Effective Density and IPSD Measurements of solid PM from a Lean and Stoichiometric GDI Engine Operating on Ethanol Blends

Weiqi Chen, Noah Bock, Will Northrop, David Kittelson
Department of Mechanical Engineering

25th ETH-Conference on Combustion Generated Nanoparticles
June 21-23, 2022, online

Outline

- Introduction
- Effective Density
- Size Distributions
- Solid Particle Number and MSS Black Carbon Mass
- Integrated Particle Size Distribution (IPSD) Mass vs Black Carbon Mass
- Summary

Introduction

- Gasoline direct injection (GDI) engines are being widely adapted for light-duty vehicles
  - Increased power output
  - Higher efficiency
  - Reduced CO_2 emissions
- But GDI engines produce higher levels of PM and PN, especially lean burn engines
- Lean burn GDI
  - **Higher efficiency – approaching Diesel**
  - More difficult to control NOx emissions
  - May have higher PM, PN emissions
  - Limited applications in Japan , Europe
  - Not used in US – stoichiometric burn only

Engine and fuels

Table 1. Engine specifications.	
Model Number	BMW N43B20
Displacement (cc)	1995
Bore x Stroke (mm)	84 x 90
Compression Ratio	12:1
Rated Power (kW)	125 @ 6700 rpm
Rated Torque (Nm)	210 @ 4250 rpm
Induction	Naturally Aspirated
Injection	Central Spray Guided Piezo
Max Rail Pressure (bar)	200

Table 2. Fuel specifications.

Fuel	Aromatics (%)	T90 (°C)	EtOH (%)	RON/MON (AKI)
E10 (Baseline)	27	162	9.9	96.2/85.4 (90.8)
E30	21	-	30	-
E50	15	-	50	-

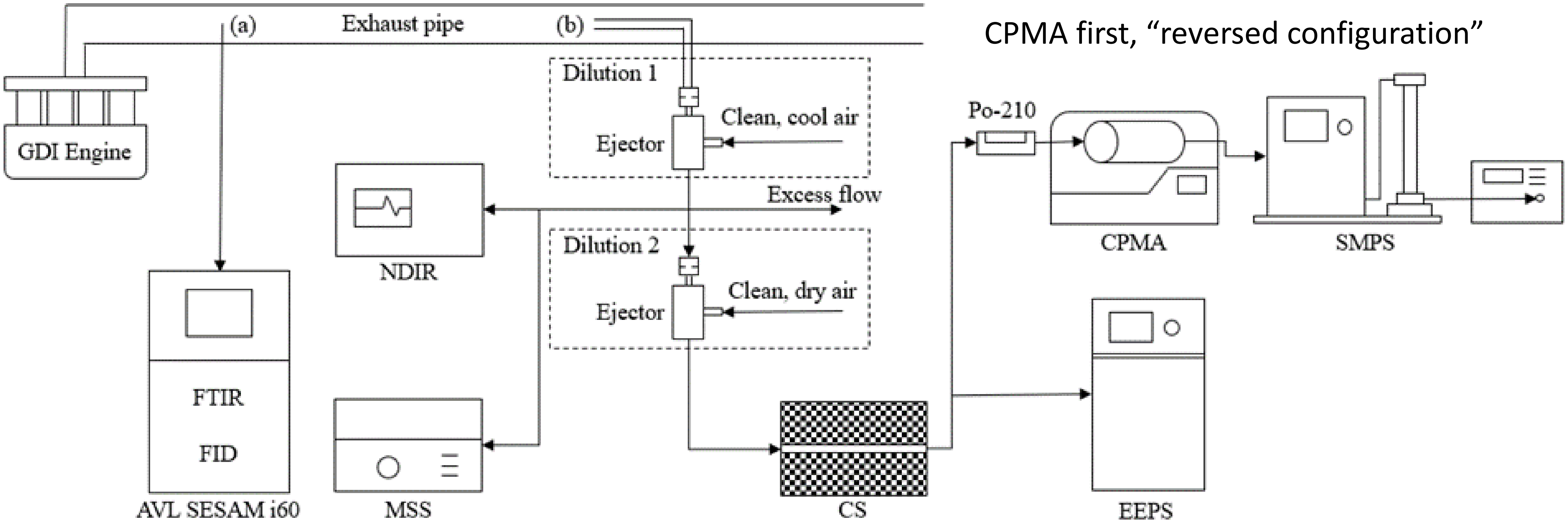
Table 3. Engine testing conditions: S=stoichiometric; LH=Lean homogeneous; LS=lean stratified

Speed (RPM)	BMEP (bar)	Mode	Fuel-air equivalence ratio
2000	7	S	1
2000	7	LH	0.69
2000	4	LS	0.65

Instruments

- Particle size distributions
  - TSI EEPS (5.6 to 560 nm) using soot inversion matrix
  - Catalytic stripper to remove semi-volatile particles
- Black carbon – AVL Micro Soot Sensor
- Effective density –
  - Cambustion CPMA – TSI SMPS so called “reversed” method much faster
  - TSI DMA – CPMA – CPC – traditional method validation check
- Solid particle mass and number by integrated particle size distribution (IPSD) method

