A COMPARISON OF AEROSOL INSTRUMENTS TO REGULATED PM/PN EMISSIONS FROM GDI AND PFI VEHICLES

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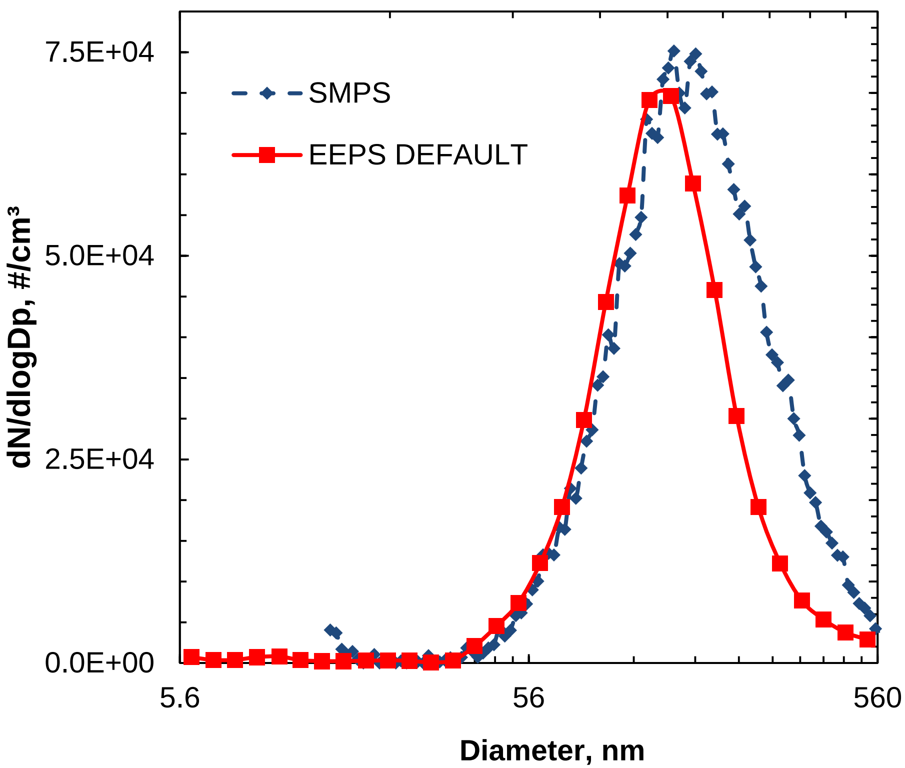
20th ETH-Conference on Combustion Generated Nanoparticles
June 13–16, 2016
at ETH Zentrum, Zürich, Switzerland

UNDERSTANDING, ACCELERATED

Research and Advanced Engineering

Background and Motivation



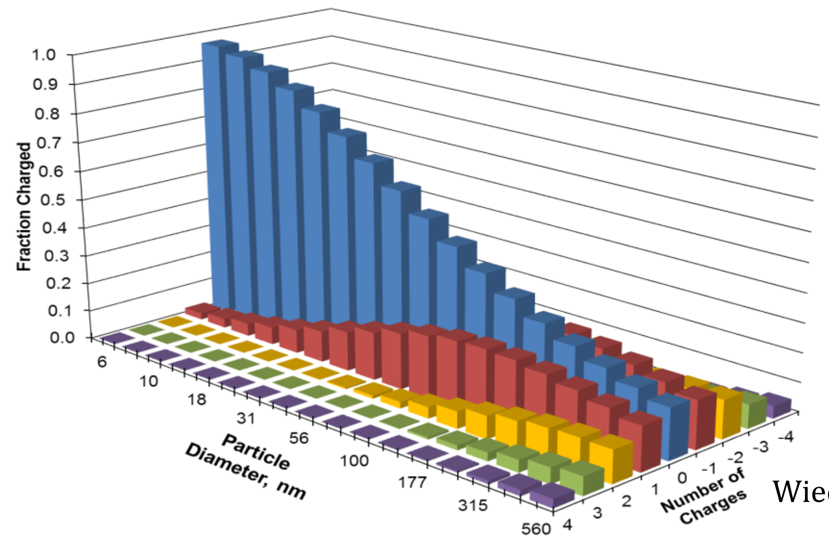
- Discrepancies have been reported between data collected by EEPS (and FMPS) and SMPS
  - Jeong and Evans 2009; Asbach et al., 2009; Zimmerman et al., 2014; and others.
- In general, particles larger than ~80 nm are undersized by EEPS using "Default" matrix
- Resulting in:
  - Narrower size distribution
  - Smaller mean diameter
  - Reduced concentration of large particles (large particle "roll off")
- Solution: New instrument matrices- empirically calibrated

