# ASSESSMENT OF nvPM SYSTEM LOSS PREDICTION WITH SIZE MEASUREMENT TOWARDS AVIATION ENGINE REGULATION

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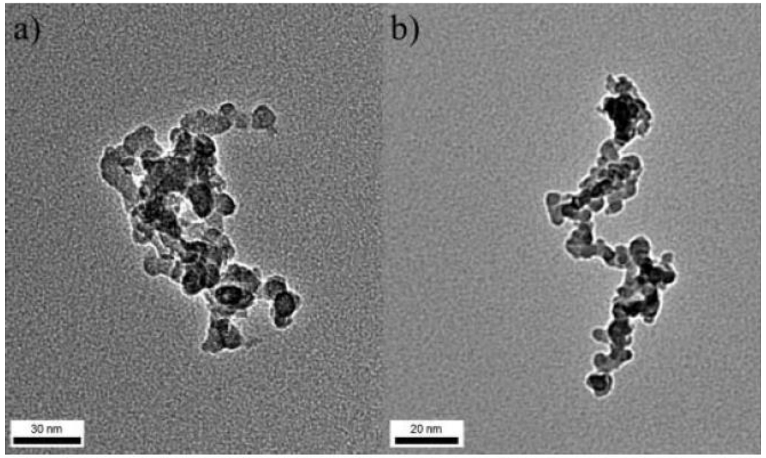
# Context (1)

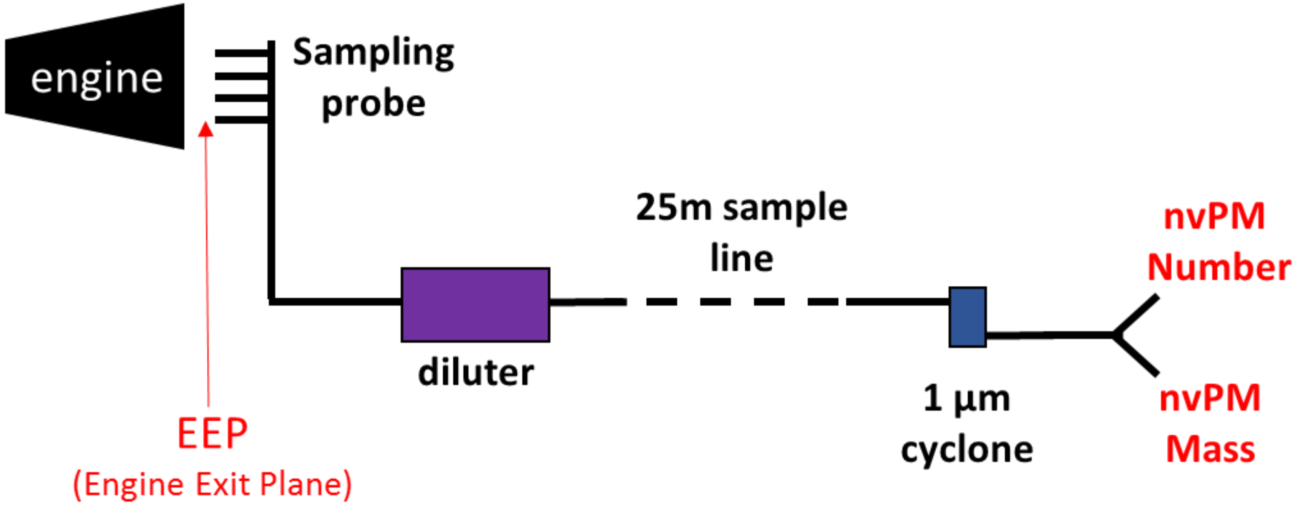
- **Aircraft gas turbines produce soot <200 nm**
  - → *Local air quality & potential environmental hazard*
  - → *Aircraft exhaust is a harsh environment = need for a sampling system*




**TEM images of two 15 nm particles (mobility-selected) emitted from an aircraft engine [Boies et al. 2015]**

- **ICAO has prescribed in 2017 a methodology for the reporting of aircraft non-volatile Particulate Matter (nvPM) emissions**
  - → *Towards mitigation of harmful emissions*
  - → *Reporting of nvPM number and mass Emission Indices (EIs)*
  - → *nvPM size measurements not prescribed (traceability, morphology)*

- **ICAO compliant standardised sampling & measurement system:**
  - – ≤35 m (including collection section, Diluter, 25 m line & Analysers
  - – Cools, dilutes and transports exhaust aerosol
  - → *Significant particle loss not corrected in reported nvPM EIs (except thermophoresis)*




**Simplified diagram of an ICAO compliant sampling system**

# Context (2)

- **SAE E-31 system loss correction methodology:**
  - Methodology referred as System Loss Tool (SLT)
  - Accounts losses in sampling & measurement system

→ *with SLT, EIs can be reported at the Engine Exit Plane (EEP) for airport inventories*

