Characterization of Pre-commercial Gasoline Engine Particulates Through Advanced Aerosol Methods

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Relevance and Objectives

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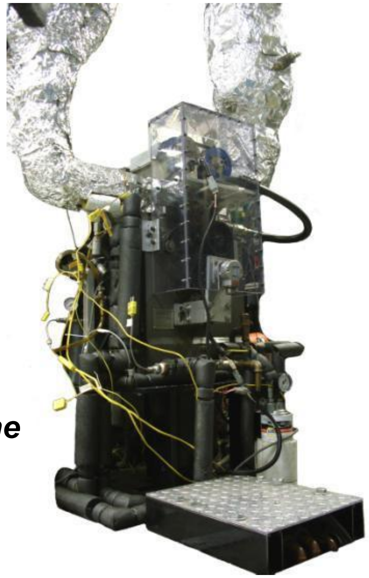
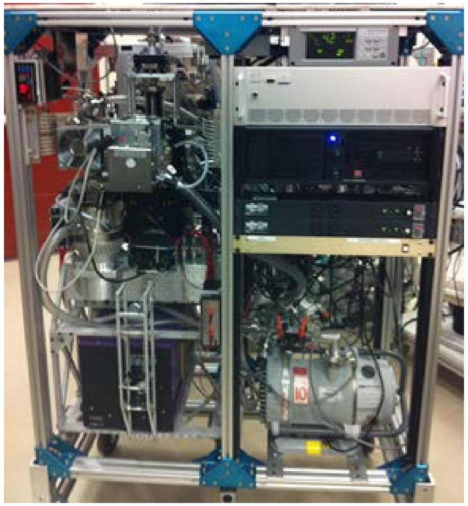
- Direct Injection Spark Ignition **(DISI)** and Gasoline Direct Injection Compression Ignition **(GDICI)** - two gasoline engine technologies with potential to achieve significant increase in fuel efficiency by operating more like diesel engines
- Unfortunately, like diesel engines, they produce exhaust particulates, which are the subject of health and climate concern
- Lack of actual emissions characterization data on pre-commercial and future combustion engines
- Advanced aerosol analysis methods have been used to examine particulates from single-cylinder test engines running on gasoline and ethanol blends



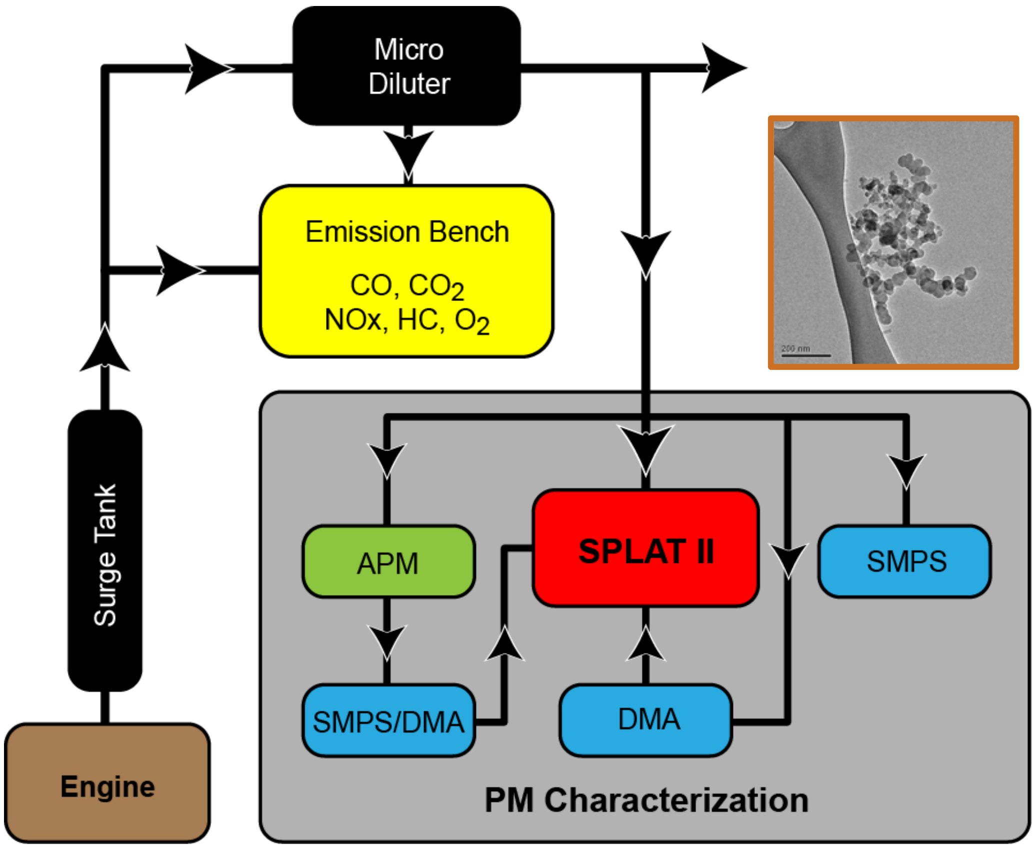
DISI engine



miniSPLAT

Experimental Setup

Real-time, *in-situ,* highly detailed particulate matter (PM) characterization:



- **<u>SMPS:</u>**
  - ✓ size distributions, d_m
- **<u>SPLAT II:</u>**
  - ✓ single particle size, d_{va}
  - ✓ single particle composition, *MS*
- **<u>DMA/SPLAT:</u>**
  - ✓ effective density, ρ_{eff}
  - ✓ fractal dimension, D_{fa}
  - ✓ primary spherule diameter, d_p
- **<u>APM/DMA/SPLAT:</u>**
  - ✓ particle mass, m_p
  - ✓ fractal dimensions, D_{fm}, D_{pr}
  - ✓ primary spherule diameter, d_p
  - ✓ number of spherules, N_p
  - ✓ void fraction, Φ
  - ✓ shape (χ_t , χ_v)