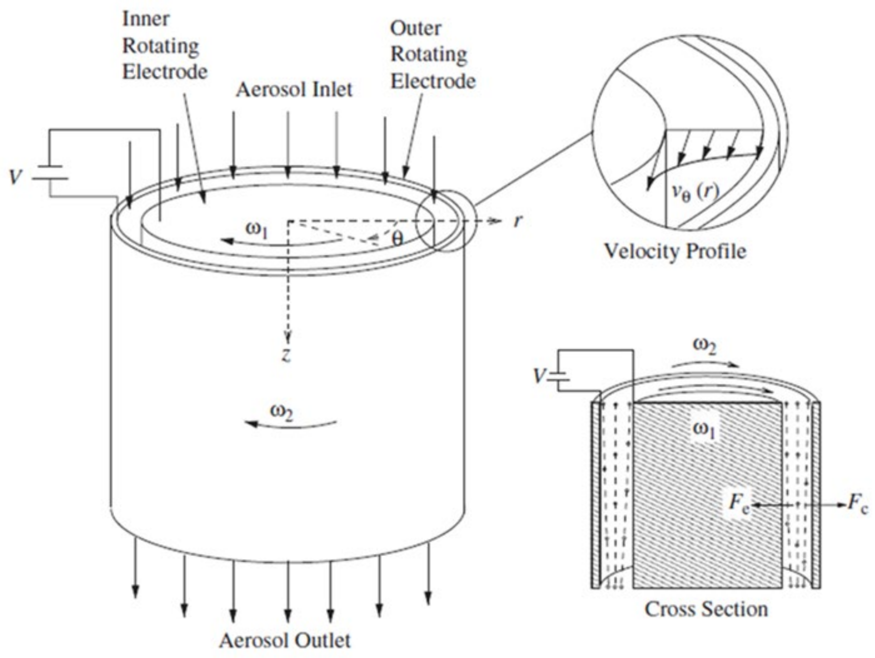
Experimental Setup



CPMA first, "reversed configuration"

Effective density and IPSD mass

- CPMA mass, m, and DMA mobility diameter, dm, used to find effective density.
- EEPS size distribution and effective density distribution used to find integrated size distribution (IPSD) mass



