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Center of Excellence for Aerospace Particulate Emissions Reduction Research

Updates to System Loss Correction Model for Jet Engine Exhaust Measurement

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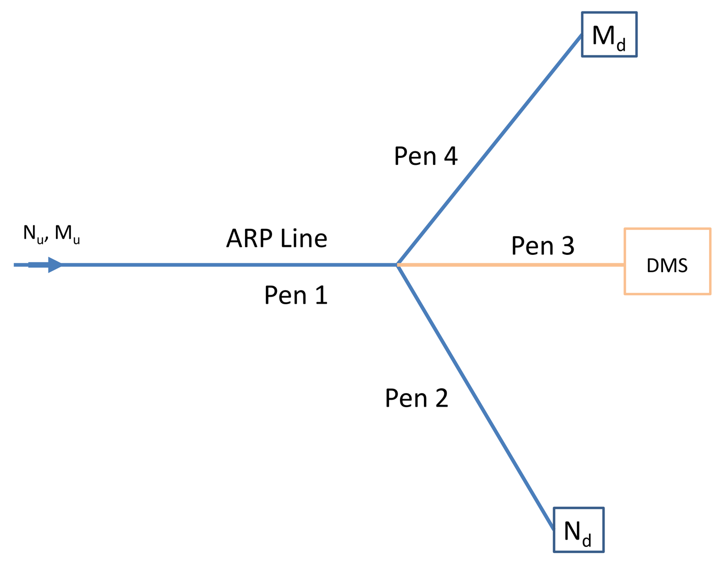


Line Loss Correction

- Measurement data: {M_d, N_d, pen1, pen2, pen4}
- $N_u = facN_{(M_d,\ N_d,\ pen)} * N_d$
- $M_u = facM_{(M_d,\ N_d,\ pen)} * M_d$

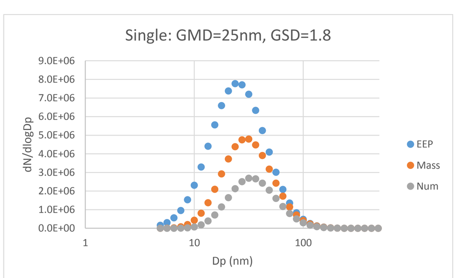
	FacN_dms			FacM_dms	
	Apride2	Apride5		Apride2	Apride5
	Dec 2011	Aug 2013		Dec 2011	Aug 2013
Min	1.39	2.31		1.18	1.06
Max	2.25	6.01		1.35	1.19
Avg	1.70	4.15		1.26	1.12
σ	0.26	1.44		0.04	0.04

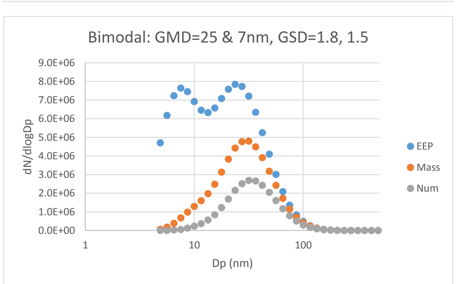
↑ No CS ↑ With CS

Engine Test Campaigns

- APRIDE 2
  - SR Technics, Zurich CH, Dec 2011
  - 3 engine types
  - Wide range of engine conditions
  - 56 test points
- APRIDE 5
  - SR Technics, Zurich CH, Aug 2013
  - 2 engine types
  - Wide range of engine conditions
  - 39 test points
  - Catalytic stripper

Sample Size Distributions





$N = \sum \Delta_i\ (dN/dlogDp)_i$

$M = (\pi\rho/6)\sum Dp_i^3 \Delta_i\ (dN/dlogDp)_i$

Sample train cuts out Dp < 10nm

With downstream size distributions, correction factors can be generated:

- Know downstream $(dN/dlogDp)_i$
- $N_{ds} = \sum \Delta_i\ (dN/dlogDp)_i$
- $N_{us} = \sum \Delta_i\ (dN/dlogDp)_i / penN_i$
- $facN = N_{us} / N_{ds}$
- $M_{ds} = (\pi\rho/6)\sum Dp_i^3 \Delta_i\ (dN/dlogDp)_i$
- $M_{us} = (\pi\rho/6)\sum Dp_i^3 \Delta_i\ (dN/dlogDp)_i / penM_i$
- $facM = M_{us} / M_{ds}$

Don't have measured size information LLC model

- Construct an upstream lognormal size distr that has the same losses as the real one, and calc line loss correction factors for it.
- Engine exhaust aerosols are generally lognormal in shape.
- Lognormal parameters: N, GMD, GSD
- $dN/dlogDp = \frac{2.30N}{\sqrt{2\pi}\, s} e^{-(lnDp - lnGMD)^2/(2\ln GSD^2)}$
  - Know GSD ~ 1.8 from many engine test campaigns
  - Need GMD, GSD