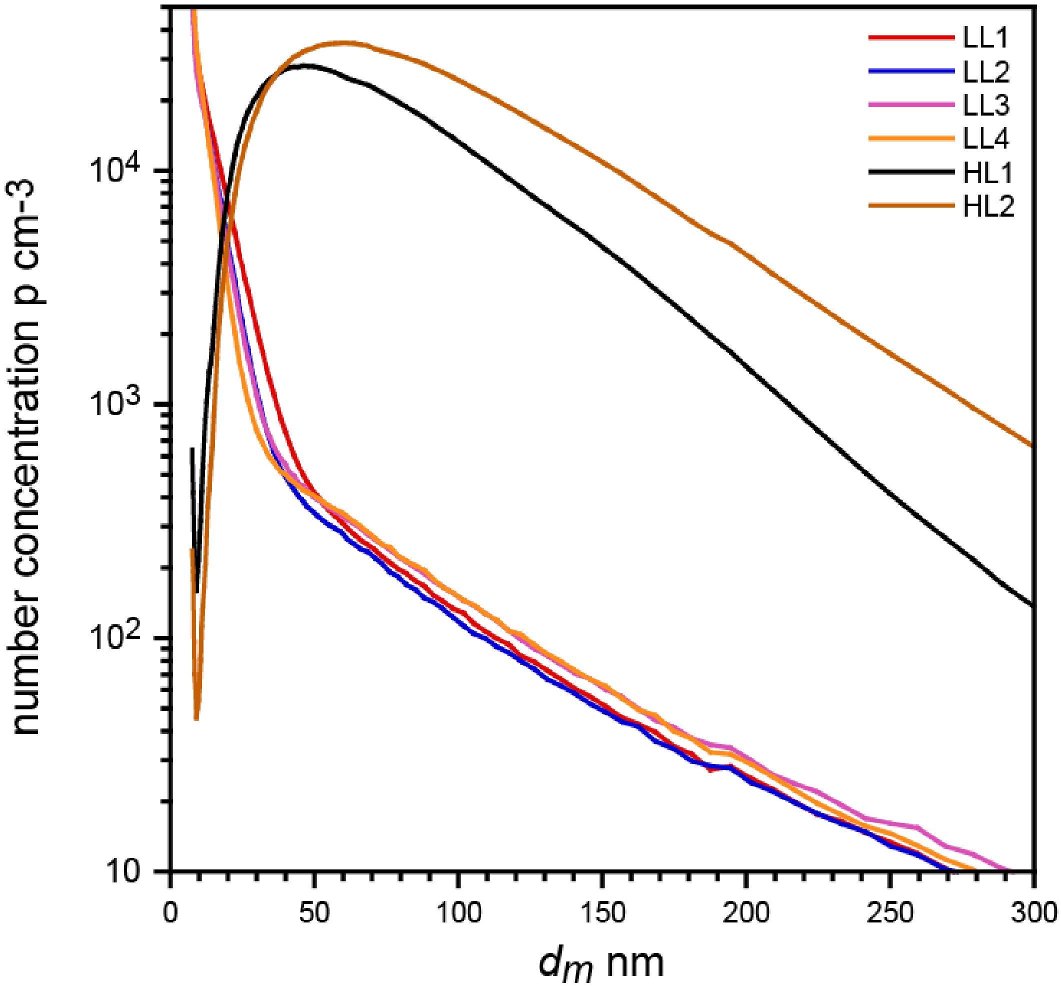
Gasoline Direct Injection Compression Ignition (GDICI)

- GDICI is a low temperature combustion (LTC) strategy that offers the potential to reduce both NOx and PM emissions
- This combustion strategy is highly dependent upon direct injection of gasoline near TDC (within 40° BTDC)
  - The timing and duration of this near-TDC injection can be tailored (based on speed and load) to create an optimized equivalent ratio distribution leading to a stable, staged combustion event (low noise)
- Unlike diesel LTC, GDICI requires no EGR up to 7 bar net IMEP, and PM emissions remain <0.1 g/kg-FI at loads in excess of 14 bar net IMEP.

Condition	LL1	LL2	LL3	LL4
IMEP [bar]	5.5	5.5	5.5	5.5
Speed [rpm]	2000	2000	2000	2500
SOI1 [°bTDC]	350	350	350	350
SOI2 [°bTDC]	39	36	33	39
SOI3 [°bTDC]	-	-	-	-

Condition	HL1	HL2
IMEP [bar]	14	14
Speed [rpm]	2000	2000
SOI1 [°bTDC]	350	350
SOI2 [°bTDC]	21	21
SOI3 [°bTDC]	-	10

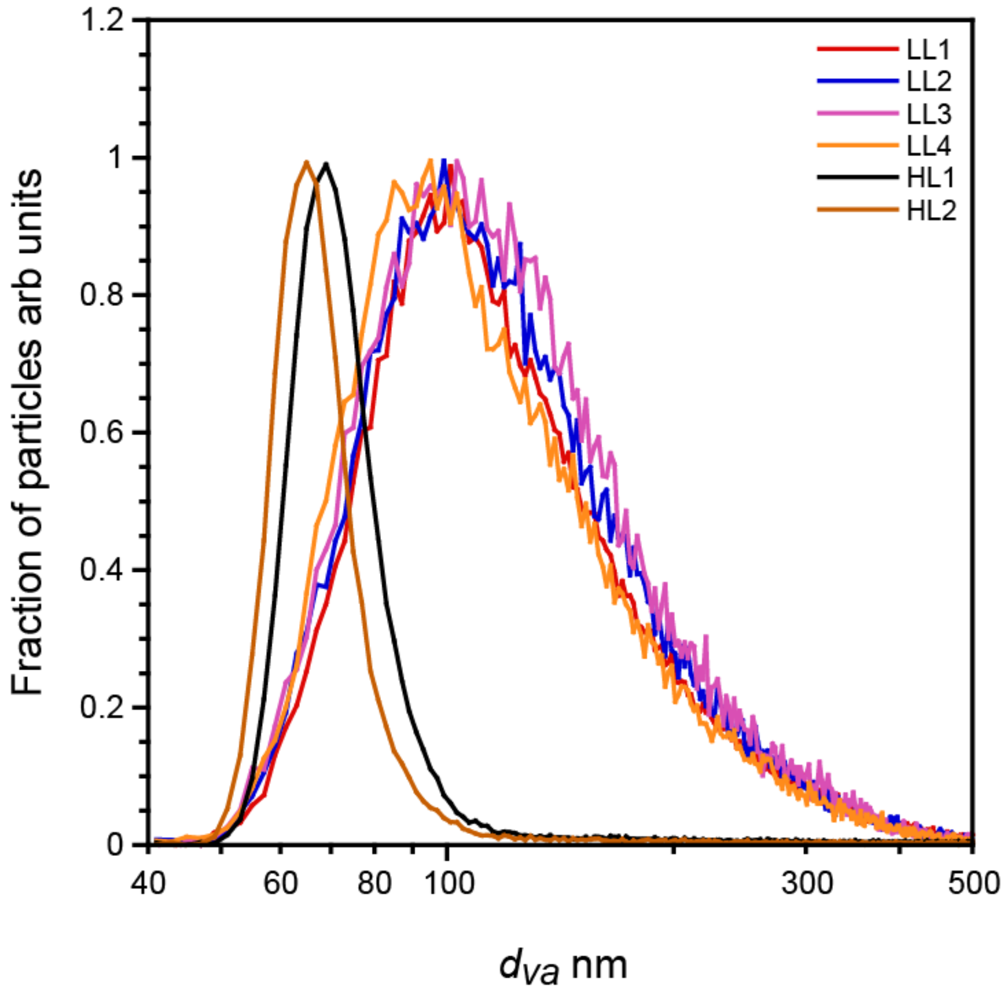
GDICI



Condition	LL1	LL2	LL3	LL4	HL1	HL2
IMEP [bar]	5.5	5.5	5.5	5.5	14	14
Speed [rpm]	2000	2000	2000	2500	2000	2000
SOI1 [°bTDC]	350	350	350	350	350	350
SOI2 [°bTDC]	39	36	33	39	21	21
SOI3 [°bTDC]	-	-	-	-	-	10