  - Challenge: size-dependent losses but no size measurement

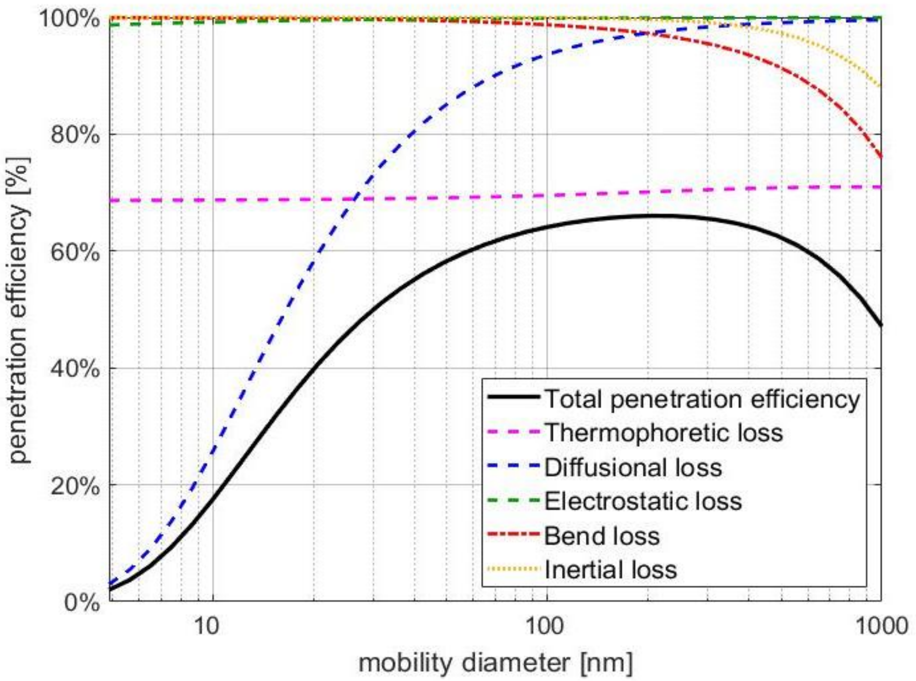
- **How SLT works:**

➢ Uses measured nvPM Number and Mass (N/M ratio) to predict a GMD

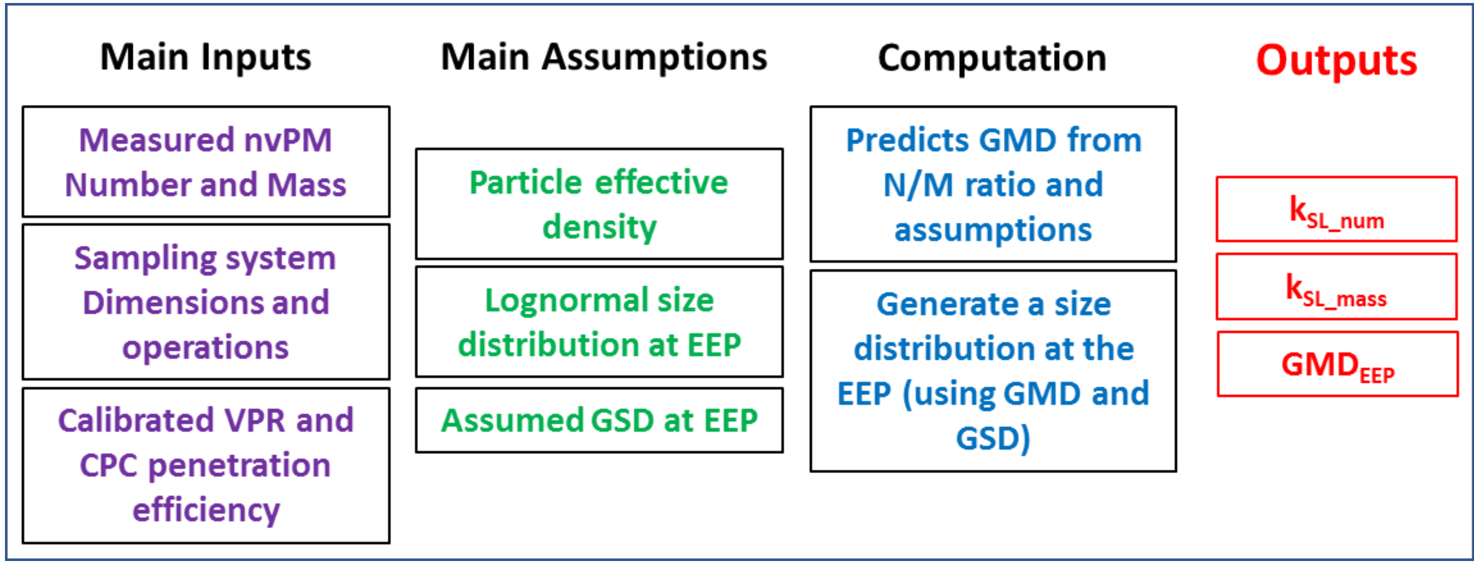
➢ Requires assumptions to operate:

- Average particle effective density: **1 g/cm³**
- Geometric Standard Deviation (GSD) at EEP: **1.8**
- lognormality of particle size distribution at EEP

