Project 48
Analysis to Support the Development of an Engine nvPM Emissions Standard

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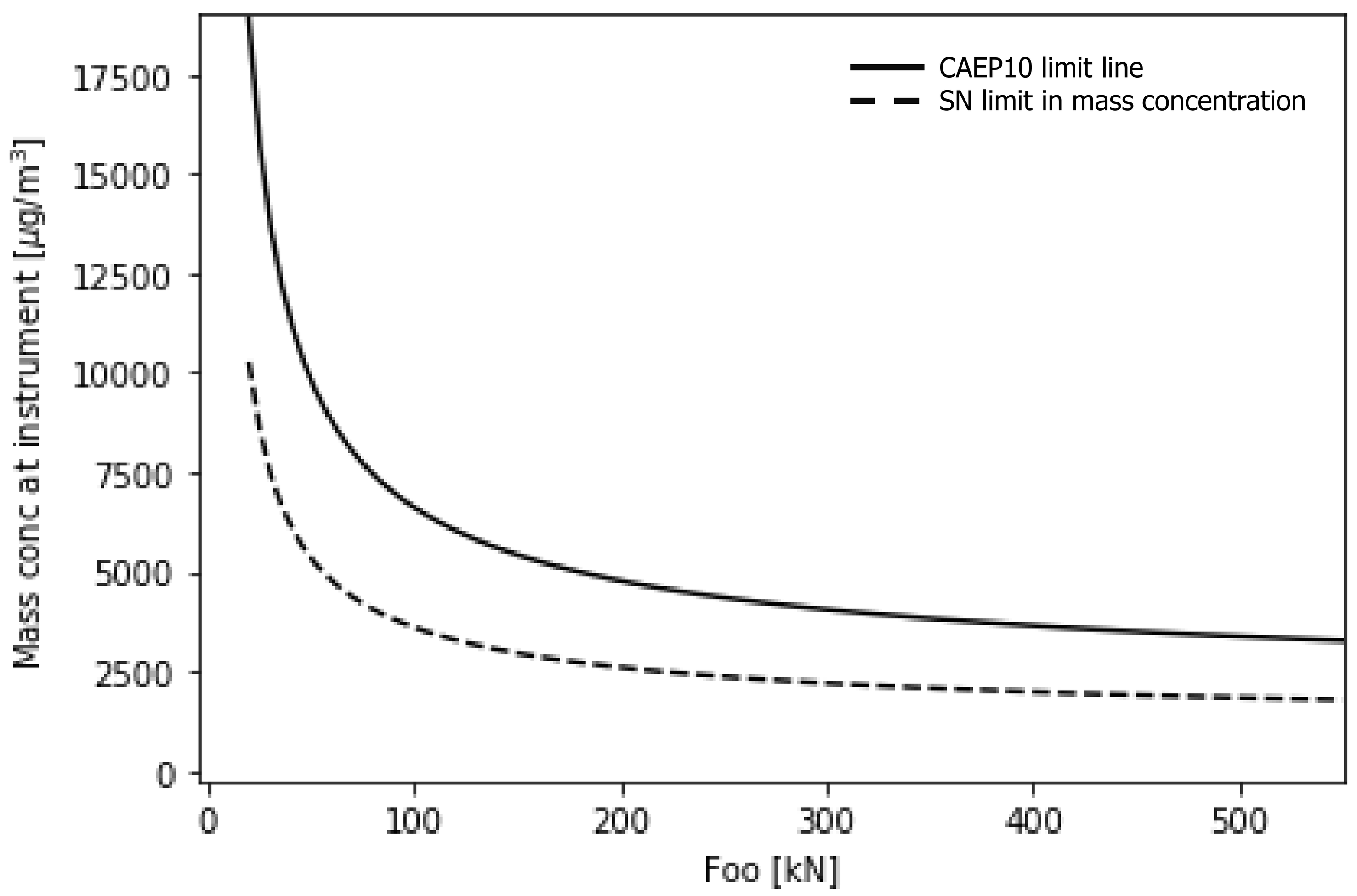
Motivation