- Mobility size distributions of exhaust particles produced during 4 low load runs (LL) and 2 high load runs (HL)
- Only small changes in between different LL runs
- Very different size distributions for HL runs

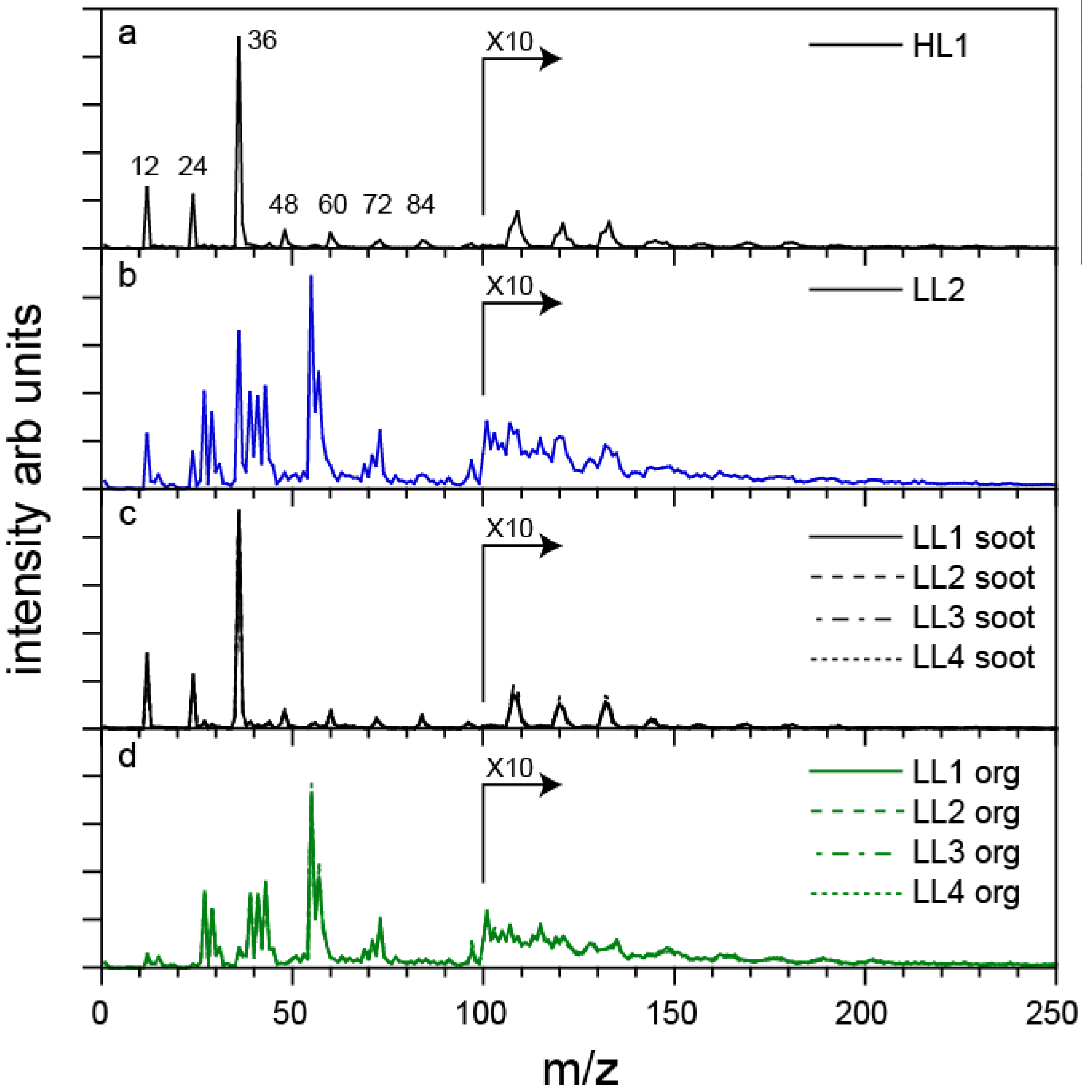
GDICI



Condition	LL1	LL2	LL3	LL4	HL1	HL2
IMEP [bar]	5.5	5.5	5.5	5.5	14	14
Speed [rpm]	2000	2000	2000	2500	2000	2000
SOI1 [°bTDC]	350	350	350	350	350	350
SOI2 [°bTDC]	39	36	33	39	21	21
SOI3 [°bTDC]	-	-	-	-	-	10

- SPLAT's recorded d_{va} size distributions of exhaust particles produced during 4 low load runs (LL) and 2 high load runs (HL)
- Only small changes in between different LL runs
- Very different size distributions for HL runs