Adapted from Olfert, et al., JAS 37 (2006) 1840-1852

$$mr\omega^2 = qE = \frac{N_q eV}{r\ln\left(\frac{r_o}{r_i}\right)}$$

$$\frac{m}{N_q} = \frac{eV}{r^2\omega^2\ln\left(\frac{r_o}{r_i}\right)}$$

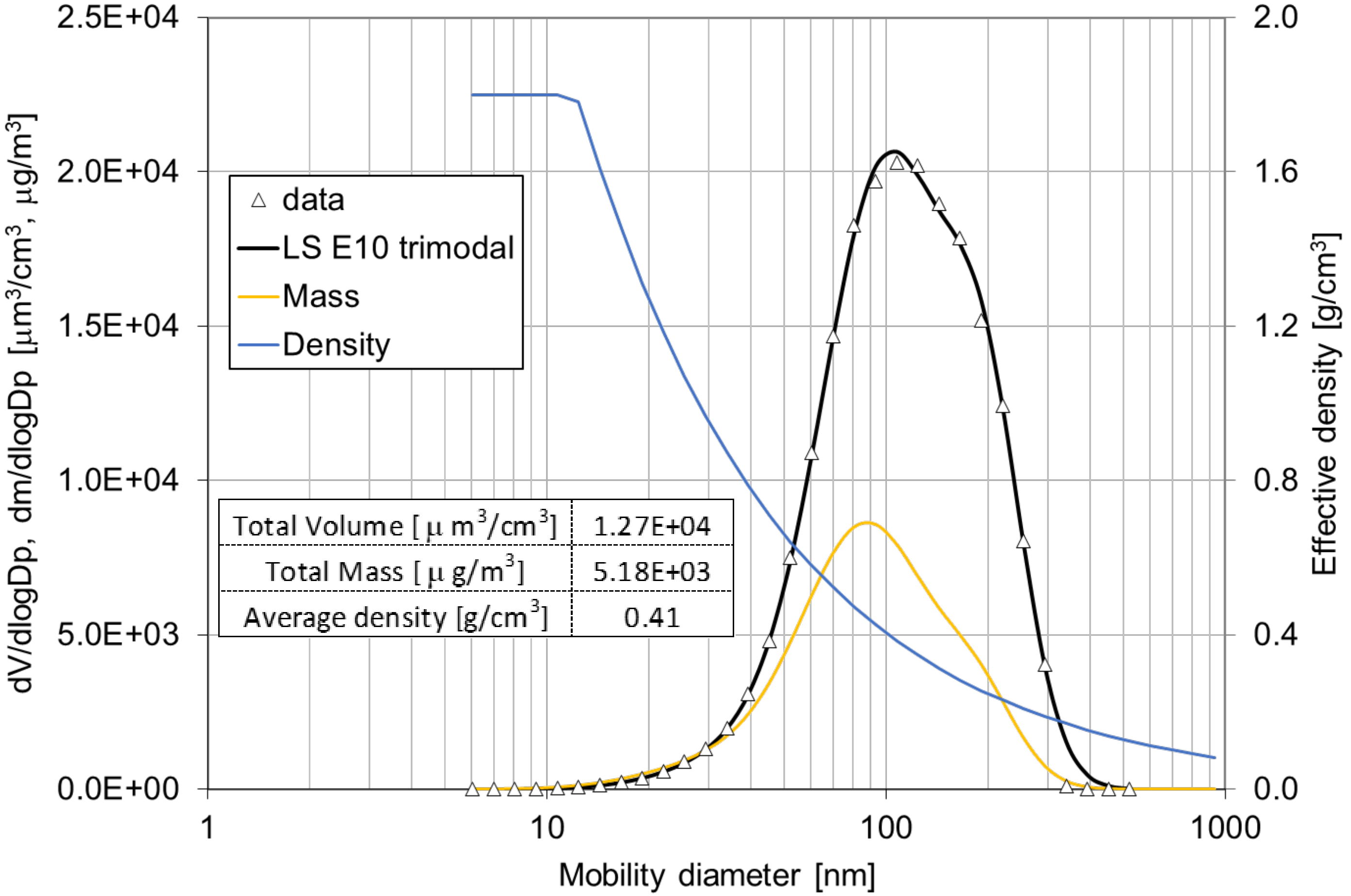
$$m = kd_m^{Dmm}$$

$$\rho_{eff} = \frac{m}{\pi\frac{d_m^3}{6}} = \frac{6k}{\pi}d_m^{(Dmm-3)}$$

$$\frac{dV(d_m)}{dLog(d_m)} = \frac{dN(d_m)}{dLog(d_m)}\frac{\pi(d_m)^3}{6}$$

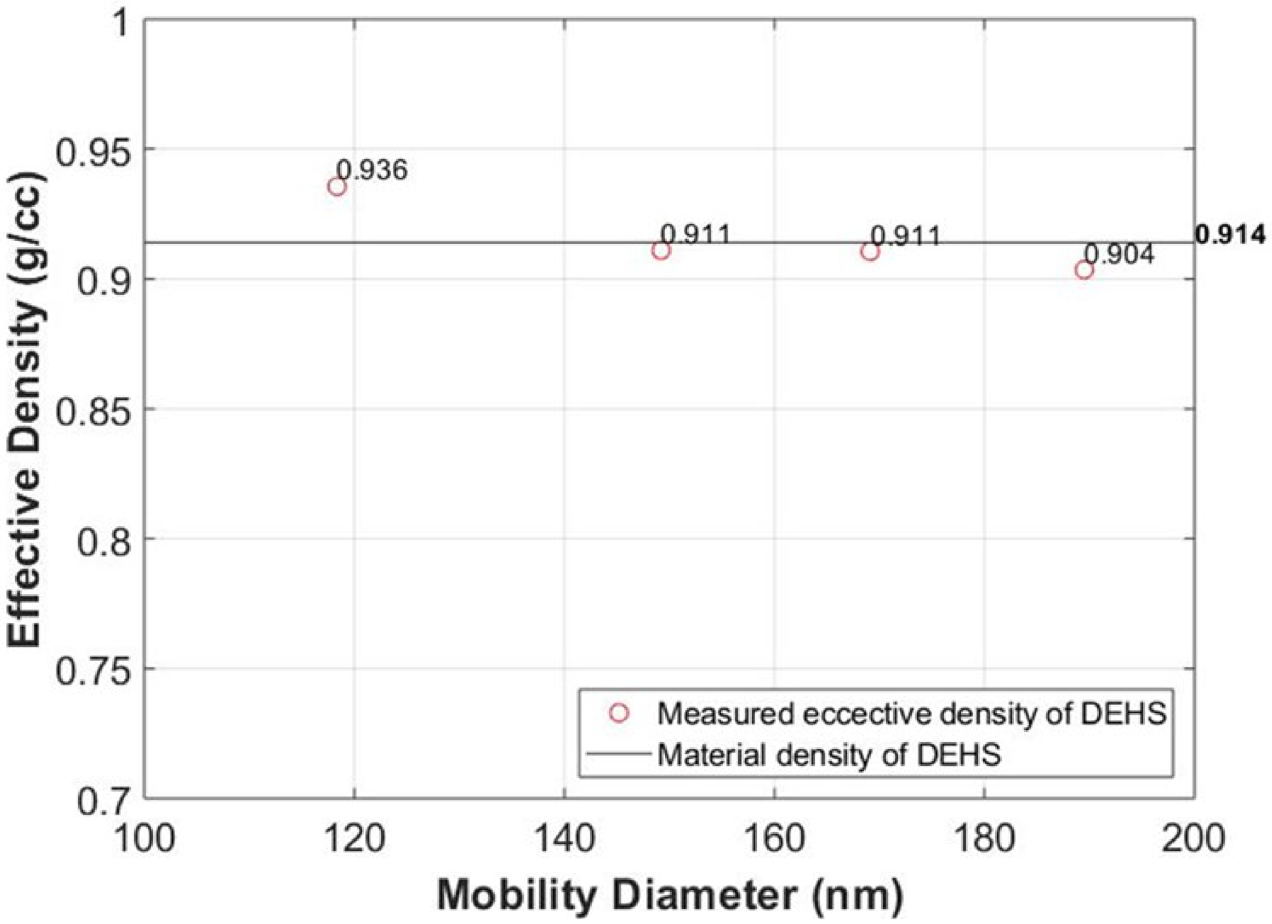
$$IPSD(mass) = \int \rho_{eff}(d_m)\frac{dV(d_m)}{dLog(d_m)}dLog(d_m)$$

Example of IPSD method – integrate the product of volume and density across the size distribution



