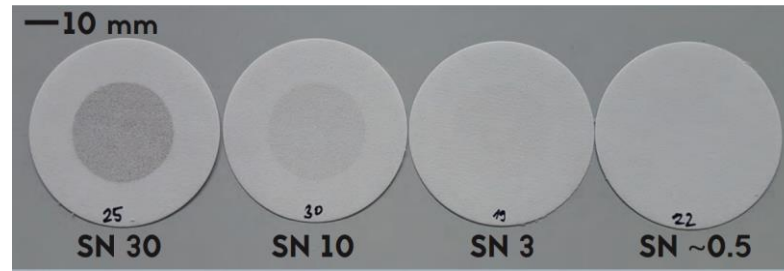
SCOPE11

Method and data	R ² of linear interpolation	RMSE (#/kg fuel)
SCOPE11 all data	0.3	2.13e15
SCOPE11 core flow only	0.04	1.77e15
SCOPE11 MTF with adjusted SN-nvPM mass correlation	0.1	3.5e15

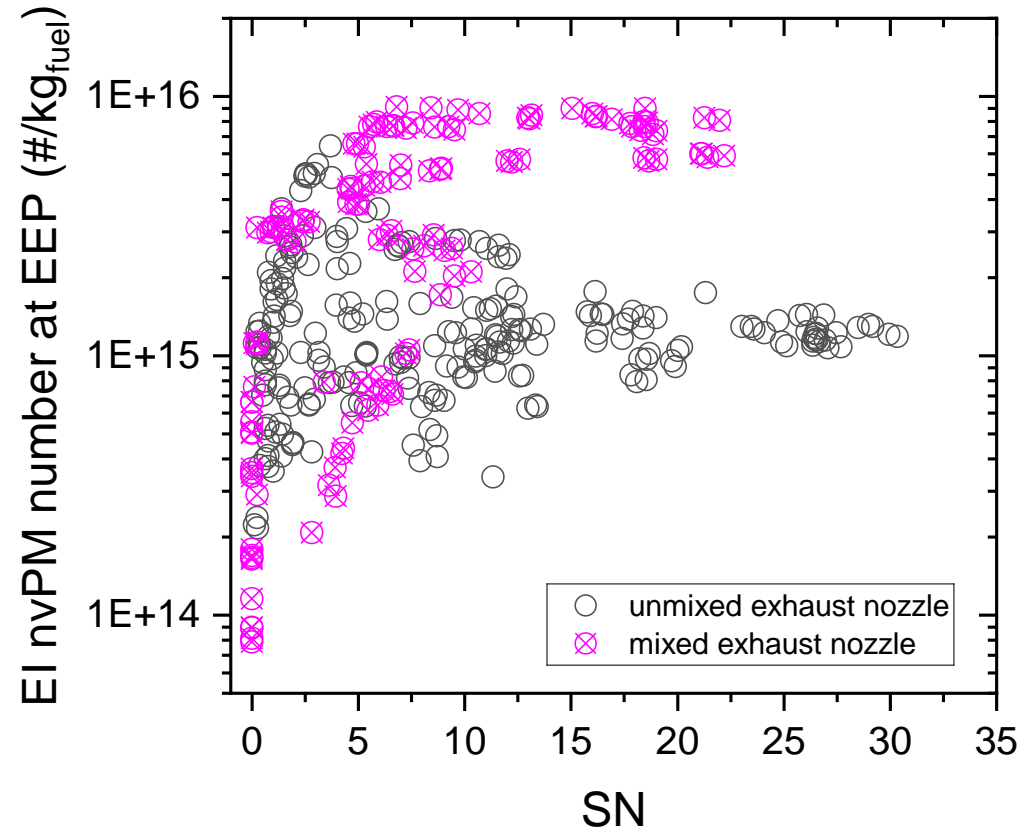
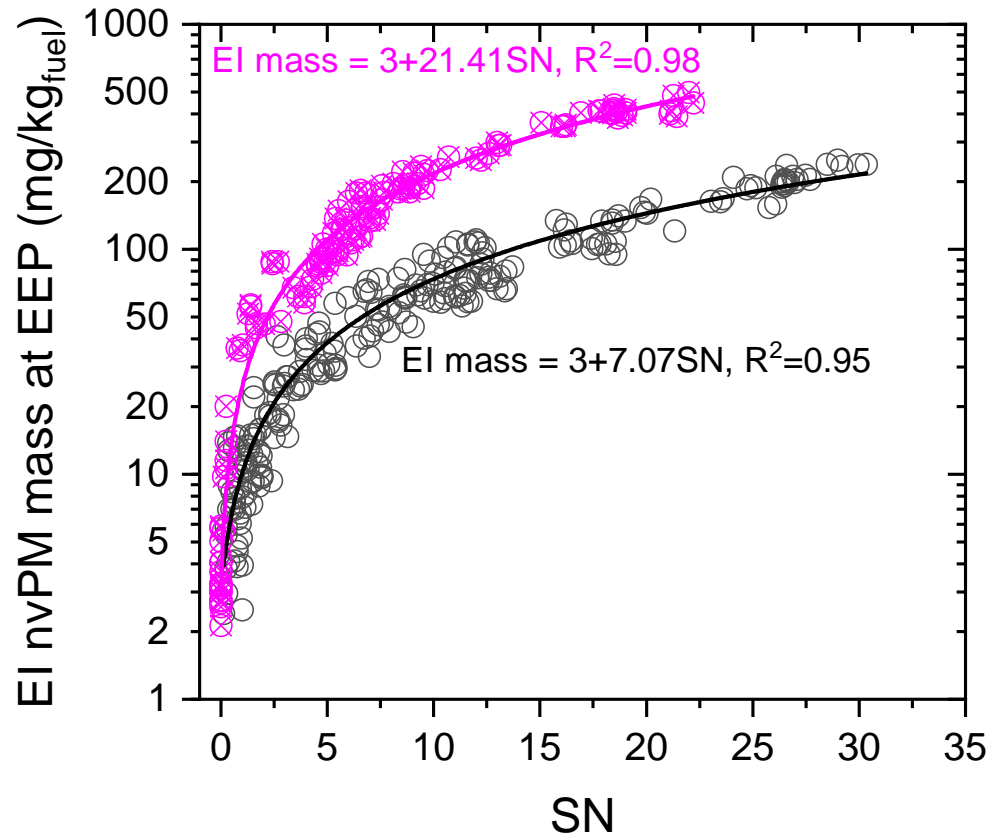
GMD vs %Foo, updated GSD and GMD