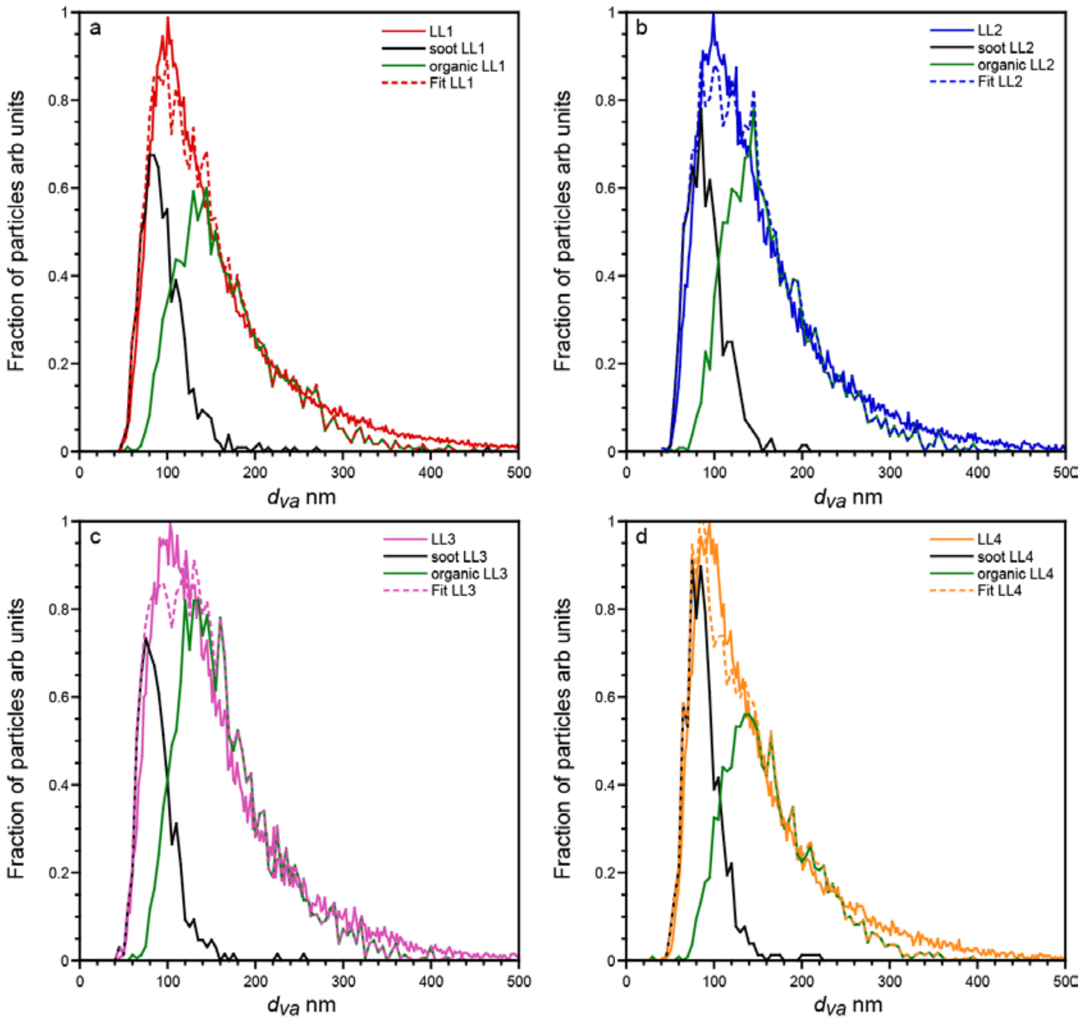
GDICI



Condition	LL1	LL2	LL3	LL4	HL1	HL2
IMEP [bar]	5.5	5.5	5.5	5.5	14	14
Speed [rpm]	2000	2000	2000	2500	2000	2000
SOI1 [°bTDC]	350	350	350	350	350	350
SOI2 [°bTDC]	39	36	33	39	21	21
SOI3 [°bTDC]	-	-	-	-	-	10

- SPLAT II recorded *MS*:
  - ✓ Av. mass spectrum for HL1 (a)
  - ✓ Av. mass spectrum for LL2 (b)
- 2 types of particles were produced during LL runs
  - ✓ Mass spectra of the fractal soot particles produced during LL1 – LL4 runs (c)
  - ✓ Mass spectra of the compact organic particles produced during LL1 – LL4 runs (d)