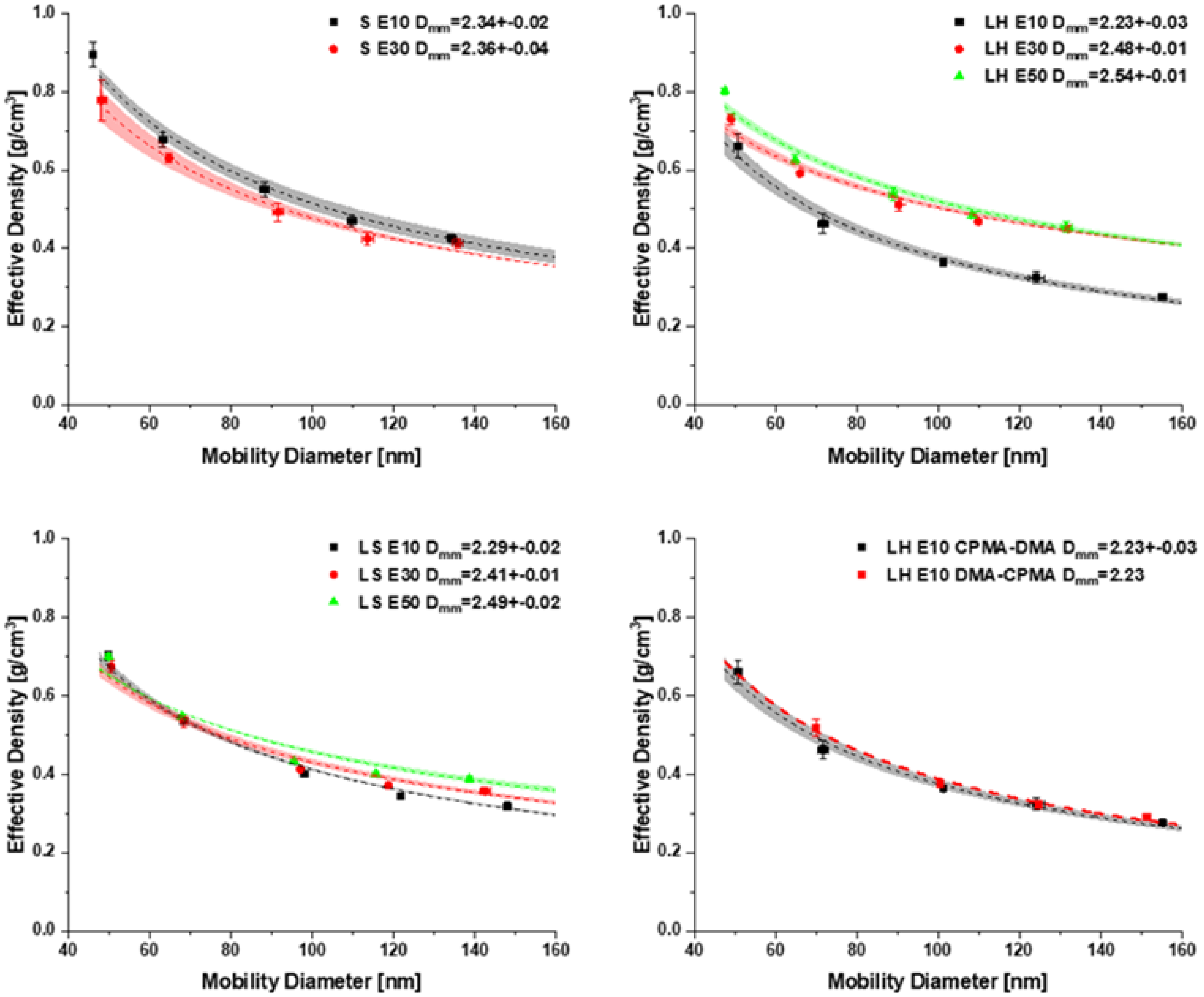
Calibration

- CMPA and DMA calibrated against 100, 125, 152, 203 nm polystyrene latex (PSL) spheres
- Calibration checked by measuring density of Di-Ethyl-Hexyl-Sebacat (DEHS) particles, $\rho = 0.914$ g/cm^3
- Apparent density increase at smaller size due to evaporation



Effective densities of non-volatile soot particles

- Fuels: E10, E30, E50
- S=stoichiometric 2000 RPM 7bar BMEP
- LH=Lean homogenous 2000 RPM 7bar BMEP
- LS=lean stratified 2000 RPM 4bar BMEP
- Shaded areas uncertainty bands
- CPMA-SMPS and DMA-CPMA-CPC configurations, ***lower right panel***, agree within experimental error (± 3 %)