Difference in measurement principle is cause for discrepancy

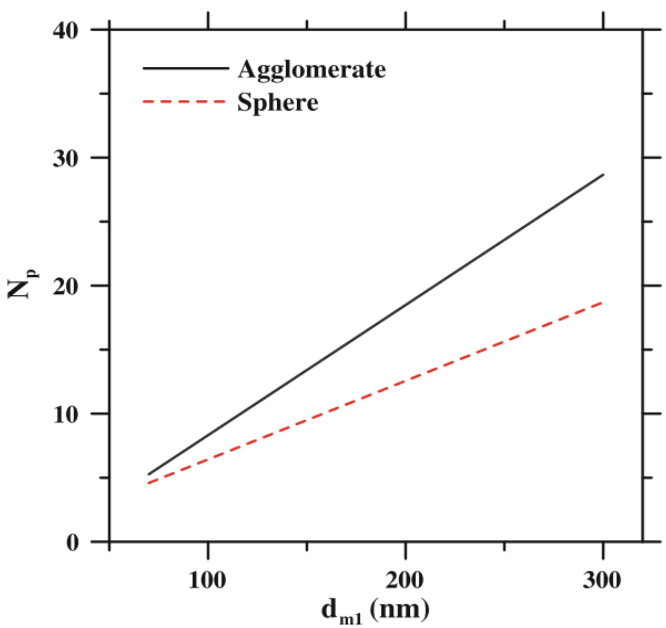
- SMPS: Bipolar neutralizer- morphology independent
- EEPS: Unipolar charger- higher charge state, morphology dependent
  - Unipolar charger necessary to achieve electrometer signal above background noise
  - Particle morphology dependent charging characteristics complicate charge state to particle size correlations
  - Challenge: distinguishing large particles with more charges from small particles with fewer charges

Bipolar versus unipolar charging

<u>Bipolar</u>
+ Used in SMPS
+ Dominated by ion diffusion
+ Largely independent of particle morphology
+ **Predictable**



Wiedensohler (1988)



<u>Unipolar</u>
+ higher charge than bipolar
+ ion diffusion *and* electrostatic forces
+ **morphology dependent**
  - surface area
  - capacitance
  - Agglomerates ~30% more charge[1,2]
+ steady-state charge **unpredictable**

[1]Oh H, et al. AST. 2004 [2]Awasthi A, et al. Mapan – J. Metrology Soc. India. 2013
[2]Biskos et al. (2005) paper "Description and Theoretical Analysis of a Differential Mobility Spectrometer" in AS&T 39: 527–541

Summary of alternative EEPS inversion matrices

- Two new matrices developed by TSI and Xiaoliang Wang of Desert Research Institute (DRI) with the help of the University of Minnesota Center for Diesel Research (CDR)
  - **Developed by empirically calibrating EEPS to SMPS**
- "Soot" matrix for agglomerates like engine exhaust
- "Compact" matrix for compact (near spherical) aerosols
- "Default" matrix developed in 2004 by Aadu Mirme of Tartu University
  - Based on theoretical and experimental data from different aerosol types