- The ICAO smoke number (SN) limit for aircraft engines was developed to prevent the visibility of engine exhaust plumes
- The ICAO CAEP/10 nvPM mass concentration standard was developed as an all-pass standard.
- The CAEP/10 limit was determined by using a relationship between SN and mass concentration and shifting the line upwards by two standard deviations to ensure engines passing SN limit would pass CAEP/10 limit



- To end the applicability of the SN regulation and replace it with the CAEP/10 nvPM mass concentration standard, need to validate that the mass concentration limit line is as effective at preventing plume visibility at the engine exit plane

Method

The method to predict the visibility of aircraft engines exhaust plumes can be split into three steps:

1. Estimate the exhaust nozzle diameter
2. Calculate exit plane mass concentration at the threshold for plume visibility
3. Convert exit plane emissions to instrument measured values at standard conditions

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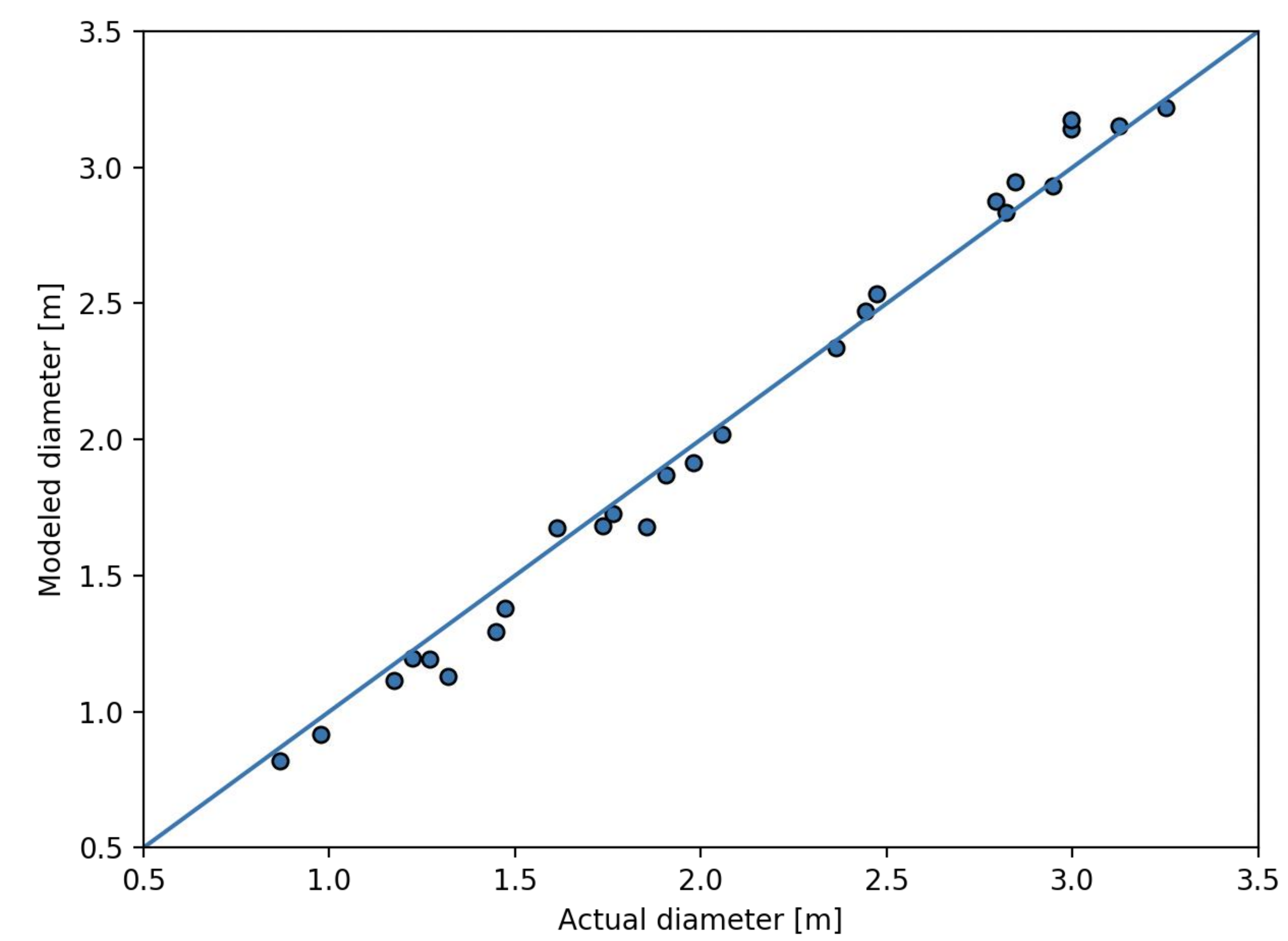
Exhaust nozzle diameter