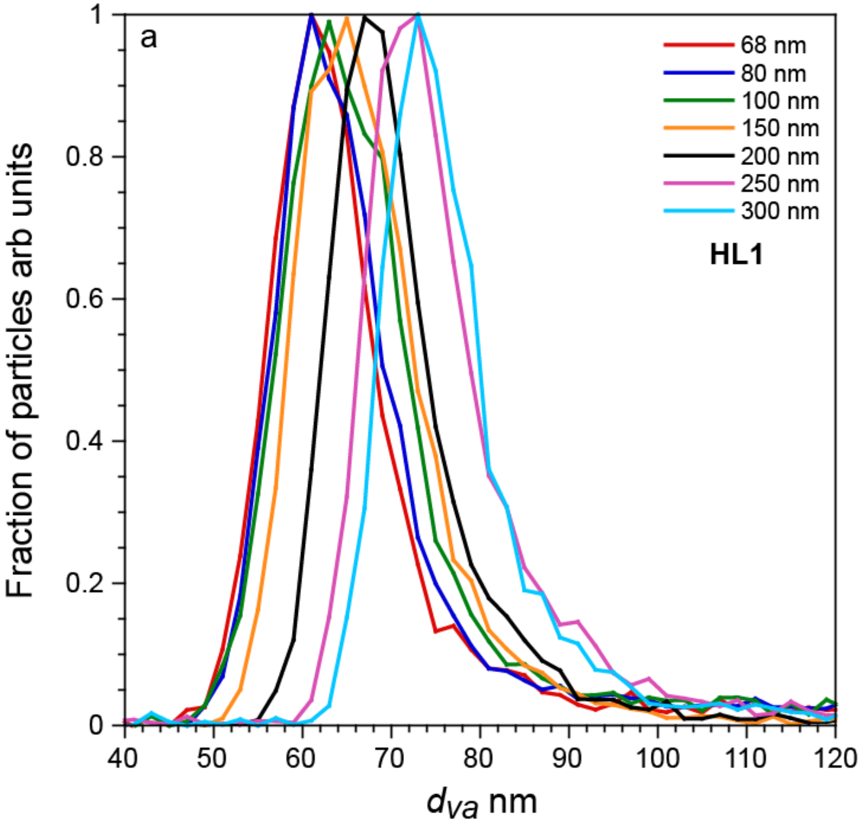
GDICI

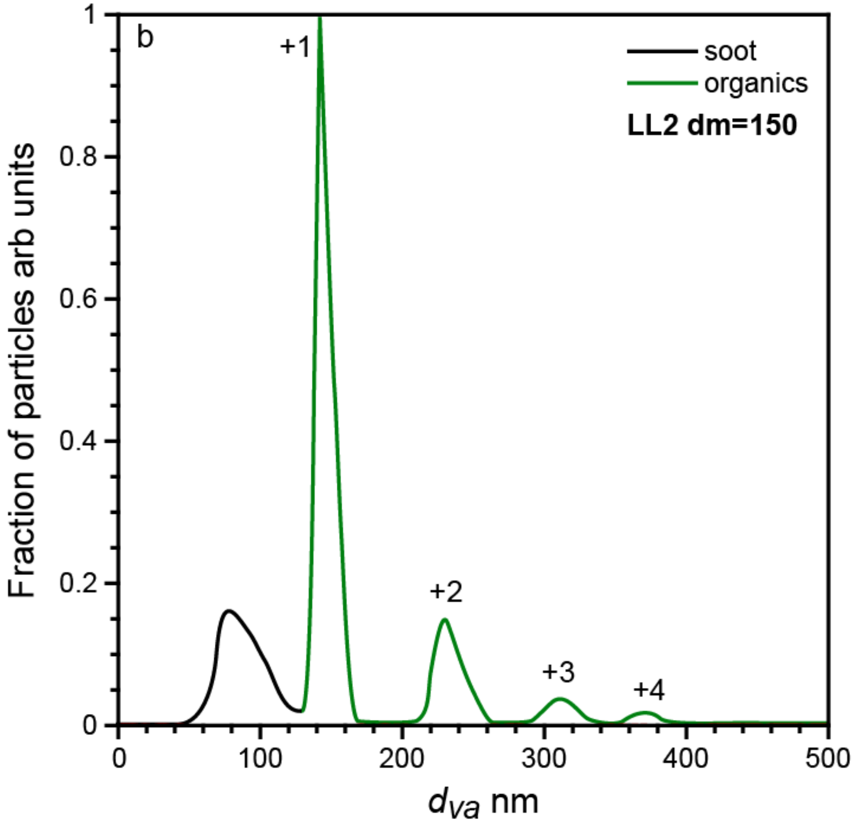


Condition	LL1	LL2	LL3	LL4
IMEP [bar]	5.5	5.5	5.5	5.5
Speed [rpm]	2000	2000	2000	2500
SOI1 [°bTDC]	350	350	350	350
SOI2 [°bTDC]	39	36	33	39
SOI3 [°bTDC]	-	-	-	-

- SPLAT II recorded d_{va} distributions for particles produced during 4 LL runs.
- d_{va} distributions were deconvoluted into the fractal soot particles (black) and compact organic particles (green). Dashed lines are the sum of the two.
- Soot fractions are 35%, 32%, 27%, and 38% for the LL1 - LL4 runs, respectively.

GDICI

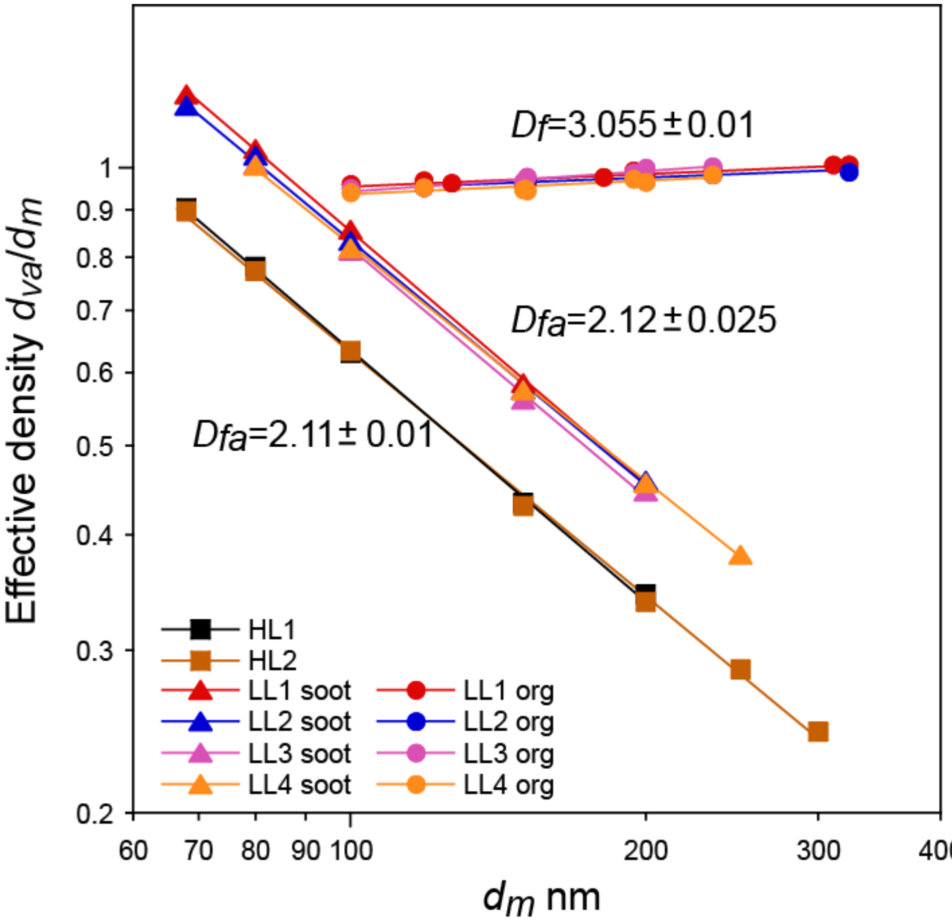




- d_{va} distributions for particles produced during HL1 run classified by the DMA at d_m 68 nm to 300 nm. Note only small change in d_{va}.

- d_{va} distributions for particles produced during LL2 run classified by the DMA at d_m = 150 nm.
- 2 types of particles are present: fractal soot (black) and compact organic particles (green peaks indicating multiply charged particles).

GDICI



Condition	LL1	LL2	LL3	LL4	HL1	HL2
EC	56.3	56.3	55.5	52.2	54.8	54.3
OC	40.8	40.9	41.7	45.0	43.7	43.7
PAHs	21.4	23.0	23.9	26.5	26.4	26.4

- Effective densities as a function of mobility diameter for all runs. Slopes yield fractal dimensions.
- The two HL runs yield $D_{fa} = 2.11$.
- The four LL runs show two very different sets of lines that correspond to fractal soot particles with $D_{fa} = 2.12$ and the compact organic particles with $D_{fa} = 3.05$ and density of 0.98 g cm^{-3}.
- Soot produced in LL runs has very similar composition, but higher effective densities, thus larger d_p