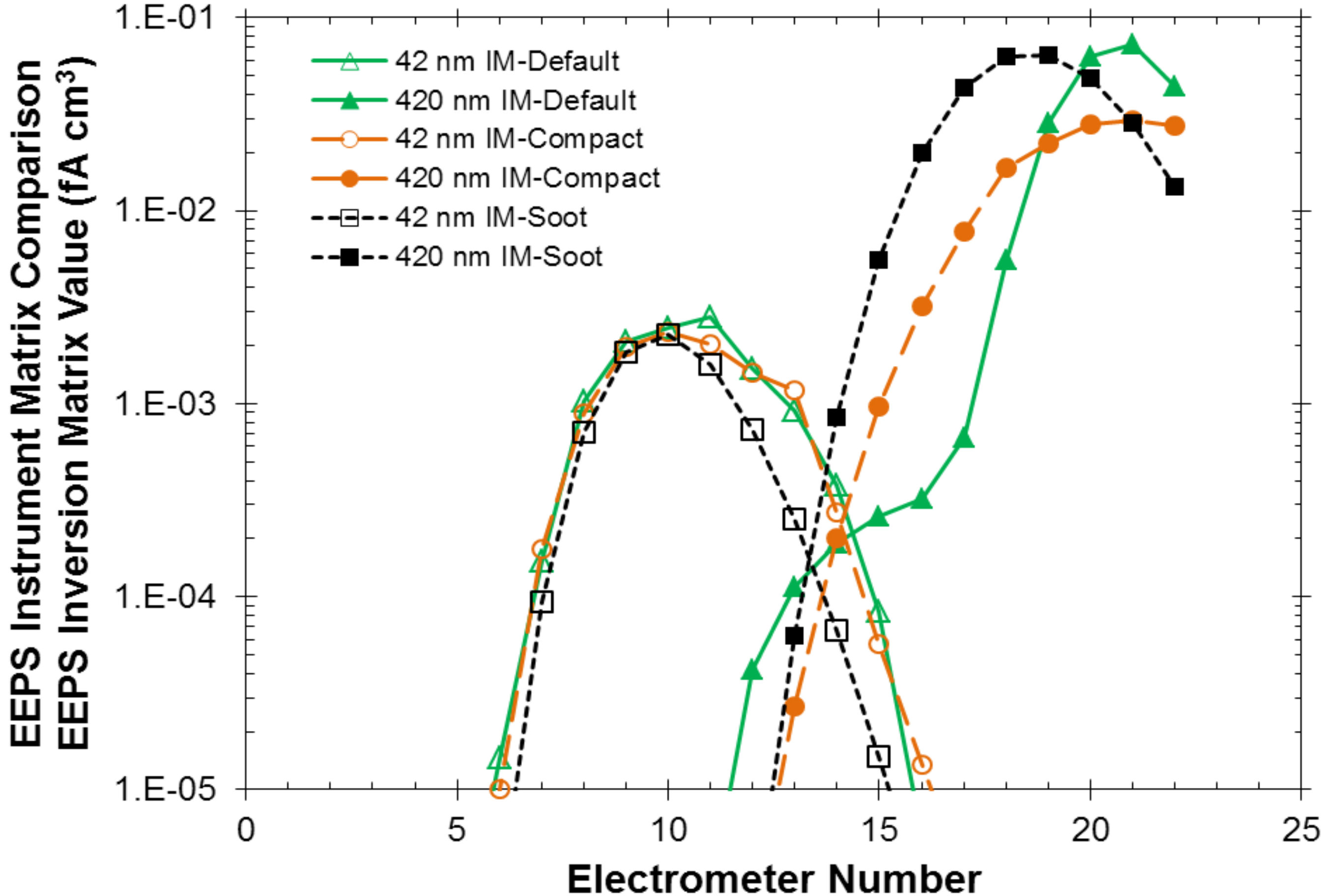
Development of EEPS matrices

1. Polydisperse aerosol generated
2. Monodisperse aerosol classified at EEPS primary channel diameters
3. Aerosol simultaneously measured with EEPS, SMPS, and CPC
4. EEPS data corrected for multiple charges
5. Inversion matrix, $H_{j,i}$ is determined.

$$I_j = H_{j,i} f_i + u_j$$

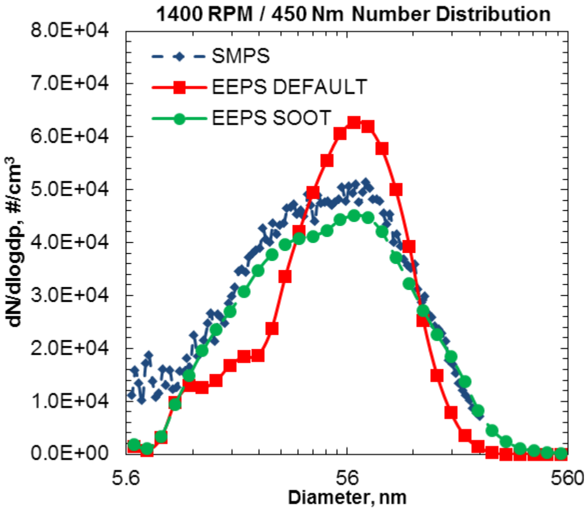
Inversion matrix, $H_{j,I}$ relates particle size distribution, f_i to electrometer currents, I_j and offsets, u_j .