*Are those assumptions accurate for all aircraft engines?*




**Typical Particle loss when transported in an ICAO compliant sampling system**

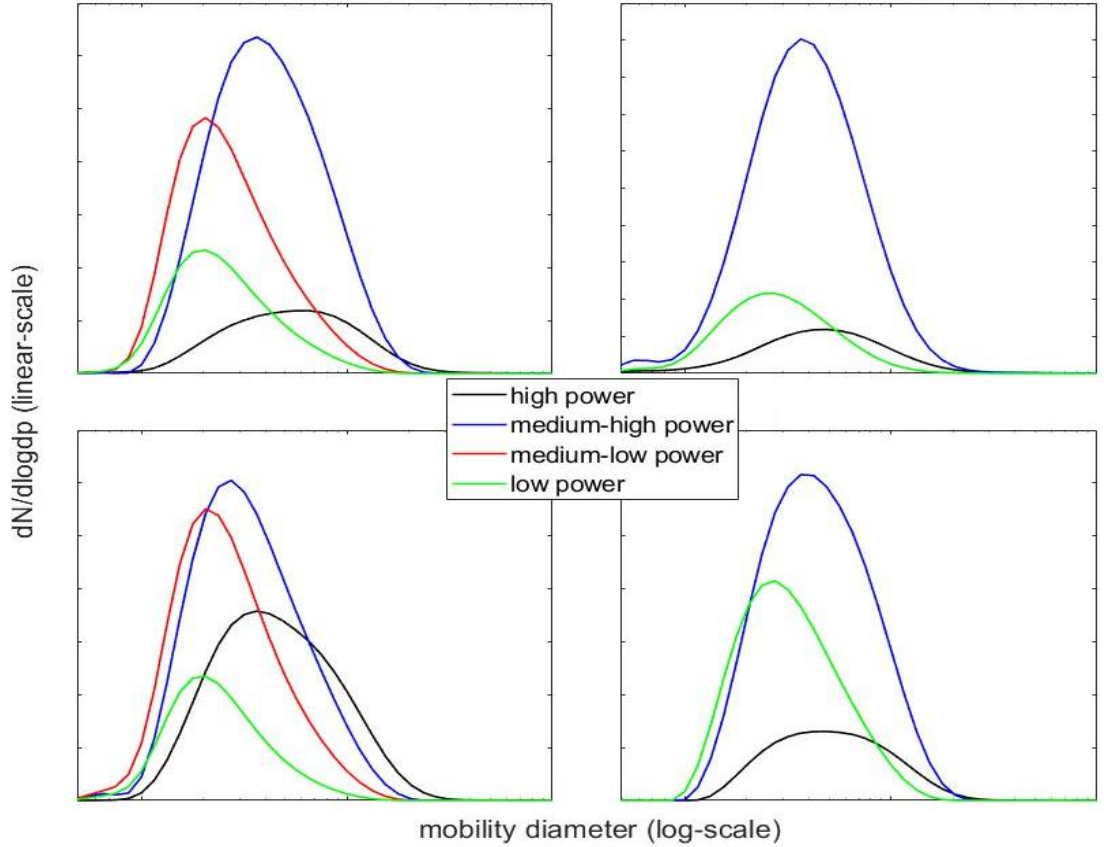



**Block Diagram of the SLT correction methodology**

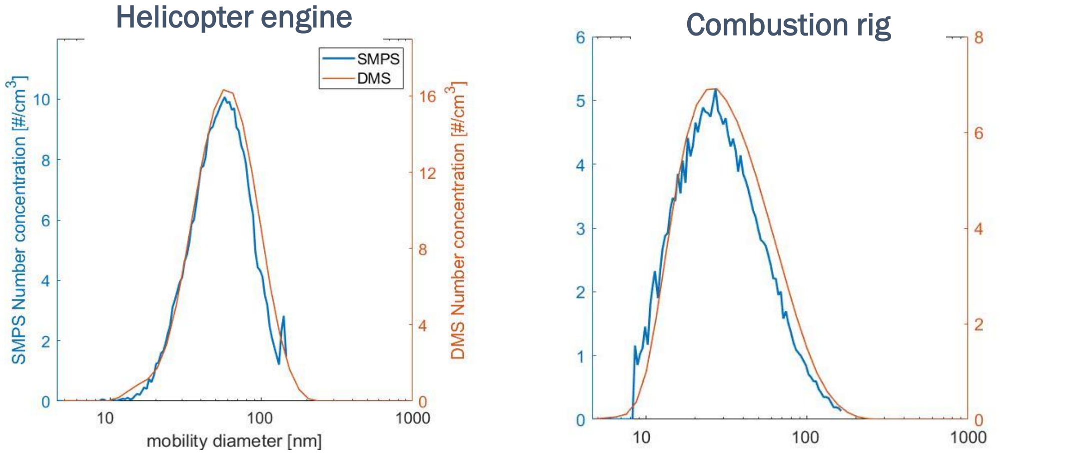
# Background

## Data presented and discussed:

- 4 engine types (7 engines) from Rolls-Royce (RR)
  - Different technologies & thrust levels representative of in-service engines
  - nvPM ICAO compliant system
  - Across all (LTO) engine powers (relative thrust 7-100%)
- Additional particle size measurement performed using a Cambustion DMS-500
  - Suitable for fast aerosol measurements at high powers
  - *GMD 20-50 nm - GSD 1.6 - 2.1*
  - Monomodal but deviation from lognormality
  - GMD increases with power
- Comparison DMS-500 / SMPS
  - Good correlation for GMD & GSD (same shape)




**Normalised size distributions of 4 engine types at different engine powers**




**Normalised DMS-500 and SMPS size distributions measured on various sources**

# Loss corrected particle size distributions (PSD)

- **Additional particle size measurement used for:**
  - Deriving an average particle effective density
  - Deriving a GMD and GSD at the EEP

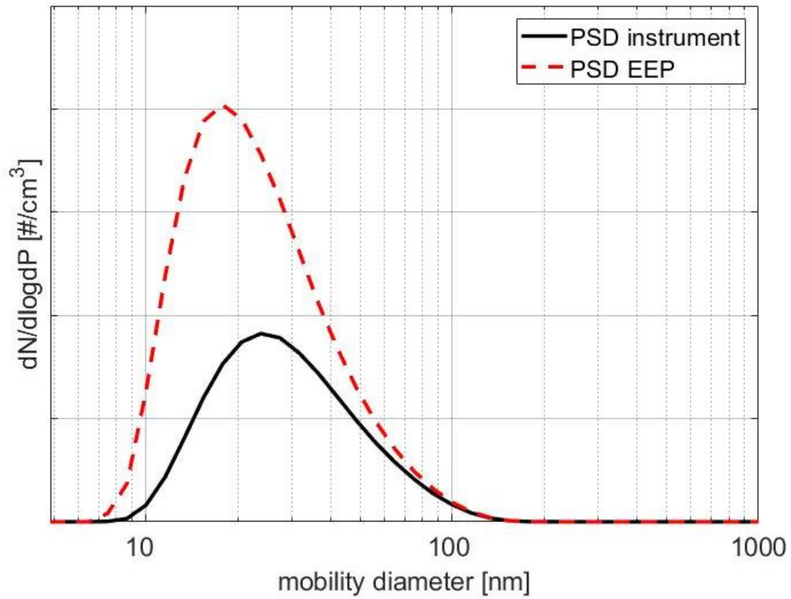
*Measured-derived GMD compared with SLT GMD predictions*

- **How PSD was corrected at EEP:**
  - Penetration efficiency between instrument → EEP

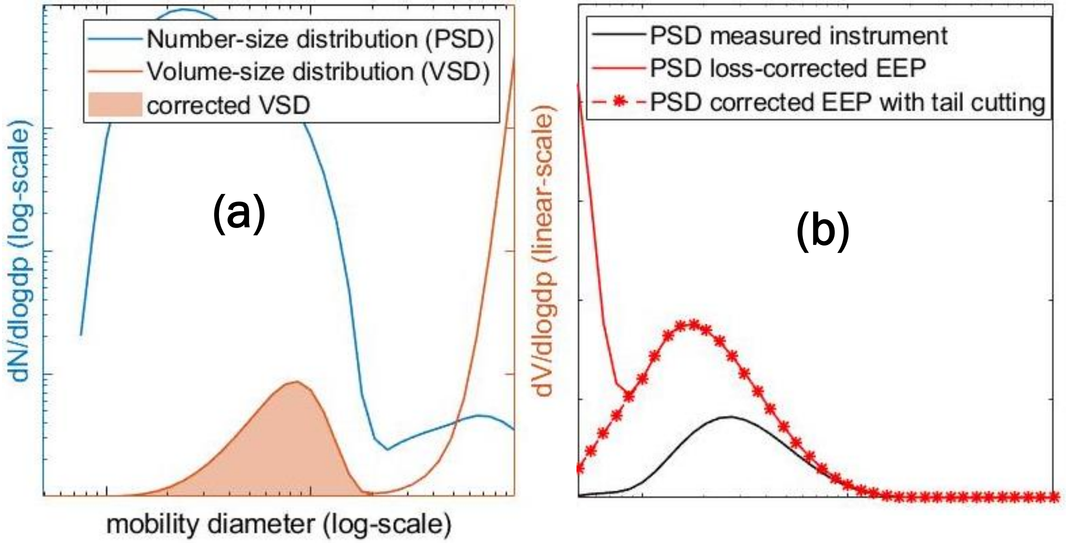
*Accounting for Diffusion, thermophoresis, electrostatic, bend and inertial losses (UTRC model)*

  - Size-dependent loss = higher concentrations & smaller GMD at the EEP

- **'Tail-cutting' sometimes required to remove artefacts:**
  - **(a)** >200 nm for VSD (line shedding, DMS noise)
  - **(b)** <10 nm (high correction factors at EEP)




**Example PSD at different locations of sampling system**




**Example of PSD artefacts corrected with tail-cutting method**

# Assessment of lognormality at EEP

- Using measured-derived PSD at EEP
- 2 methods to assess lognormality:
  - ➢ *CMD Vs. GMD (mean Vs. median)*
  - ➢ *$GSD_{PSD}$ Vs. $GSD_{VSD}$*
- Results PSD at EEP:

– Difference ≠ 0 → Generally not lognormal

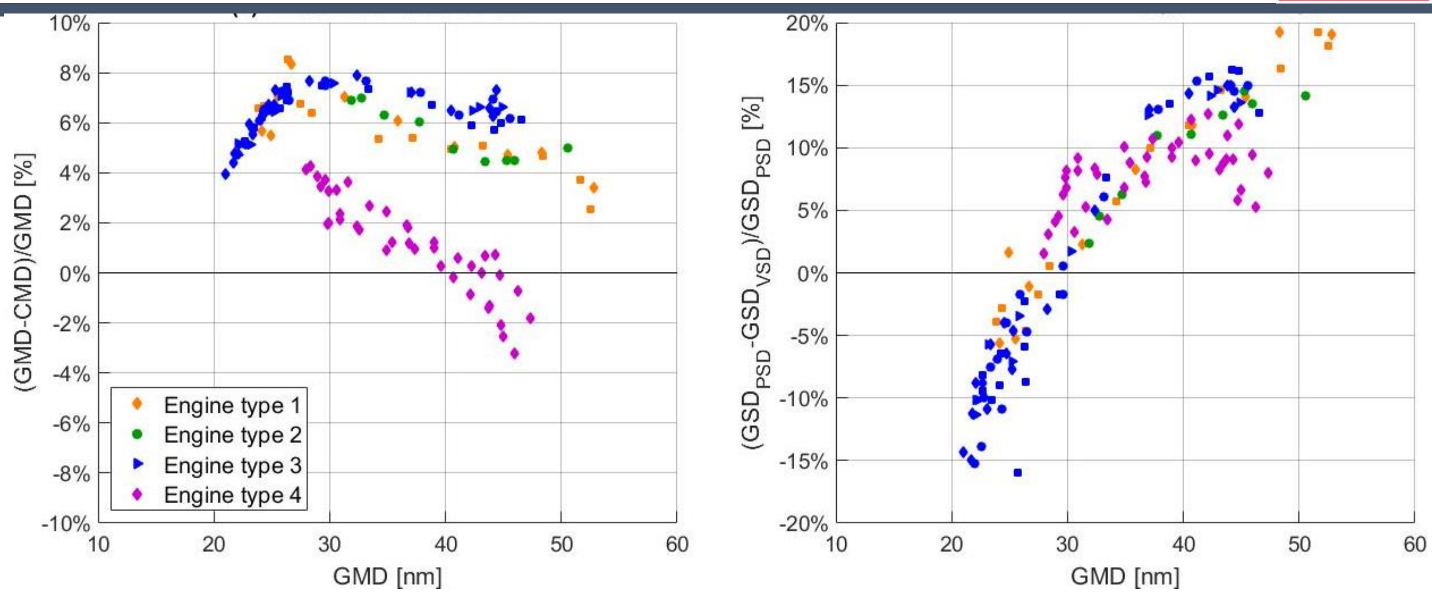
– Lognormality engine type and GMD (i.e. thrust) dependent

- Impact of SLT lognormal assumption on $k_{SL}$:

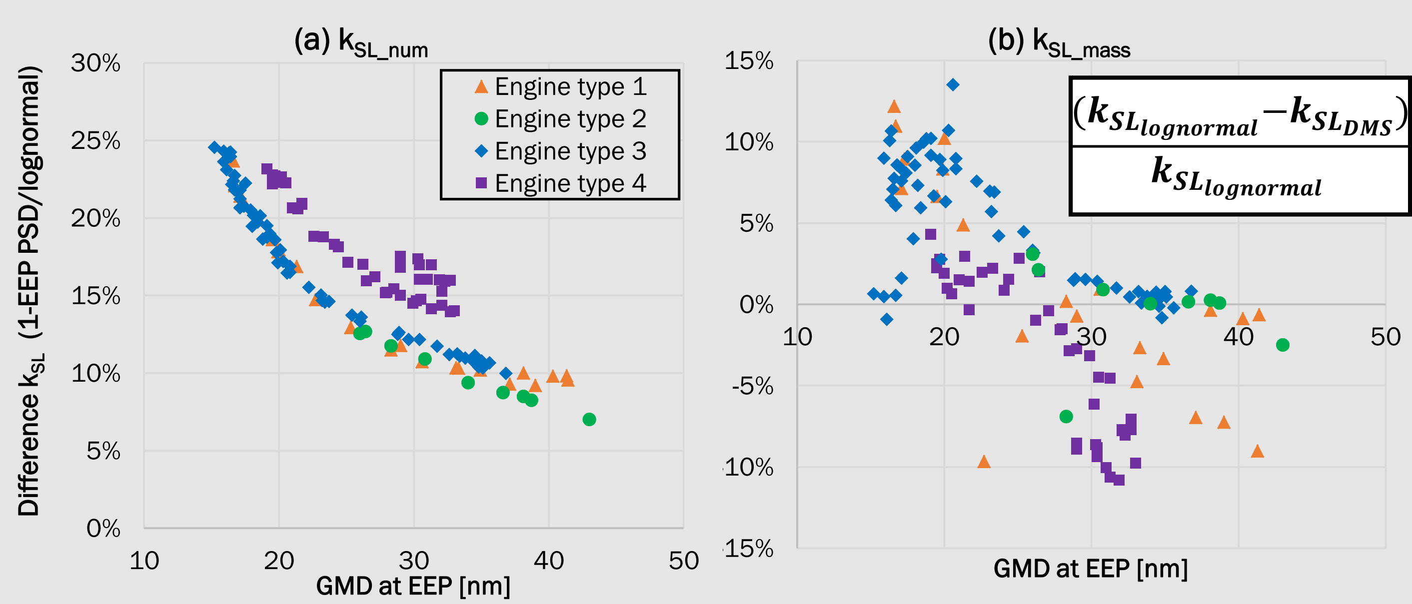
➢ Difference ≠ 0 → Lognormal assumption overpredicts $k_{SL}$ at low GMD

➢ Better agreement at larger GMDs (more lognormal, lower $k_{SL}$)

Lognormal assumption = uncertainty $k_{SL}$ (up to 25%)




**Lognormality assessment of 4 engine types at EEP**




$$\frac{(k_{SL_{lognormal}} - k_{SL_{DMS}})}{k_{SL_{lognormal}}}$$

**Uncertainty in number and mass $k_{SL}$ caused by lognormal assumption**

# Average particle effective density

- <u>Density calculation:</u>
  - nvPM mass/Total volume
  - Volume derived from DMS (number-weighted PSD ⟶ volume-weighted VSD)

$$V(d_p) = N(d_p) \times \frac{\pi d_p^3}{6}$$

- Average effective density ≠ size-dependent effective density

$$\rho_{eff}\,(avg) = \frac{nvPM\ Mass_{mi}}{total\ PM\ Volume_{PSD}}$$

- <u>Results (average effective density):</u>

– 0.3 - 0.8 $g/cm^3$ (mean: 0.56 $g/cm^3$)

– Density is engine type dependent

– Density decreases with increasing N/M ratio and decreasing GMD → density thrust dependent