Method and data	R ² of linear interpolation	RMSE (#/kg fuel)
SCOPE11 all data	0.34	5.57e15
SCOPE11 core flow only	0.36	1.2e15
SCOPE11 MTF with adjusted SN-nvPM mass correlation	0.16	4e15

Direct correlation SN – EI?



SN – EI mass and number correlations



- Good correlation EI mass - SN with distinct trends for unimixed and mixed-flow engines
- Poor / no correlation EI number - SN

Summary

- The correlation between SN and nvPM mass concentration used in the SCOPE11 and FOA4 methods is appropriate
 - This study's MTF engines with a high bypass ratio showed lower nvPM mass for a given SN than the samples obtained from unmixed nozzles
- The assumed reference AFRs for the LTO points and their interpolation are reasonable for regulated and unregulated engines
- The predicted EI mass for unmixed engines agreed well with observations, with most points within 50% of the 1:1 line and $R^2=0.96$
- Between the two standard options for EI number, FOA4 with fixed GMD for LTO modes and SCOPE11 with GMD correlated with combustor-exit nvPM mass concentration, SCOPE11 provided significantly better agreement with observations (~60% lower RMSE when applied to all data in this study).
- An alternative method to FOA4 for EI number was proposed with better correlation and agreement than FOA4.
 - the lognormal distribution parameters were adjusted using the latest research findings with GMD parametrized as a linear function of % thrust, with adjusted GSD and density
- EI nvPM mass correlated strongly with SN ($R^2=0.95-0.98$), with two distinct functions for unmixed and mixed flow nozzles. However, such a correlation was not found feasible for nvPM number.