Comparison of Instrument matrices

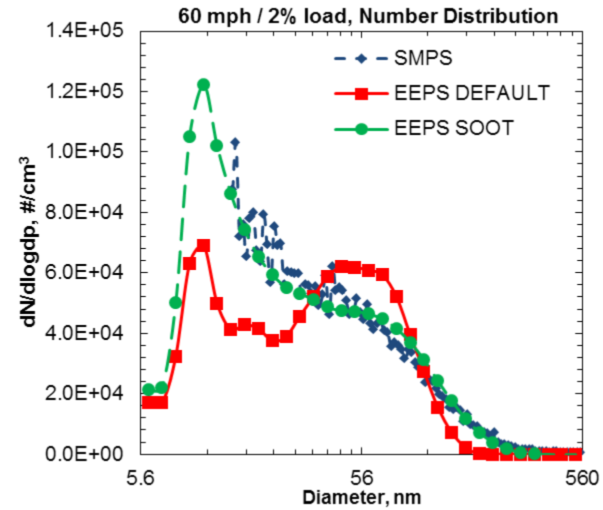


SMPS and EEPS with Soot Matrix

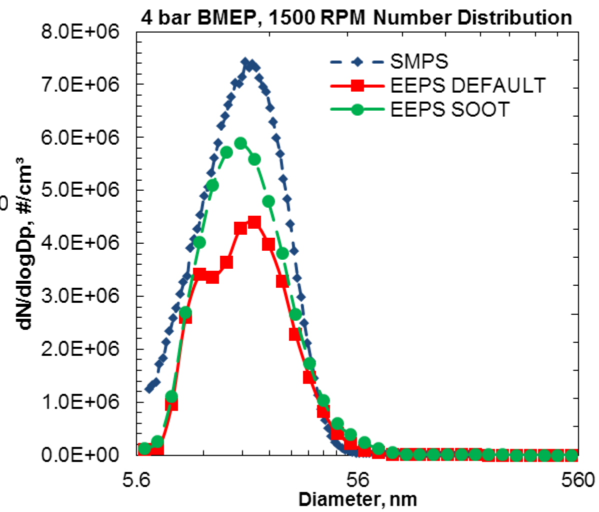
Heavy-duty diesel engine



GDI vehicle



Light-duty diesel engine

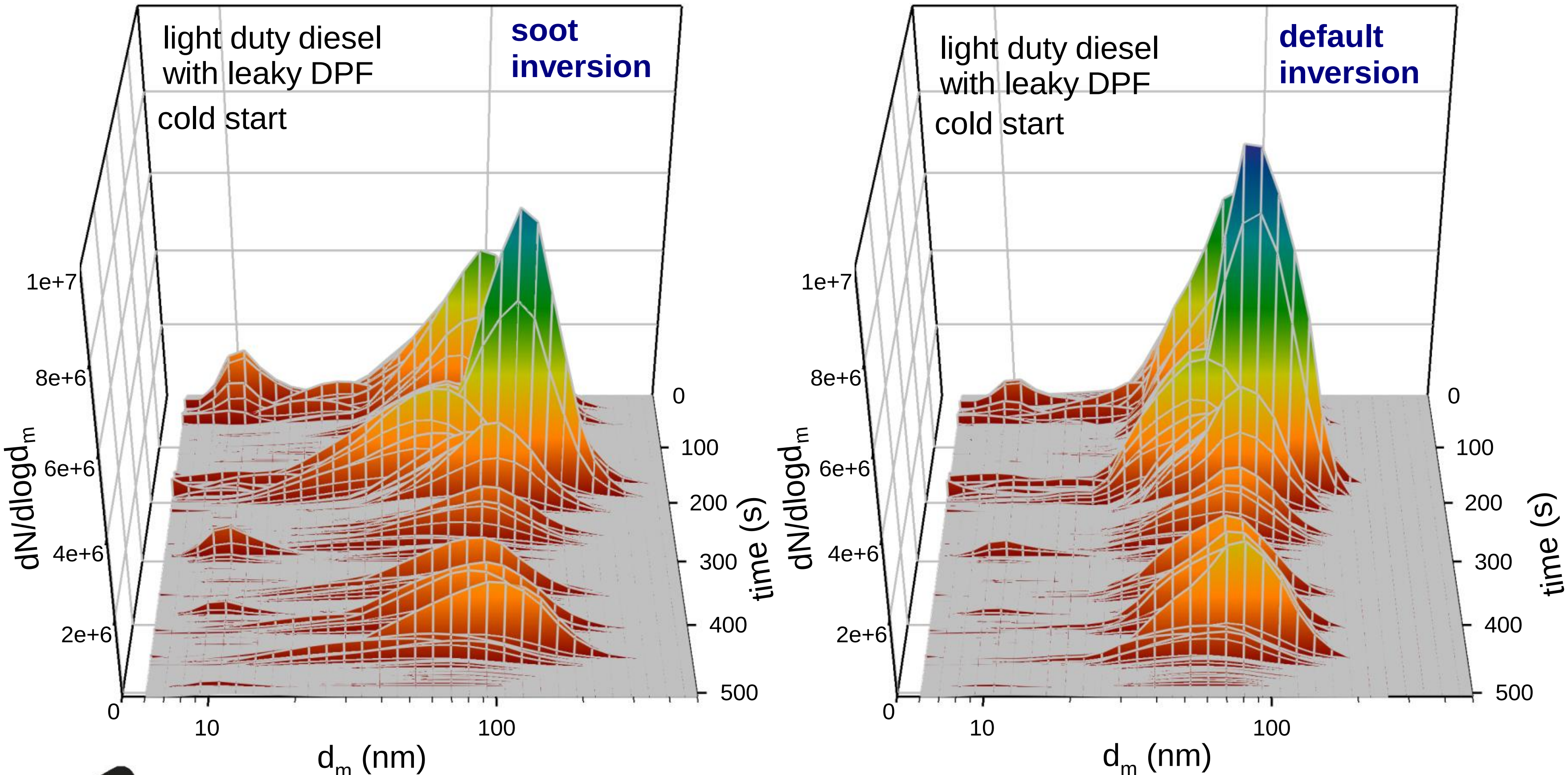


+ Soot Matrix Particle size distributions compare well to GDI vehicle, light duty diesel engine or heavy duty diesel engine

Wang, X. et al. , J. Aerosol Sci., 2016

Soot inversion results in broader accumulation mode

- Soot GSD =1.64 (agrees better with literature)
- Default GSD = 1.52
- Small shift in GMD
- Particle number is largely unaffected