GDICI

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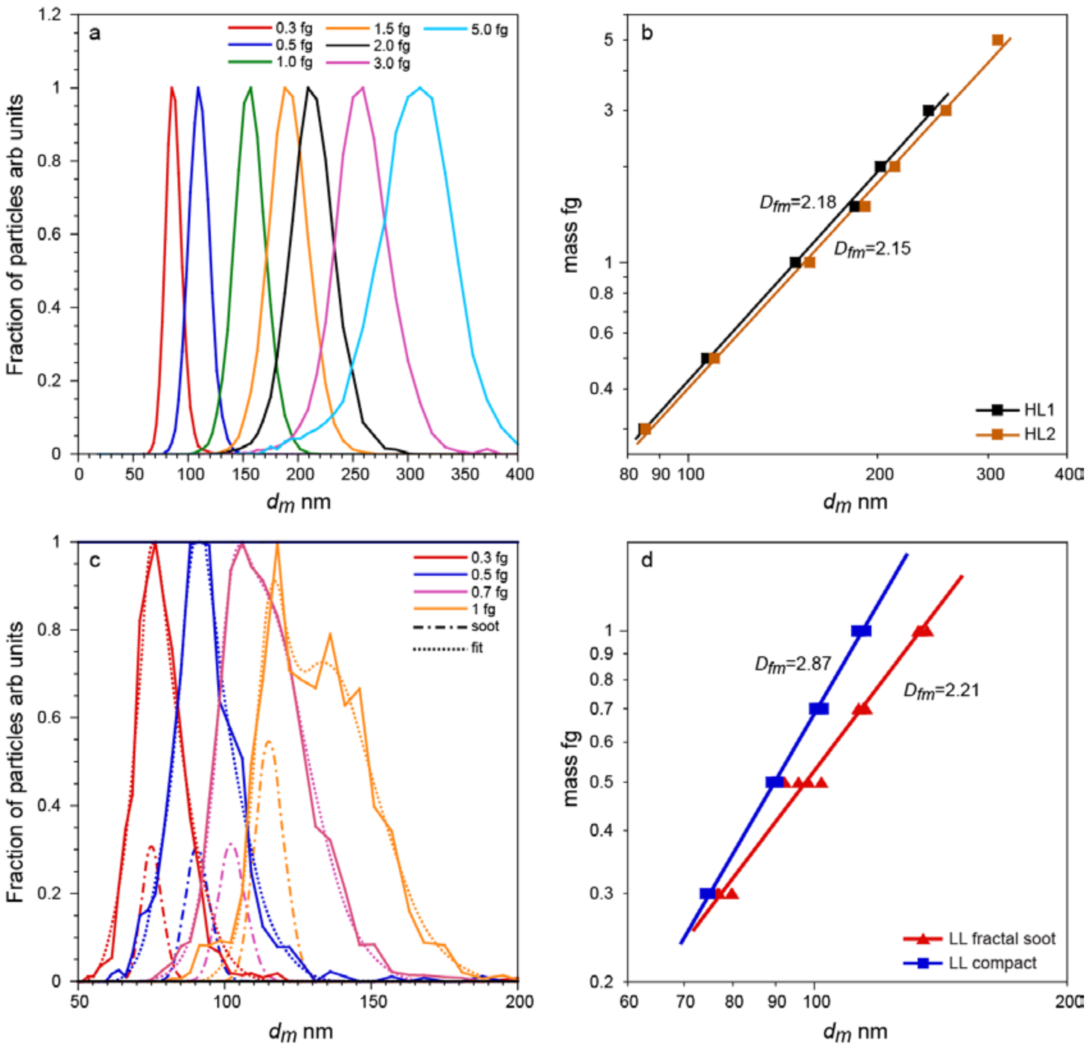

- d_m distributions for APM mass classified particles.
- The two HL runs yield $D_{fm} \cong 2.2$.
- d_m distributions for LL runs were deconvoluted to reflect the presence of 2 types of particles.
- Mass vs. mobility plots for LL yield $D_{fm} \cong 2.2$ and $D_{fm} \cong 2.9$ for the fractal soot and compact organic particles, respectively.

GDICI

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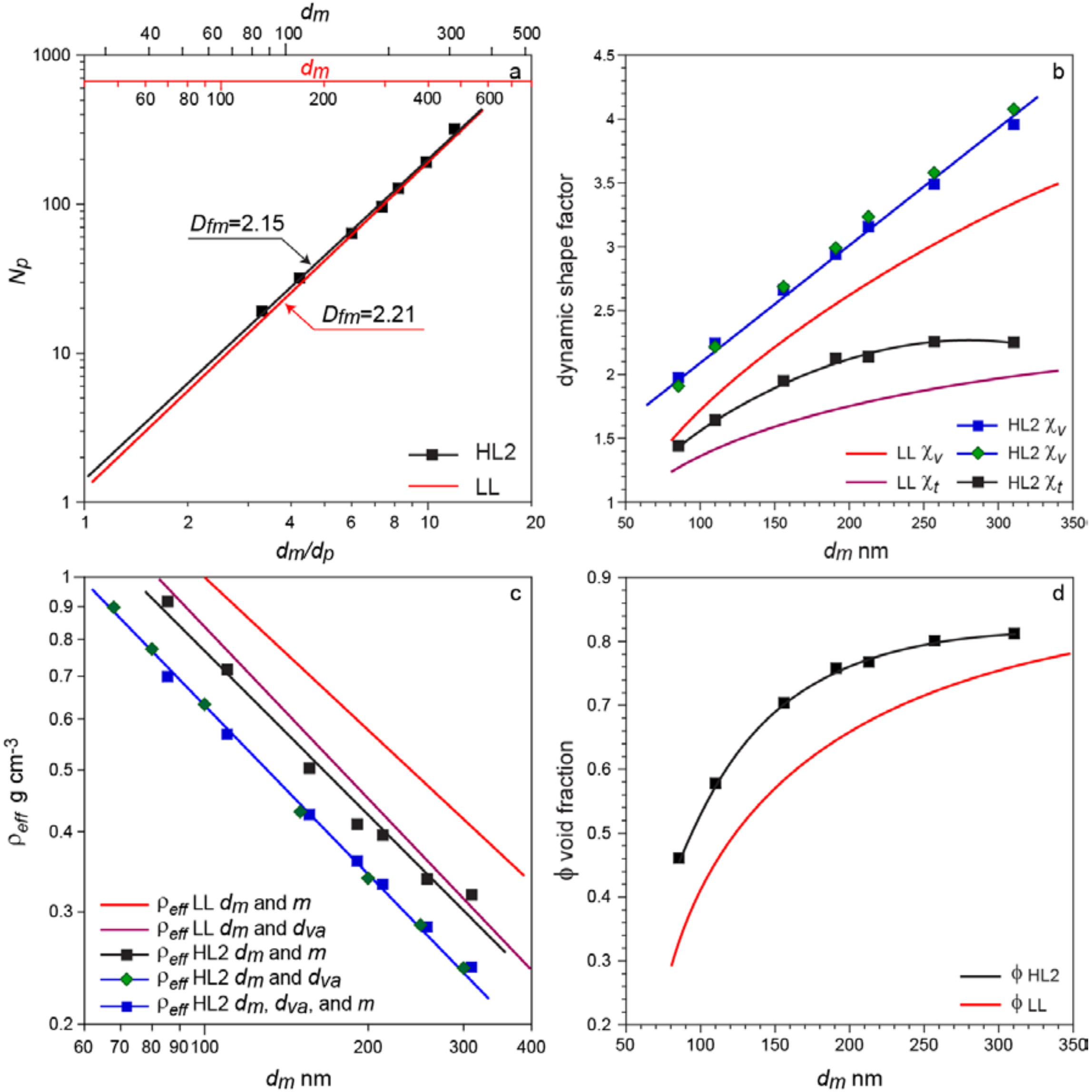
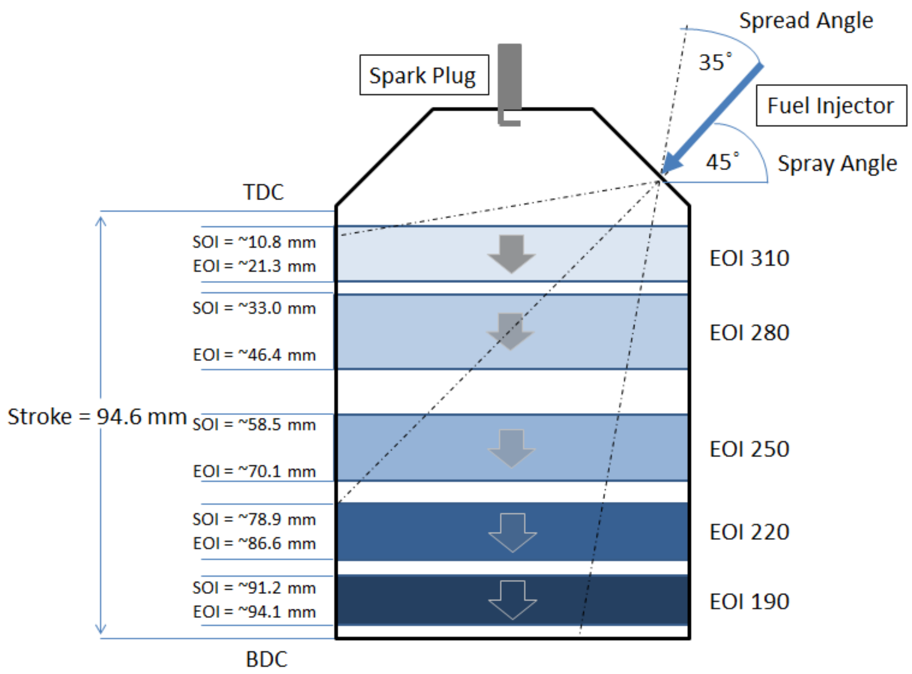