Summary of Effective Density Measurements for GDI Engines

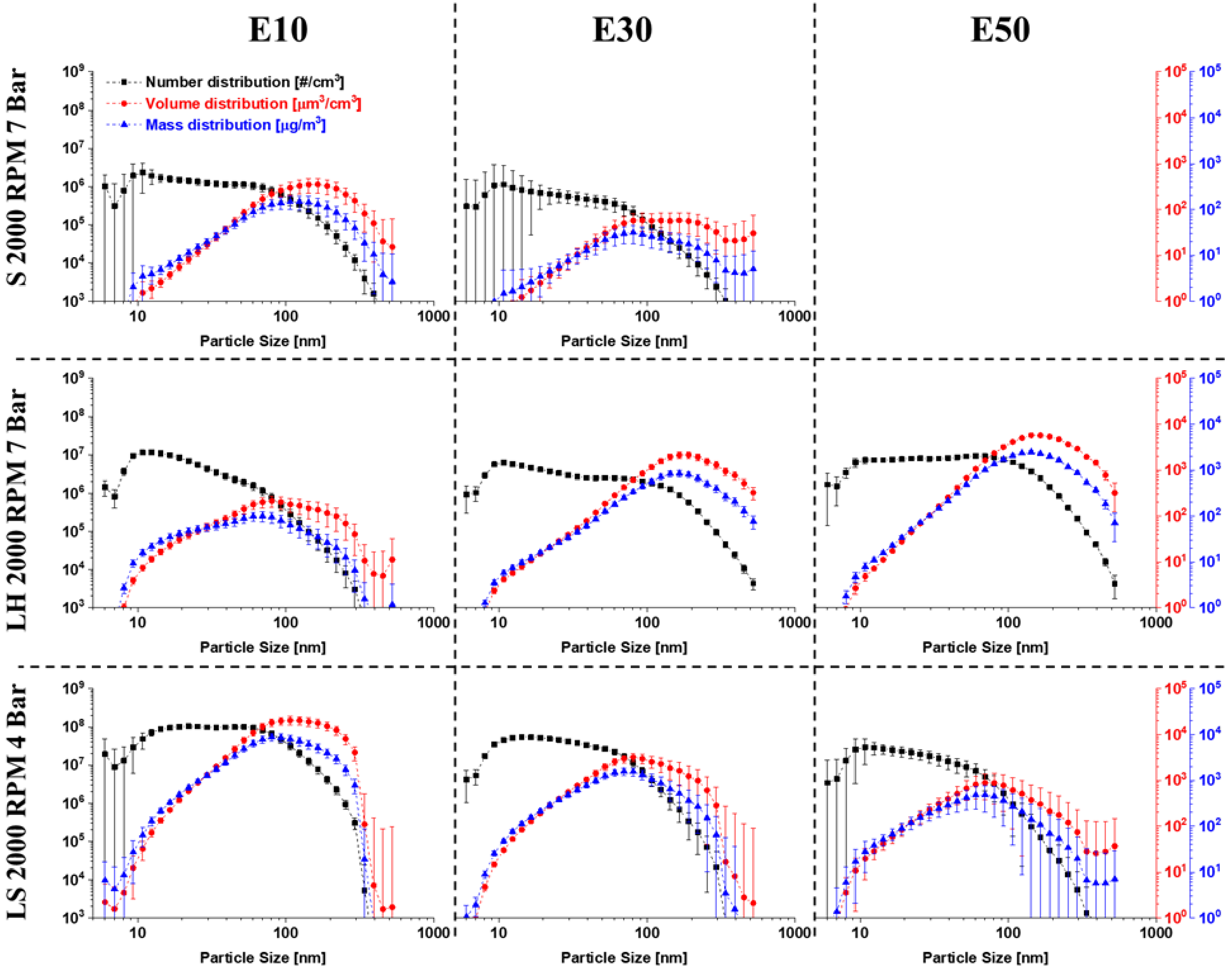
Study	Condition	Aftertreatment	Sample treatment	Method	Fuel	Constant	D_{mm}	D_p [nm]	rho [g/cm^3]
Graves et al., 2017 [24] , 1 engine, engine dyno	Average of Idle, 4%, 13%, 26%	3-way cat	Thermal denuder	DMA-CPMA	E0	5.22	2.49	100	0.50
	Average of Idle, 4%, 13%, 26%				E10	5.54	2.48	100	0.51
	Average of Idle, 4%, 13%, 26%				E50	5.95	2.43	100	0.43
Quiros et al., 2015 [31] , 2 vehicles, chassis dyno	Average moderate load	3-way cat	None	DMA-CPMA	E10	6.00	2.45	100	0.48
	Average high load				E10	14.00	2.30	100	0.56
Momenimovahed and Olfert, 2015 [32], Average of 5 vehicles, chassis dyno	Average 60 kph, 0, 5, 10% rated power	3-way cat	Thermal denuder	DMA-CPMA	Commercial gasoline	3.22	2.61	100	0.52
	Average 60 kph, 0 , 5, 10% rated power		None			4.28	2.56	100	0.57
Symonds et al., 2008 [add] , 1 engine, engine dyno	1000 rpm, 3.27 Bar BMEP	3-way cat	None	DMA-CPMA	EN228:2004 compliant gasoline	3.29	2.65	100	0.66
Maricq and Xu, 2004 [30] , 1 vehicle, chassis dyno	Average 20, 40, 50, 60, 70 kph	3-way cat	None	DMA-ELPI	Indolene clear (E0)	15.70	2.30	100	0.63
Zelenyuk et al., 2014 [43], 1 engine, engine dyno	High load average 2000-2500 rpm 5.5 bar BMEP	None	None	APM-SMPS		38.81	2.17	100	0.83
	Low load average 2000 rpm 14 bar BMEP					38.43	2.21	100	1.01
Zelenyuk et al., 2017 [10], 1 engine, engine dyno	Stoichiometric 2000 rpm 2 Bar BMEP	3-way cat	None	APM-SMPS	E0	NA	2.10	NA	NA
	Lean stratified 2000 rpm 2 Bar BMEP					47.88	2.12	100	0.83
This study, 1 engine, engine dyno	Stoichiometric, 2000 rpm 7 Bar BMEP	None	Catalytic stripper	CPMA-SMPS	E10	10.94 ± 0.55	2.34 ± 0.02	100	0.52
	Stoichiometric, 2000 rpm 7 Bar BMEP				E30	9.25 ± 1.76	2.36 ± 0.04	100	0.49
	Lean homogeneous, 2000 rpm 7 Bar BMEP			DMA-CPMA	E10	13.52	2.23	100	0.39
	Lean homogeneous, 2000 rpm 7 Bar BMEP			CPMA-SMPS	E10	13.42 ± 1.92	2.23 ± 0.03	100	0.39
	Lean homogeneous, 2000 rpm 7 Bar BMEP				E30	4.13 ± 0.25	2.54 ± 0.01	100	0.50
	Lean homogeneous, 2000 rpm 7 Bar BMEP				E50	5.59 ± 0.22	2.48 ± 0.01	100	0.51
	Lean stratified, 2000 rpm 4 Bar BMEP				E10	10.65 ± 0.99	2.29 ± 0.02	100	0.40
	Lean stratified, 2000 rpm 4 Bar BMEP				E30	6.39 ± 0.30	2.41 ± 0.01	100	0.42
	Lean stratified, 2000 rpm 4 Bar BMEP				E50	4.89 ± 0.43	2.49 ± 0.02	100	0.47
Olfert and Rogak, 2019	**Universal effective density distribution**					**5.59 ± 0.09**	**2.48 ± 0.02**	**100**	**0.51**

Summary of Density Measurements, GDI Engines

$$\rho_{eff} = C d_m^{\,Dmm-3}$$

Sample treatment	C	Dmm	density eff @ 100 nm
undenuded[1]	8.7 ± 5.8	2.45 ± 0.16	0.58 ± 0.07
denuded[2]	5.0 ± 1.2	2.5 ± 0.07	0.49 ± 0.04
This study - catalytic stripper	8.2 ± 3.4	2.39 ± 0.11	0.46 ± 0.05
Olfert and Rogak - universal (denuded)[3]	5.59 ± 0.09	2.48 ± 0.02	0.51
Diffusion limited Cluster Aggregate[4]		2.2	