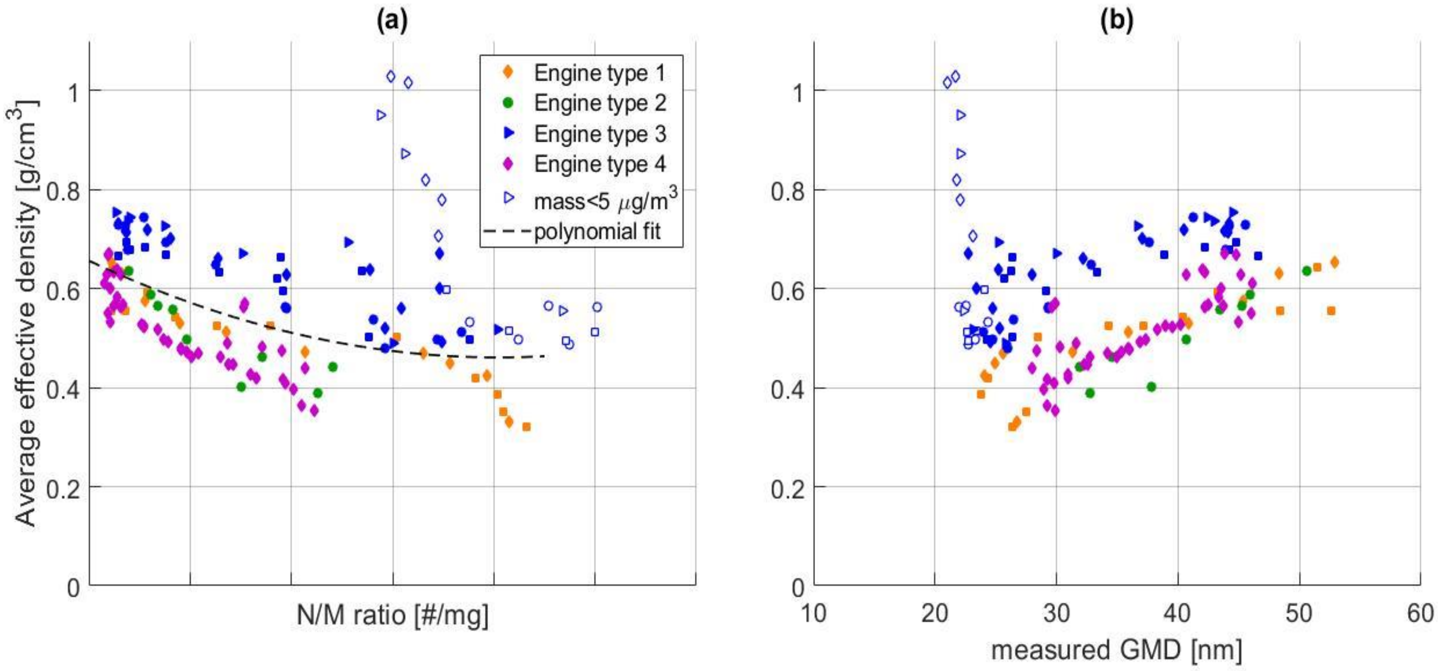
→ *Higher density with thrust (larger primary particle size)*

– Other average densities reported in the literature:

*Timko et al. 0.4-0.45 $g/cm^3$ (PW308 – JP-8 only)*

*Durdina et al. ~1 $g/cm^3$ (CFM56-7B26/3)*

*Beyersdorf et al. ~ 1.1 $g/cm^3$ (CFM56-2C1)*




<u>**Average particle effective density against N/M ratio (a) and GMD (b)**</u>

# Assessment of GSD and Density assumptions

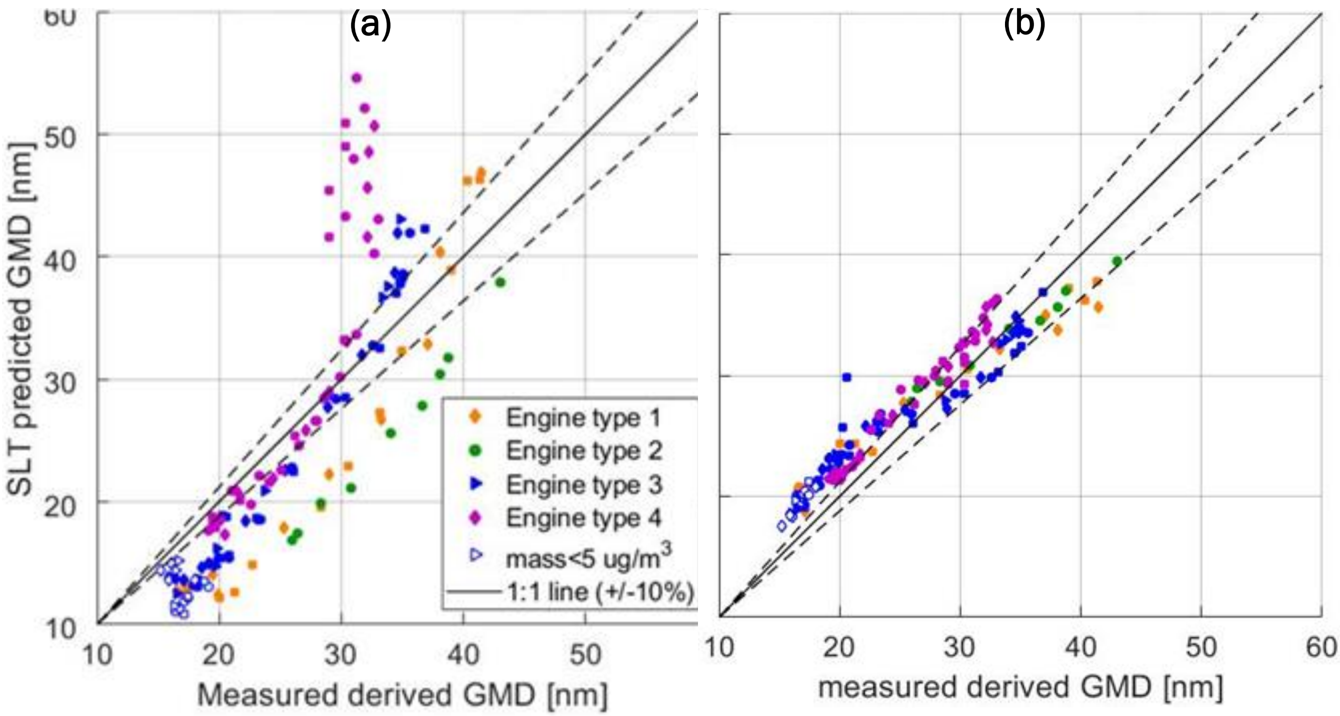
- Density and GSD impact SLT GMD predictions
- Are there better assumptions for this data?
  - Comparing GMD SLT and measured-derived GMD
  - Comparison performed at EEP

- <u>Results (GMD comparison):</u>

➢ (a) Using current GSD (1.8) and density (1 g/cm$^3$):
  - Average GMD difference: <u>19.5%</u>
  - GMD difference appears engine specific

→ *Uncertainty measured Number and Mass, variable density and GSD for 4 engine types*

➢ (b) Using measured-derived GSD and density:
  - GSD from DMS, density from total volume and nvPM mass *(previous slide)*
  - Average GMD difference: <u>9.5%</u> at EEP
  - SLT overpredicts GMD for GMD < 25 nm




<u>**Comparison between measured-derived GMD and SLT predicted GMD using default (a) or measured-derived (b) GSD and density assumptions**</u>