- Measurements of m_p, d_{va}, and d_m can be used to calculate primary spherule diameters, d_p, for fractal soot particles produced during HL (d_p=26 nm) and LL (d_p=40 nm) runs.
- Using density of 1.7 g cm^{-3}, derived from mass spectra, we can determine number of spherules (N_p), void fraction (*Φ*), and dynamic shape factors (χ_t, χ_v) as function of particle size for all HL and LL conditions.

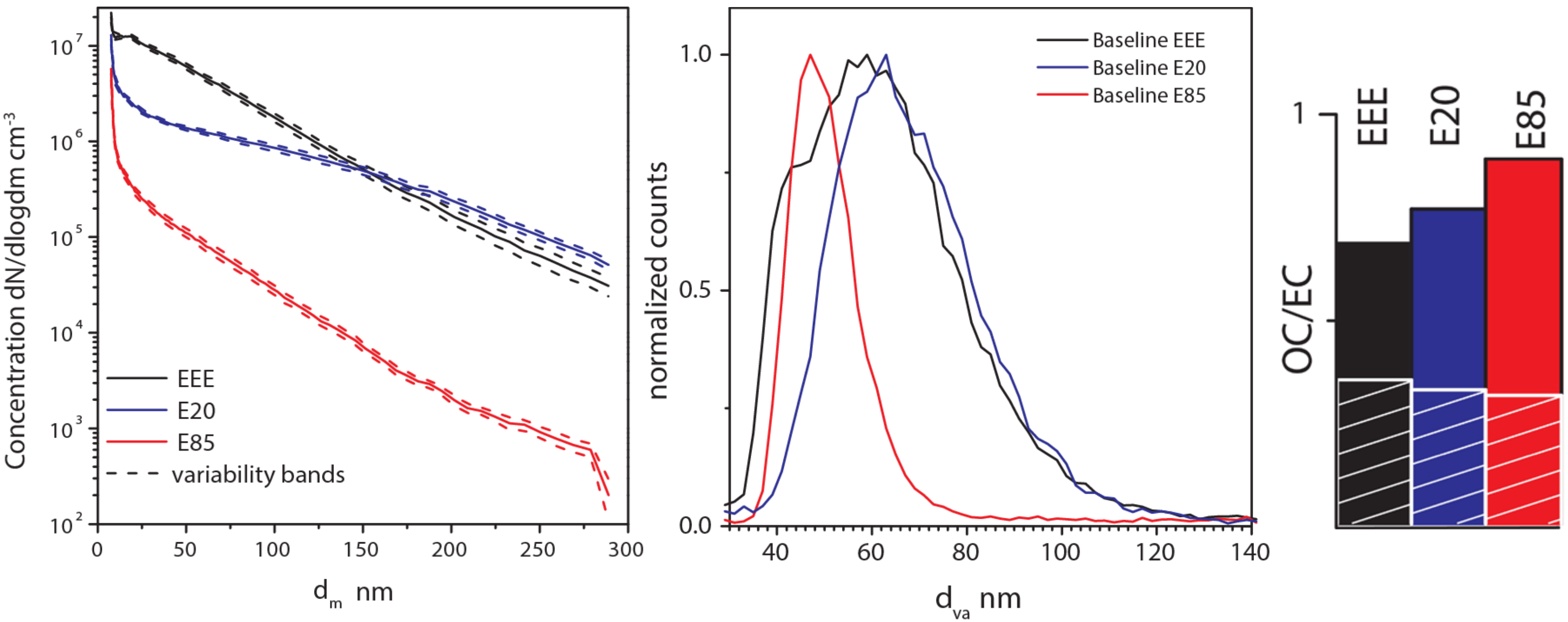
Direct Injection Spark Ignition (DISI)

- DISI is currently used in many light-duty passenger vehicles and offers increased fuel economy.
- Particulate number is higher with DISI than traditional spark ignition engines, which presents a challenge
- Particulate formation has been shown to be dependent on injection timing, most likely due to tradeoffs between mixing time and wall wetting.
- Equivalence ratio, load, oxygenated fuel, and fuel injection pressure have also been shown to affect particulates.