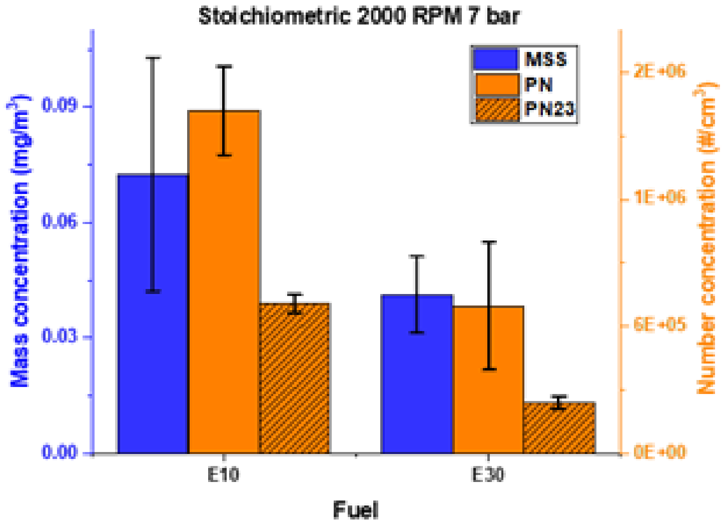
Non-volatile particle size distributions (EEPS)