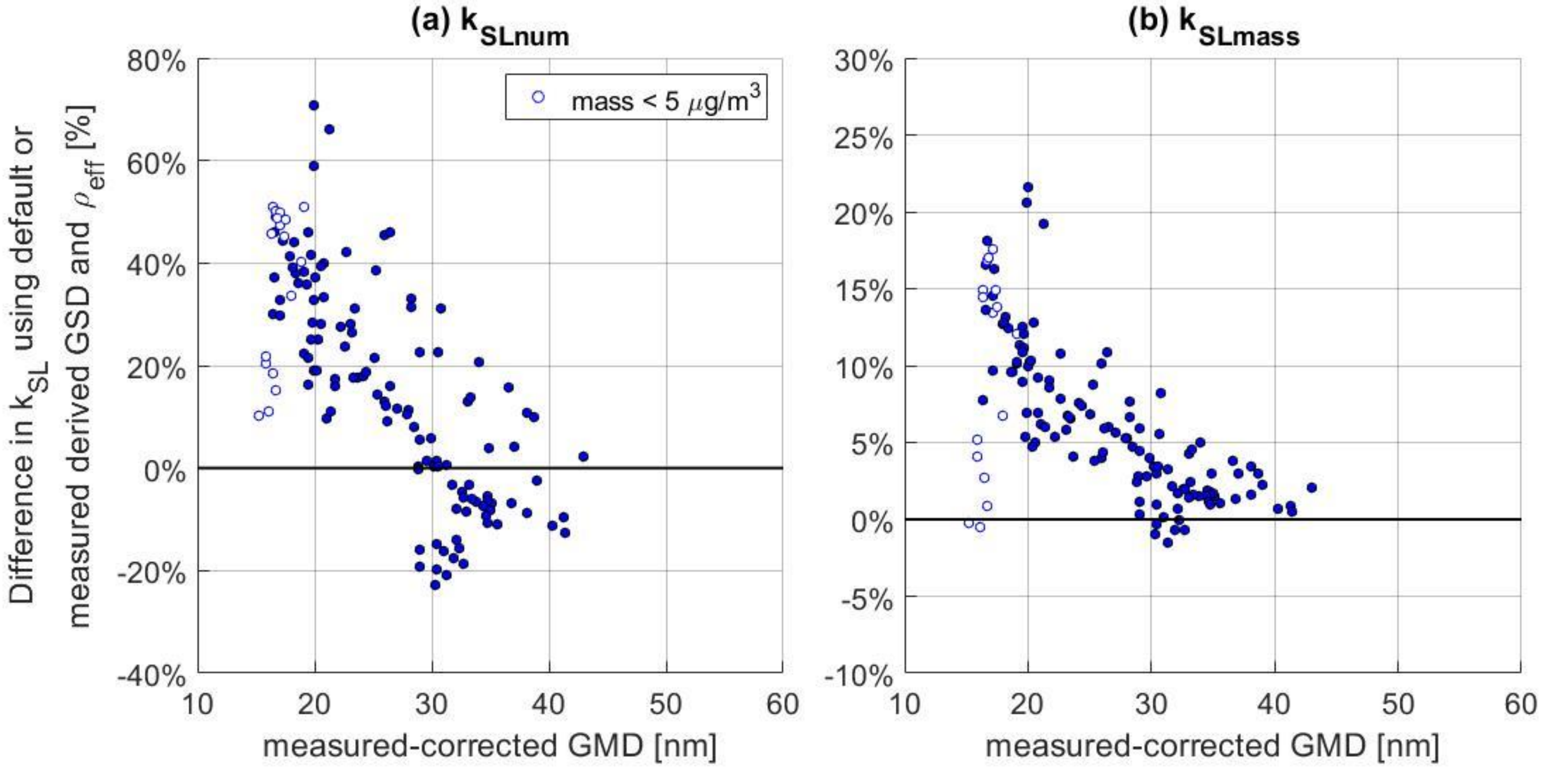
*Additional particle size measurement*

*= measured-derived GSD and density*

*= Better SLT GMD correlation*

# Uncertainty of loss correction estimation

- **Effect of density and GSD assumptions on correction factors ($k_{SL}$):**
  - At EEP $k_{SL\_num}$ 1.8 - 5.5 / $k_{SL\_mass}$ 1.1 – 1.6 *(4 engine types combined)*
  - Ratio $\frac{k_{SL_{default}} - k_{SL_{measured}}}{k_{SL_{measured}}}$ investigated *(SLT using default assumptions Vs. measured-derived)*
  - Differences up to 71% for $k_{SL\_num}$ and up to 22% for $k_{SL\_mass}$ at EEP (worse at smaller GMDs)




*SLT default assumptions (GSD:1.8 - $\rho_{eff}$=1g/cm³) generally underpredicting GMD hence overpredicting $k_{SL}$*

= uncertainty $k_{SL}$ (up to 71%)

**Difference in number (a) and mass (b) $K_{SL}$ between default and measured-derived density and GSD assumptions at the EEP**

# Conclusion

- New nvPM regulation implemented to mitigate emissions, but regulated EIs not representative of EEP concentrations
- SLT can aid to predict EIs at EEP for airport inventory, however requires lognormal, fixed GSD and constant density assumptions
- Particle size measurement removes requirement these three assumptions, improving sampling system loss correction factors

## Main Results:

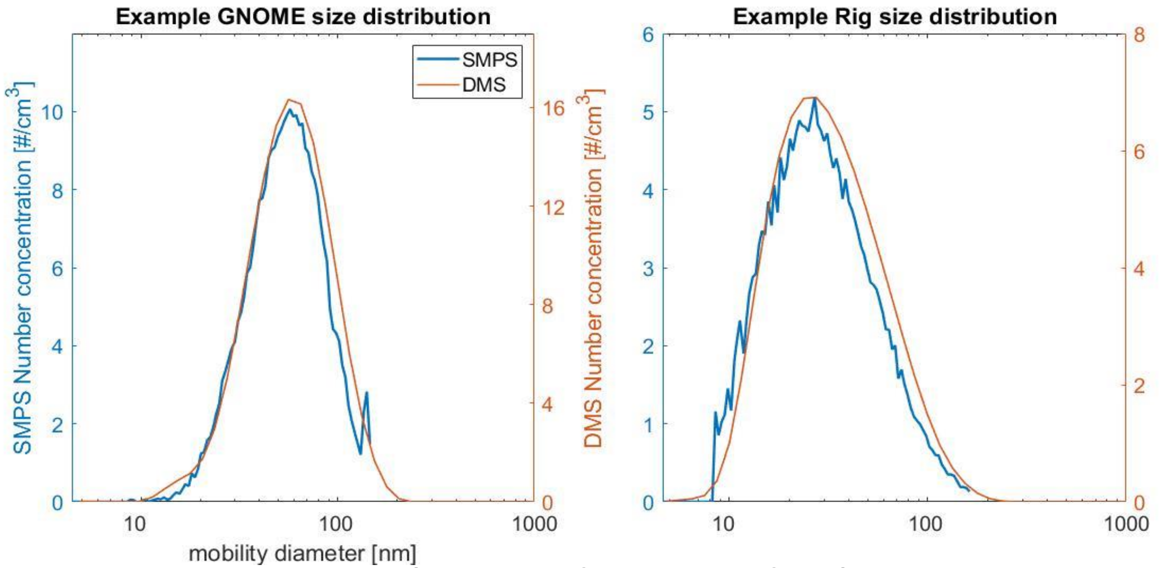
- Size distributions generally not perfectly lognormal at EEP
- 'Average' effective density ($\frac{mass}{volume}$) of 4 Rolls-Royce engine types: 0.3 - 0.8 g/cm$^3$
- SLT lognormal assumption at EEP: up to 25% added uncertainty on $k_{SL}$
- SLT Density (1 g/cm$^3$) and GSD (1.8) current assumptions: up to 71% added uncertainty on $k_{SL}$
- Size distributions may need 'tail-cutting' (left-tail PSD, right-tail VSD)