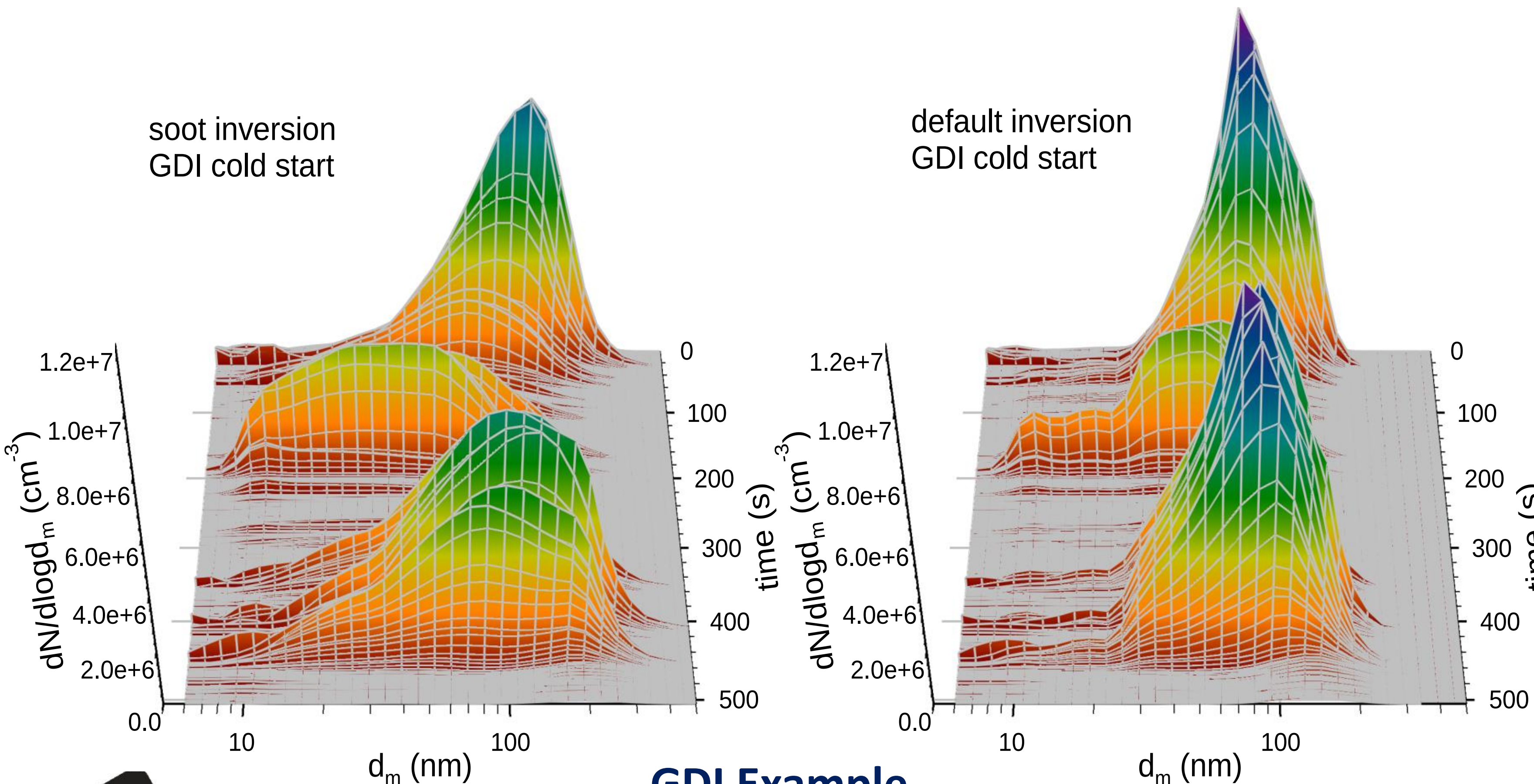


Diesel Example

Measured from CVS tunnel

Soot inversion impact is same for GDI exhaust PM

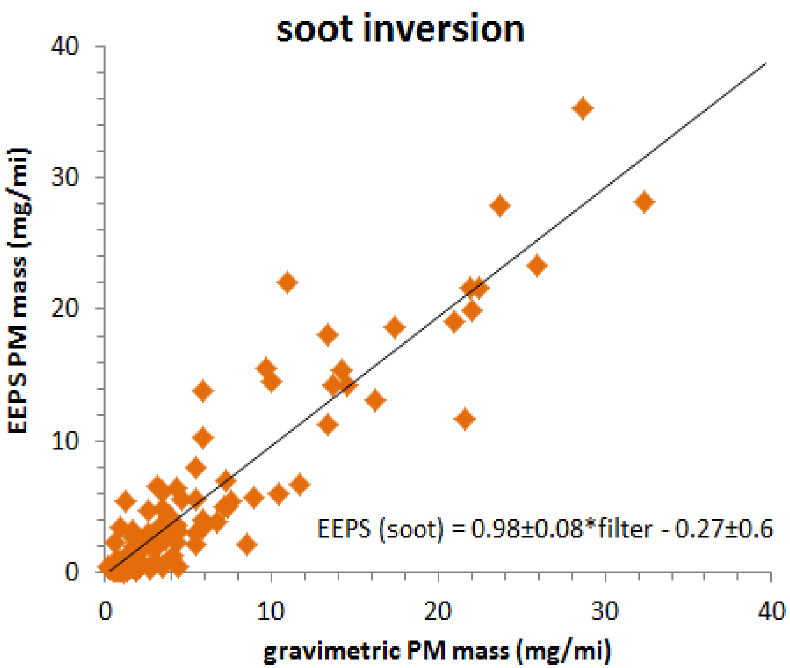
+ Soot GSD =1.9 (consistent with SMPS)
+ Default GSD = 1.6
+ GMD and particle number largely unaffected