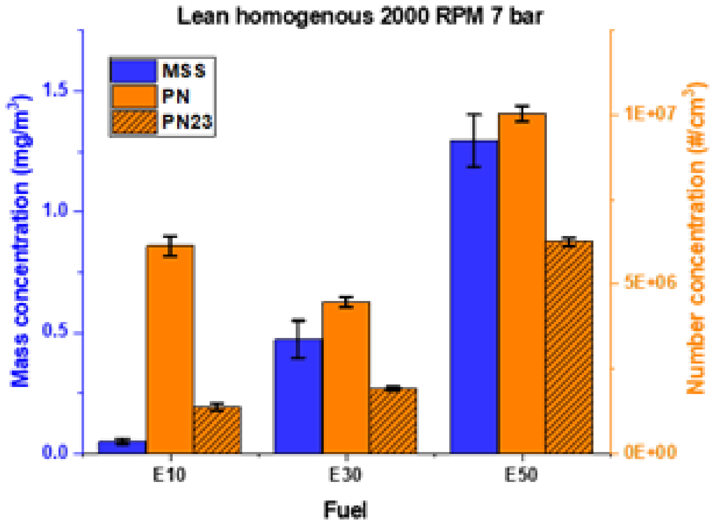


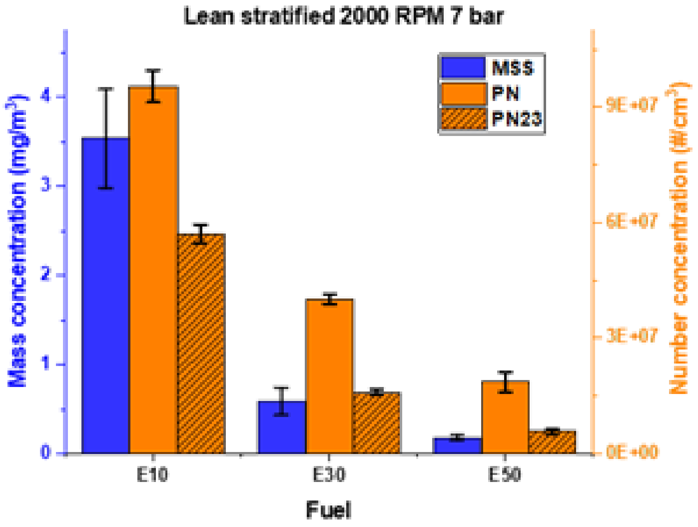
T. E. Murphy Engine Research Laboratory

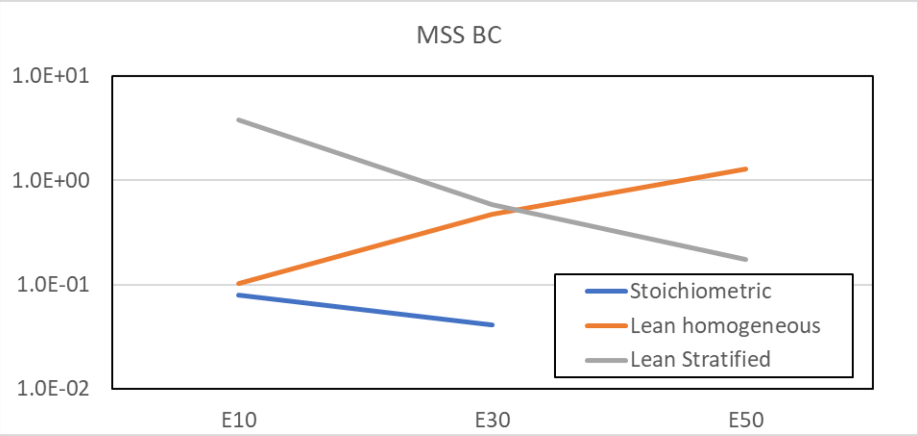
UNIVERSITY OF MINNESOTA

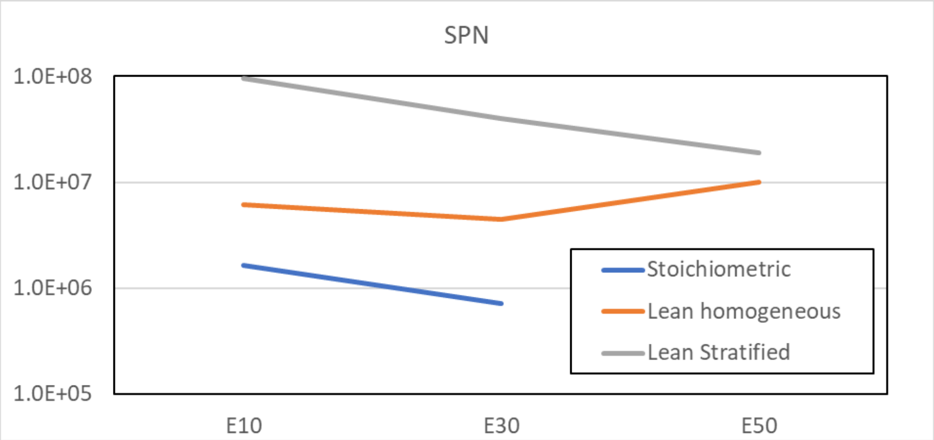
SPN23 and SPN (solid particle number > 23 and >6 nm, respectively) and MSS black carbon mass