We used 1-D gas turbine theory following Cumpsty and Heyes (2015). The following data and assumptions are used:

- Rated thrust (F_{00}), overall pressure ratio (π_{00}), bypass ratio(BPR) and fuel flow from emissions databank (EDB)
- For unmixed engines, a fixed bypass to core jet velocity ratio, $\alpha = 0.9$, is assumed
- For mixed-flow engines, we assumed matching stagnation pressure at mixing plane

This approach allows us to size an engine. We can validate our results by estimating a fan diameter and comparing this publicly available values, where we find an average error of ~3%. The approach should be reasonable for estimating nozzle diameter



Exit plane mass concentration of a visible plume

Use optics theory to estimate visible mass concentration at exit plane:

$$C_{m,e} = \frac{\rho_s \lambda \log(1/T)}{K_e L}$$

ρ_s is the soot density, $\lambda = 550\ \mathrm{nm}$ is the specified wavelength of light, $K_e = 7.5\ \mathrm{m^2/g}$ is the absorption coefficient of nvPM, $T = 98\%$ is the transmissivity of light above which plume is invisible to humans and L is the path length (equivalent to exhaust nozzle diameter).

Correction to measured emissions

We must convert exit plane emissions ($C_{m,e}$) to instrument measured values ($C_{m,i}$) which are the basis for the CAEP/10 limit. Two corrections are made:

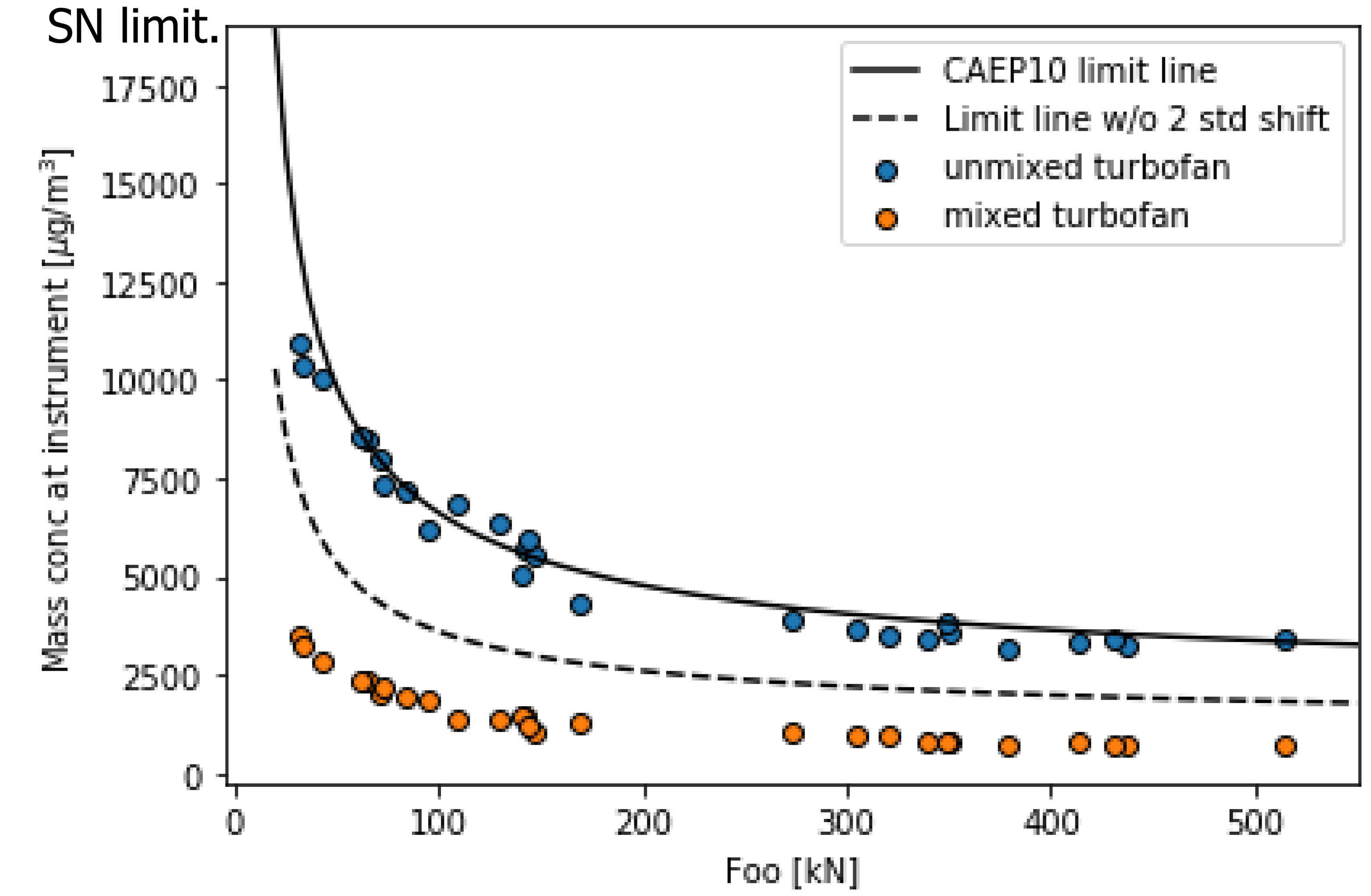
1. Correct to standard temperature and pressure (STP)
   - Scale concentration by exit plane density from gas turbine model to STP density
2. Account for particle losses in the measurement system
   - Use the relationship developed by Agarwal et al (2019):

$$C_{m,e} = C_{m,i} \ln\left(\frac{3.219\, C_{m,i}(1+\beta_{mix}) + 312.5}{C_{m,i}(1+\beta_{mix}) + 42.6}\right)$$

   - Apply iteratively to estimate $C_{m,i}$

Results

27 engines are selected from the EDB spanning range of F_{00} and $C_{m,i}$ is estimated assuming they are all unmixed turbofans (blue) or mixed-flow turbofans (orange), and that their emissions are at the visibility threshold ($T = 98\%$) used for the SN limit.



- The CAEP/10 limit line is near the visibility threshold for the exhaust plume of unmixed turbofan engines
- Variability around limit line is caused by differences in mapping of F_{00} to nozzle diameter as BPR and OPR vary
- Neither CAEP/10 limit line nor SN limit line prevent visibility of the exhaust plume of mixed-flow engines
- Use of the nozzle diameter would be a more direct and reliable approach to ensure exhaust plumes are not visible

Collaborators:

- Aerodyne: Rick Miake-Lye (ASCENT Project 2)

Cumpsty, N., & Heyes, A. (2015). Jet propulsion: a simple guide to the aerodynamic and thermodynamic design and performance of jet engines. Cambridge University Press
Agarwal, A., et al (2019). SCOPE11 method for estimating aircraft black carbon mass and particle number emissions. Env. Sci. Tech. 53 (3), 1364-1373