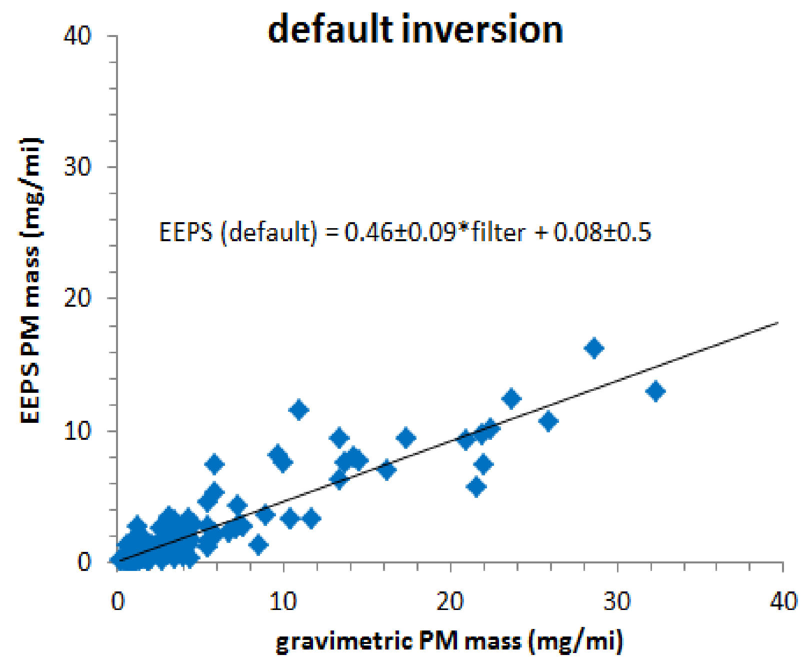


GDI Example

Measured from CVS tunnel

PM mass from EEPS vs gravimetric filter method

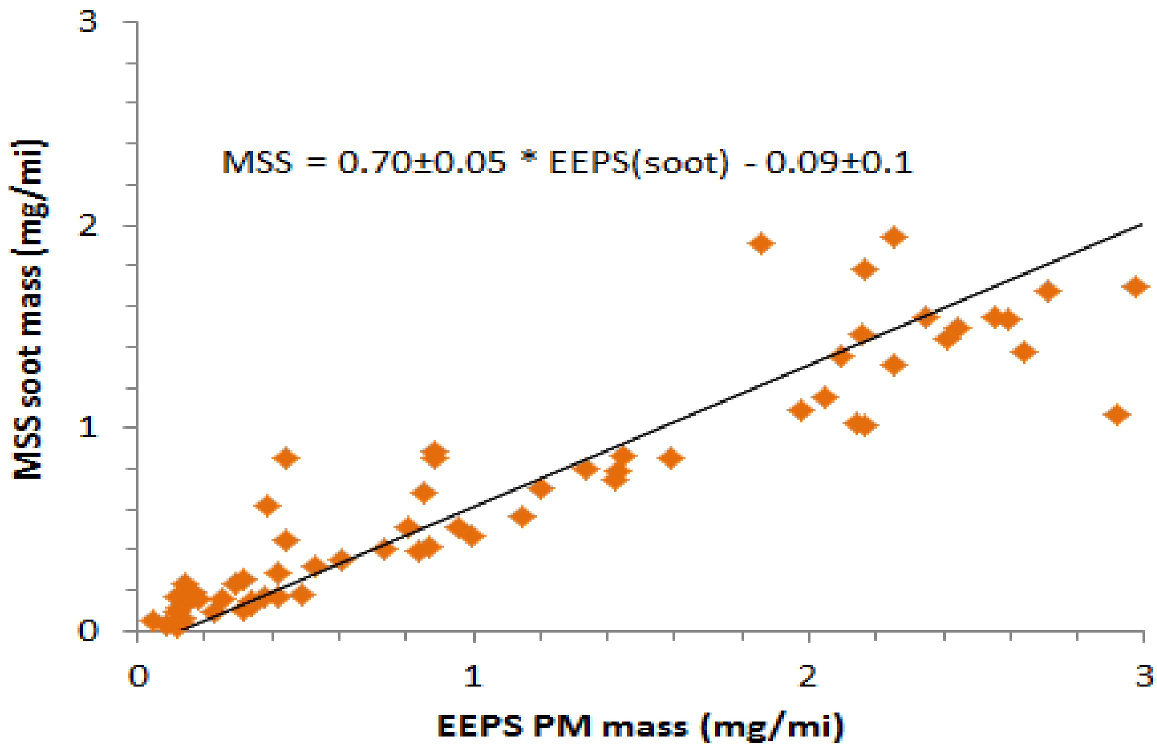




- 6 GDI development vehicles run over FTP cycle
- Effective density – $D_F = 2.3$, $r_0 = 2$, $d_0 = 20$ nm