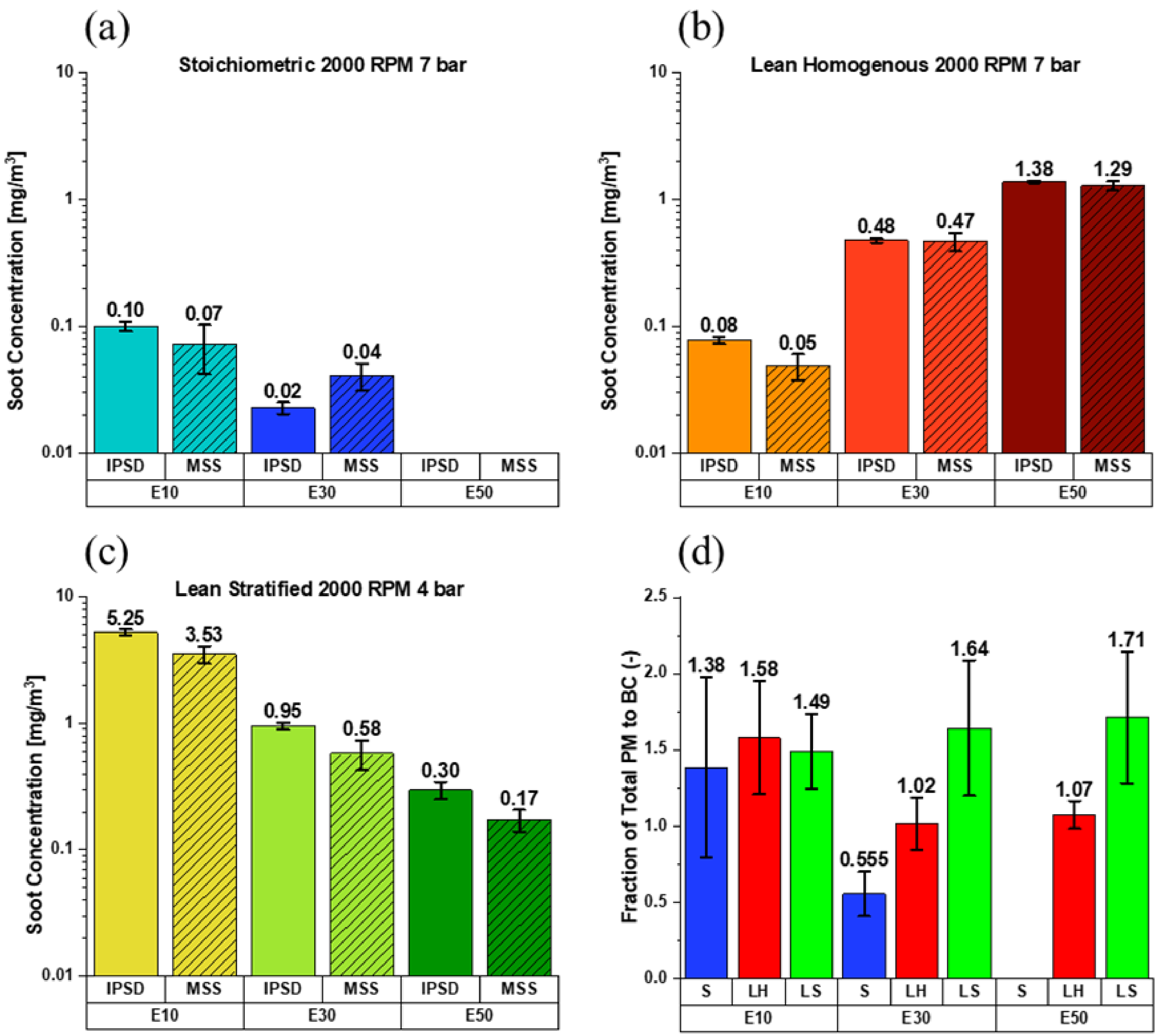








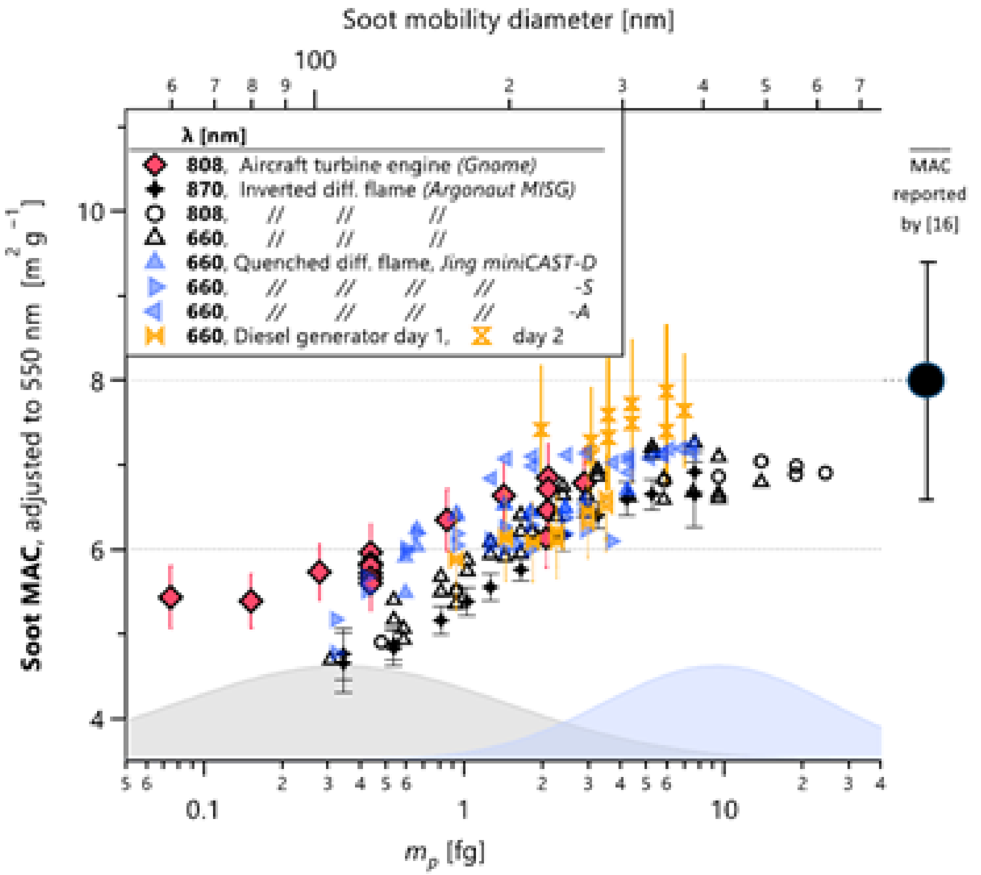
Comparison of BC mass and IPSD mass



Comparison of BC mass and IPSD mass

For most of our tests IPSD mass is larger than MSS BC mass, with IPSD/MSS averaging about 1.3 but with values as high as 1.7 for the LS condition, why?

- These ratios are higher than recently reported for GDI vehicles.
    - Xue, et al., 2016, 4 vehicles, IPSD/MSS = 1.01 to 1.18, average 1.06
    - Maricq. et al., 2016, 6 vehicles, IPSD/MSS average = 1.35
- IPSD mass includes all PM, soot, heavy semi-volatiles, ash
- MSS mass includes only black carbon
    - MSS mass assumes light mass absorption cross section (MAC) is the same as calibration source
    - Corbin, et al., 2022, show significant dependence of MAC on combustion conditions, particle size
    - Maricq, 2014 reports low BC/EC ratio, MAC, for immature soot
    - Malmborg, et al., 2021, reports immature soot in high EGR Diesel
    - Injection strategy used with LS mode may produce lower MAC soot



From Corbin, et al., 2022

Summary

- Effective densities of particles from GDI engines fall in relatively narrow range
- The "universal form" is reasonable approximation in the absence of direct measurements

$$\rho_{eff} = 5.59 dm^{(2.48-3)}$$

- Fuel ethanol content strongly influences SPN and BC
  - Decreasing them for S and LS conditions
  - Increasing them for LH condition
- This lean burn GDI forms broad non-volatile particle size distributions with little distinct modal structure
- The ratio non-volatile IPSD mass to MSS BC mass is greater than 1, especially for the LS condition where it is 1.5-1.7, suggesting that the MAC for these particles is lower than for MSS calibration particles (CAST burner)

Thank you – questions?

References for density measurements

[1] M.M. Maricq, N. Xu, The effective density and fractal dimension of soot particles from premixed flames and motor vehicle exhaust, J. Aerosol Sci. 35 (2004) 1251–1274. https://doi.org/10.1016/j.jaerosci.2004.05.002.
D.C. Quiros, S. Hu, S. Hu, E.S. Lee, S. Sardar, X. Wang, J.S. Olfert, H.S. Jung, Y. Zhu, T. Huai, Particle effective density and mass during steady-state operation of GDI, PFI, and diesel passenger cars, J. Aerosol Sci. 83 (2015) 39–54. https://doi.org/10.1016/j.jaerosci.2014.12.004.
A. Momenimovahed, J.S. Olfert, Effective Density and Volatility of Particles Emitted from Gasoline Direct Injection Vehicles and Implications for Particle Mass Measurement, Aerosol Sci. Technol. 49 (2015) 1051–1062. https://doi.org/10.1080/02786826.2015.1094181.
Symonds, J., Price, P., Williams, P. and Stone, R., 2008. Density of particles emitted from a gasoline direct injection engine. In 12th ETH conference on combustion generated nanoparticles

[2] B.M. Graves, C.R. Koch, J.S. Olfert, Morphology and volatility of particulate matter emitted from a gasoline direct injection engine fuelled on gasoline and ethanol blends, J. Aerosol Sci. 105 (2017) 166–178. https://doi.org/10.1016/j.jaerosci.2016.10.013.
A. Momenimovahed, J.S. Olfert, Effective Density and Volatility of Particles Emitted from Gasoline Direct Injection Vehicles and Implications for Particle Mass Measurement, Aerosol Sci. Technol. 49 (2015) 1051–1062. https://doi.org/10.1080/02786826.2015.1094181

[3] Jason Olfert & Steven Rogak (2019) Universal relations between soot effective density and primary particle size for common combustion sources, Aerosol Science and Technology, 53:5, 485-492, DOI: 10.1080/02786826.2019.1577949

[4] Sorensen, C. M. 2011. The mobility of fractal aggregates: A review. Aerosol Sci. Technol. 45(7):765–779. doi:10.1080/ 02786826.2011.560909.