# Thank you

# Back up

## Comparison between DMS-500 and SMPS:

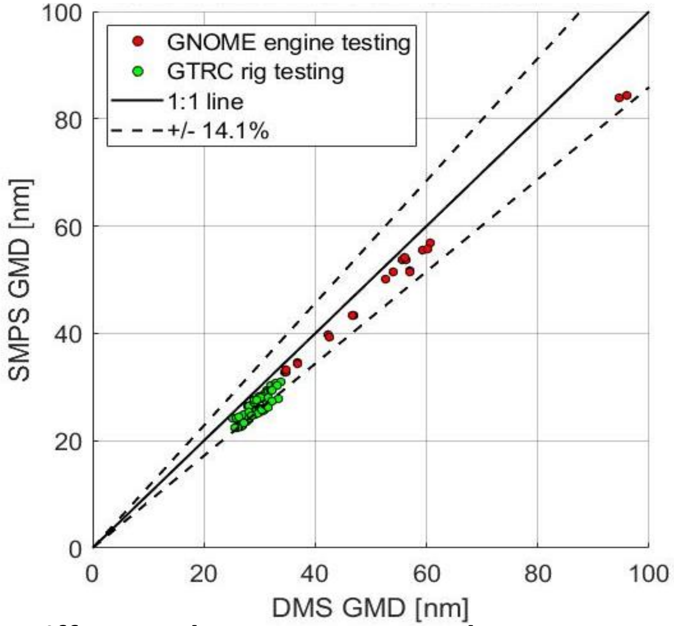
- Exhaust particles from GNOME engine and RQL rig (jet-A and alternative fuels)
  - *GMD: 30 - 90 nm*
  - *GSD: 1.4 - 1.8*
  - *$N_{tot}$: $10^5$ - $2.5x10^6$ #/$cm^3$*
- Size distribution measurements in parallel




**Example DMS and SMPS size distributions**

## Results:

- Similar shapes
- Good GMD and GSD agreement
  - $GMD_{DMS} > GMD_{SMPS}$ *3.3±1.7 nm*
  - $GSD_{DMS} > GSD_{SMPS}$ *0.04±0.03*
- $N_{DMS} > N_{SMPS}$ (≈30%)

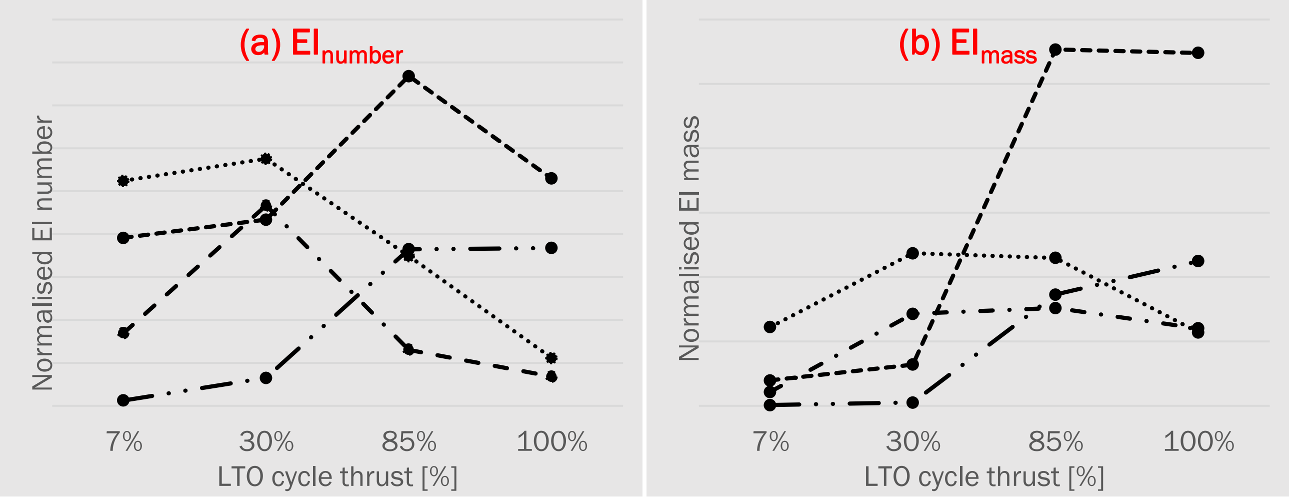



**Difference between DMS and SMPS GMD**

DMS-500 GMD and GSD (shape) reliable

# Back up

- 4 RR engine types
- nvPM Emission indices (EIs) :
  - EIs vary over 2 orders of magnitude
  - Trends are engine type dependent

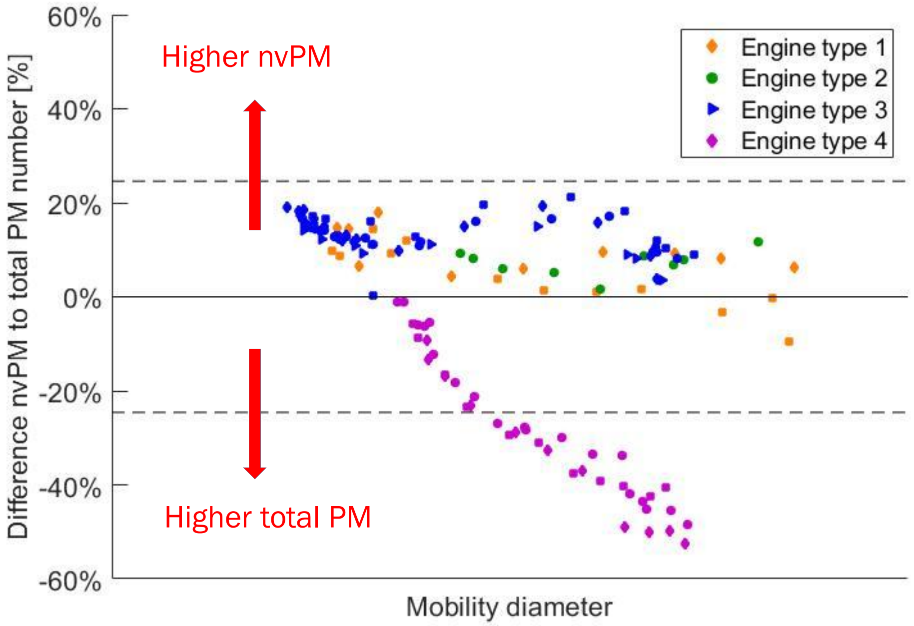



**Normalised EIs of 4 RR engine types**

- nvPM Vs. total PM number:
  - DMS-500 and CPC loss corrected to a common point
  - Good correlation for engine type 1-3 (within uncertainty bands < 24.5%)
  - Engine type 4:

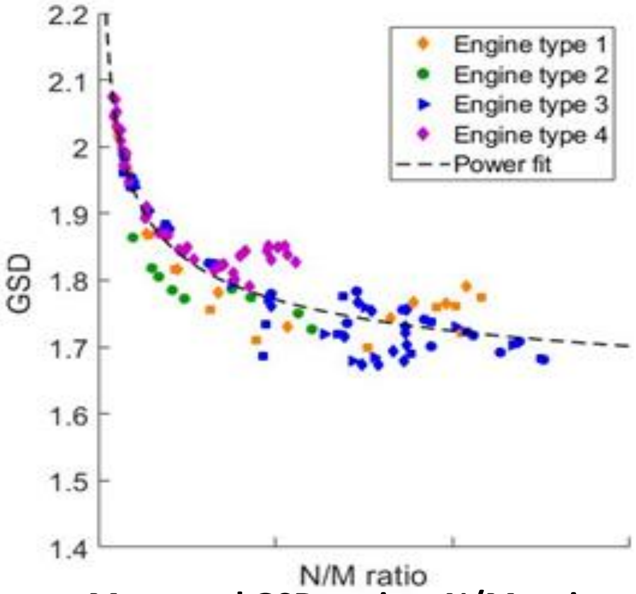
*Repeatable increase in total PM with increasing GMD (i.e. thrust)*

*Different trend observed for Engine type 4*

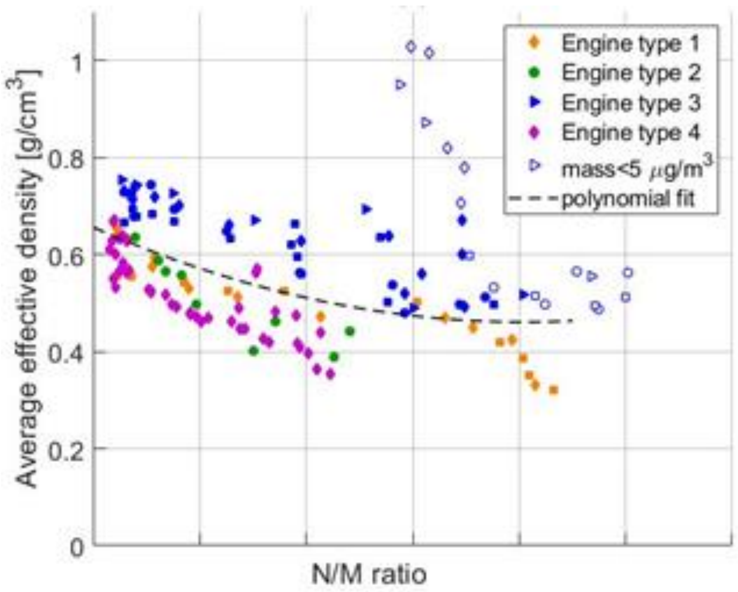



**Difference between nvPM (CPC) and total PM (DMS) number concentration**

# Assessment of System Loss Tool (5)




**Measured GSD against N/M ratio**

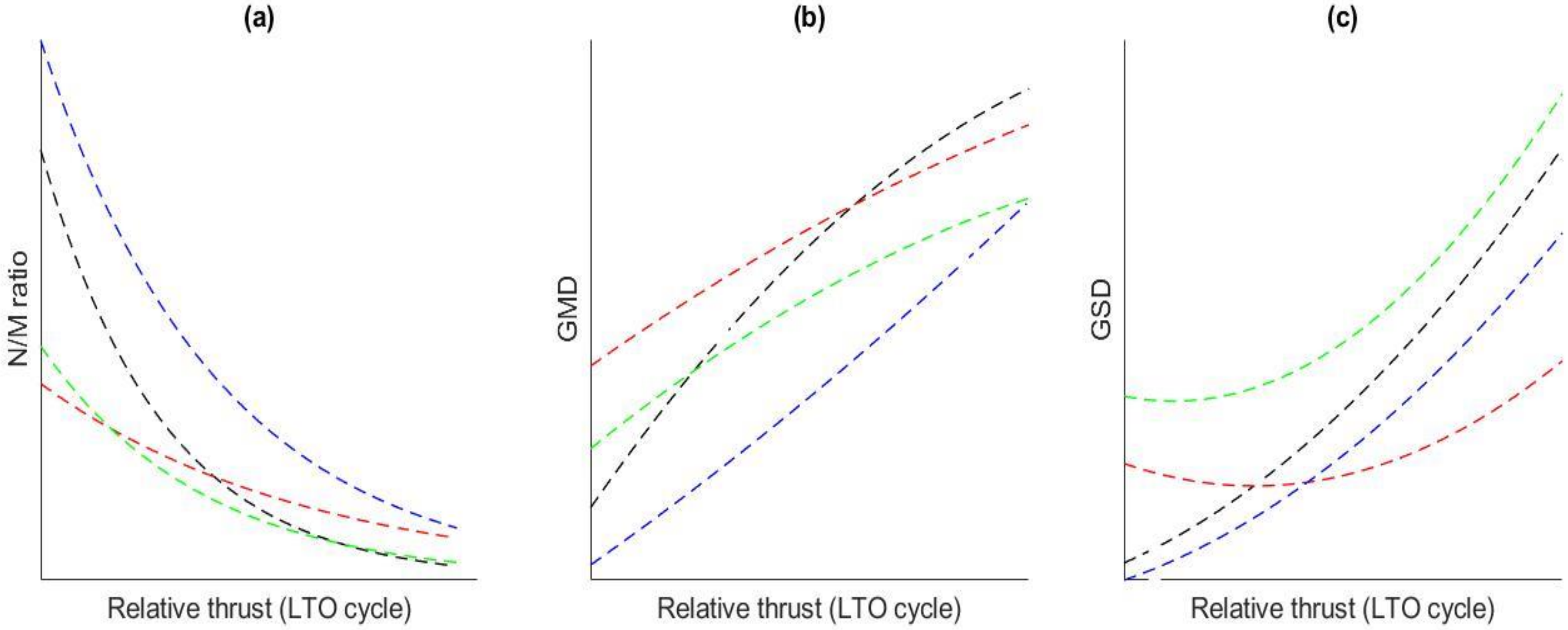



**Measured-derived density against N/M ratio**

$$GSD_{EEP}^{fit} = 2.1503 \times 10^6 \times \left(\frac{N_{meas}}{M_{meas}} \times 10^9\right)^{-0.5310} + 1.6014$$

$$\rho_{eff}^{fit}\,(avg) = 1.19 \times 10^{-28} \times \left(\frac{N_{meas}}{M_{meas}} \times 10^9\right)^2 - 9.66 \times 10^{-15} \times \left(\frac{N_{meas}}{M_{meas}} \times 10^9\right) + 0.656$$

# Back up



(a)
N/M ratio
Relative thrust (LTO cycle)
(b)
GMD
Relative thrust (LTO cycle)
(c)
GSD
Relative thrust (LTO cycle)