- Average dilution of ~20 is not optimized for LEV III / Tier 3 levels

PM mass from EEPS vs Micro Soot Sensor

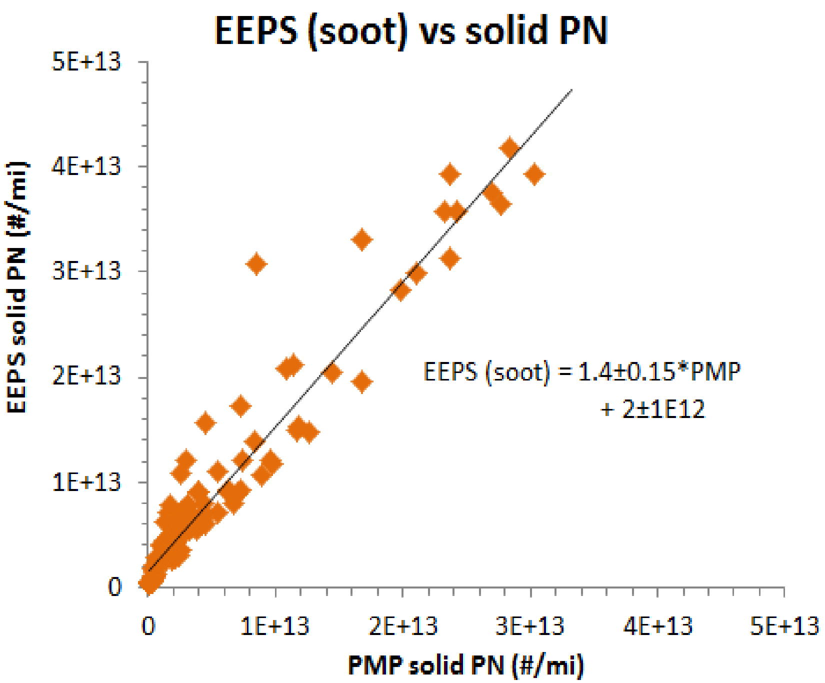
EEPS mass calculated from integrated size distribution and effective density