2 Parameter Method

- N, GMD, GSD ➔ $(dN/dlogDp)_m$
- $N_{dm} = \sum \Delta_i\ (dN/dlogDp)_{mi} * penN_i$
- $M_{dm} = (\pi\rho/6)\sum Dp_i^3 \Delta_i\ (dN/dlogDp)_{mi} * penM_i$
- $N_{dm} = N_d$
- $M_{dm} = M_d$
- 2 Eqs & 2 Unknowns: N, GMD
- $N_{um} = \sum \Delta_i\ (dN/dlogDp)_{mi}$
- $M_{um} = (\pi\rho/6)\sum Dp_i^3 \Delta_i\ (dN/dlogDp)_{mi}$
- $facN = N_{um} / N_{dm}$
- $facM = M_{um} / M_{dm}$
- N cancels out in correction factor calculation.

1 Parameter Method

- N=1, GMD, GSD ➔ $(dN/dlogDp)_m$
- $N_{dm} = \sum \Delta_i\ (dN/dlogDp)_{mi} * penN_i$
- $M_{dm} = (\pi\rho/6)\sum Dp_i^3 \Delta_i\ (dN/dlogDp)_{mi} * penM_i$
- $N_{dm} = N_d$
- $M_{dm}/N_{dm} = M_d/N_d$
- 1 Eq & 1 Unknowns: GMD
- $N_{um} = \sum \Delta_i\ (dN/dlogDp)_{mi}$
- $M_{um} = (\pi\rho/6)\sum Dp_i^3 \Delta_i\ (dN/dlogDp)_{mi}$
- $facN = N_{um} / N_{dm}$
- $facM = M_{um} / M_{dm}$

LLC Model Performance

- Challenge model with reasonable but hypothetical EEP aerosols
  - Know upstream dN/dlogDp, N_u, M_u.
  - Calc downstream N_d, M_d.
  - Calc true correction factors
    - $facN_{tru} = N_u/N_d$
    - $facM_{tru} = M_u/M_d$
  - Run LLC model
    - Input: N_d, M_d ➔ Output $facN_m$, $facM_m$
  - Compute model errors
    - $\delta facN_m = facN_m - facN_{tru}$
    - $\delta facM_m = facM_m - facM_{tru}$
  - Error contributions from N_d, M_d measurement not included.

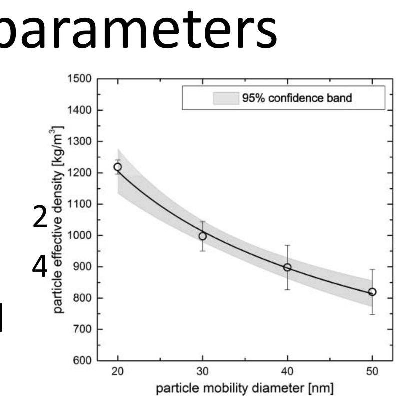
LLC Model Performance cont'd

- Challenge model with real engine test data
  - Must have size measurement data
  - Calc correction factors with the size data.
  - Calc correction factors with the LLC model.
  - Compare correction factors
- Error contributions from the model and from measurement uncertainties (e.g. N_d and M_d) are mixed together.

Challenge aerosol parameters

- ρ: ρ(x) 0.8 0.93 1.07 1.2
- GSD: 1.6 1.73 1.87 2
- Nratio: 0 0.5 1 1.5 2
- GMD1: 10 12 15 21.5 4
- GMD2: GMD1*[0.75+(sqrt(2)/2)*ln(GSD)]
  - ➢ GMD1*[0.5+sqrt(2)*ln(GSD)]
  - ➢ GMD1*[0.25+(3*sqrt(2)/2)*ln(GSD)]
  - ➢ GMD1*2*sqrt(2)*ln(GSD)

Example GMD2s for GMD1= 21.5			
23.3	25	26.8	28.6



Contribution of mode 1 is down by factor $1/e^2$ at mode 2.

Yields ~ 2100 test cases

Uncertainty assumptions

- $\delta N_{meas,ran} = 2\%$
- $\delta N_{meas,sys} = 10\%$
- $\delta M_{meas,ran} = 7\%$
- $\delta M_{meas,sys} = 15\%$
- $\delta pen\%_{ran} = 18.57/exp(0.445 * x_{nm})$
- $\delta pen\%_{sys} = 1.6703 * ln(x_{nm}) - 8.5177$

Global uncertainty weighted average errors:

- <|εfacN%|> = 6.7 ± 0.1
- <|εfacM%|> = 0.8 ± 0.1

(No contribution from N and M measurement uncertainties)

Experimental Test LLC model vs Size-based corrections

- 16 Data Sets
- 1386 Test points
- <εfacN%> < 20
- <εfacM%> < 4

Conclusion

- facN and facM corrections are important.
- Line Loss Correction model works well in generating number and mass correction factors to be used in estimating upstream number and mass concentrations.
- One parameter solution is more stable than the two parameter solution.
- Average correction factor error for number is <20%, for mass is <4%.

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