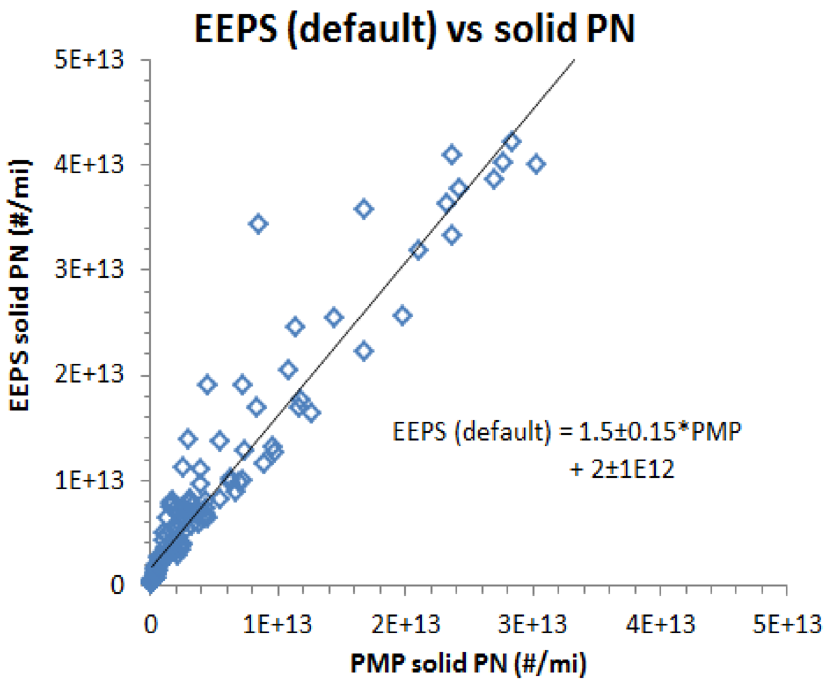


+ ~70% correlation to Micro Soot mass continues to below 1 mg/mi.
+ Consistent with EC/OC measurements

Solid particle number from EEPS vs PMP method

EEPS solid PN calculated by bimodal fit, fraction of accumulation mode above 23nm





+ Likely explanation for 40% overestimate is that some accumulation particles are mostly liquid.

Conclusions

- New matrices developed for EEPS measurement of agglomerated particles based on empirical inversion.
- New inversion agrees well with SMPS and literature data, resulting in broader size distributions relative to default
- PM mass results with good correlation to gravimetric through integrated size distribution and mass mobility exponent of 2.3 for effective density
- Solid particle number from accumulation mode is high by ~40%, likely from some being mostly liquid
- Second-by-second capability of EEPS very useful for engine research, e.g. to investigate new combustion modes, cold start strategies, fuel effects, etc

Acknowledgements

+ FORD -Joseph J. Szente, Amy L. Harwell, Michael J. Loos M.
+ TSI - Melissa Grose
+ DRI - Xiaoliang Wang
+ Univ. of Minnesota - David Kittelson, Mark Stolzenburg
+ UC Riverside - He-Jung Jung, Tom Durbin, Kent Johnson
+ CARB – David Quiros, Tao Huai, Alberto Ayala
+ SWRI –Imad Khalek

Other references

+ Matti Maricq, Joseph J. Szente, Amy L. Harwell & Michael J. Loos: How well can aerosol instruments measure particulate mass and solid particle number in engine exhaust? Aerosol Science and Technology, Volume 50, Issue 6, 2016, pages 605-614
+ Wang, X.L.; Grose, M.A.; Avenido, A.; Stolzenburg, M.R.; Caldow, R.; Osmondson, B.L.; Chow, J.C.; Watson, J.G. (2015a). Improvement of Engine Exhaust Particle Sizer (EEPS) Size Distribution Measurement - I. Algorithm and Applications to Compact Aerosols. Journal of Aerosol Science. 2016.
+ Wang, X.L.; Grose, M.A.; Caldow, R.; Osmondson, B.L.; Swanson, J.J.; Chow, J.C.; Watson, J.G.; Kittelson, D.B.; Li, Y.; Xue, J.; Jung, H.; Hu, S. (2015b). Improvement of Engine Exhaust Particle Sizer (EEPS) Size Distribution Measurement - II. Engine Exhaust Aerosols. Journal of Aerosol Science. 2016.
+ Xue J, Li Y, Wang X, Durbin TD, Johnson KC, Karavalakis G, Asa-Awuku A, Villela M, Quiros D, Hu S, et al. Comparison of vehicle exhaust particle size distributions measured by SMPS and EEPS during steady-state conditions. Aerosol Science and Technology. 2015.
+ Xue J, Li Y, Wang X, Durbin TD, Johnson KC, Karavalakis G, Quiros D, Hu S, Huai T, Ayala A, et al. Measuring particle mass emission from light-duty vehicles over a transient cycle using integrated particle size distribution (IPSD) method. Env.Science and Technology. 2015.

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