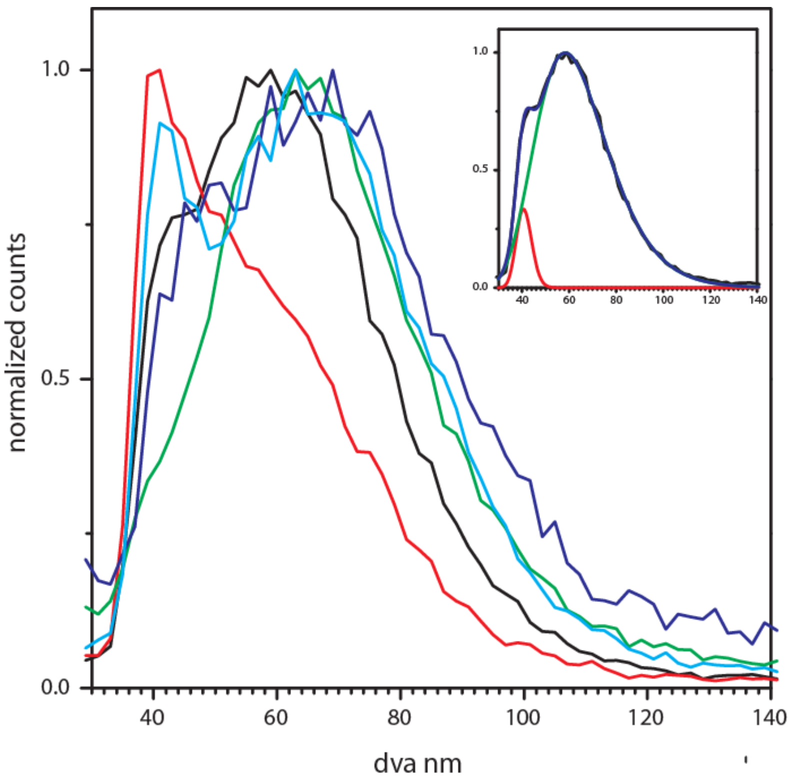
DISI
Baseline Conditions: EEE, E20, E85

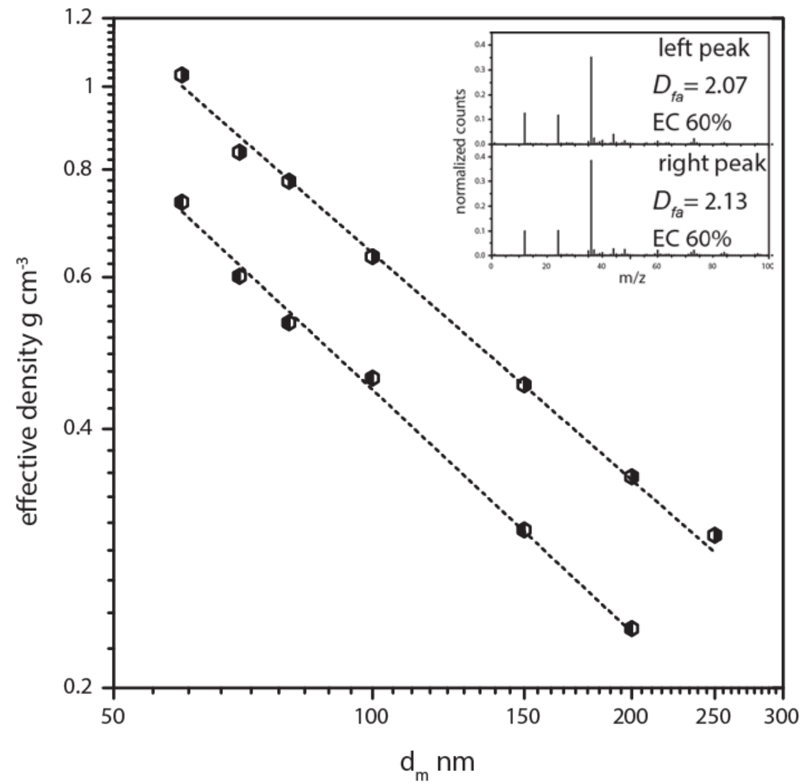
- Very large dataset: different fuel blends, a wide range of engine operating conditions, including sweeps of equivalence ratio and injection timing.



- Example: Baseline conditions for EEE, E20, & E85.
- Very different size distributions. E85 produces significantly fewer PM.
- All particles contain large fraction of tightly integrated organics (volatile particulate removal, XPS, FTIR/ATR , HRTEM: amorphous nano-structures).

DISI
Baseline Conditions: EEE

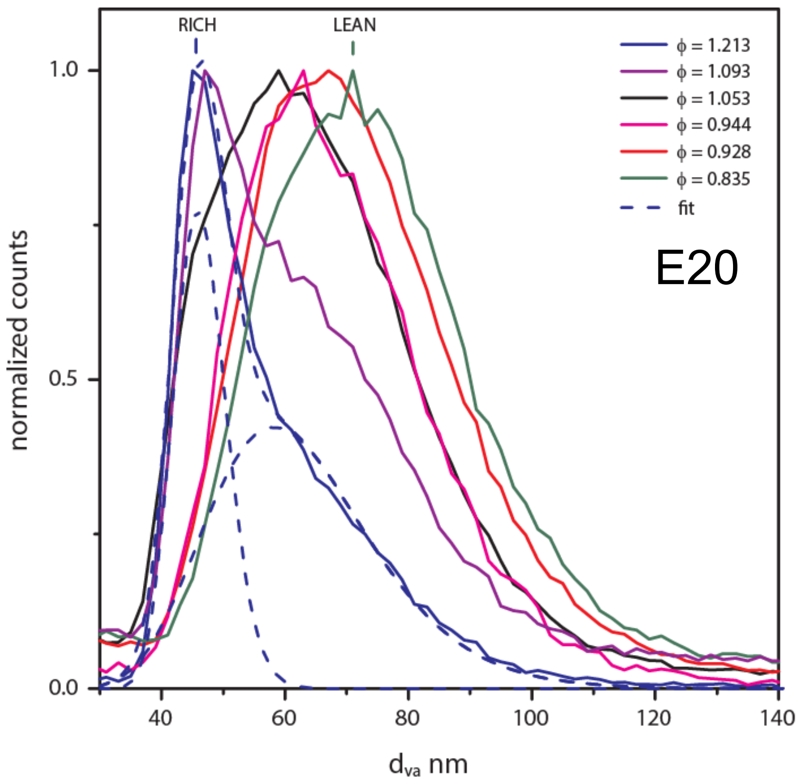


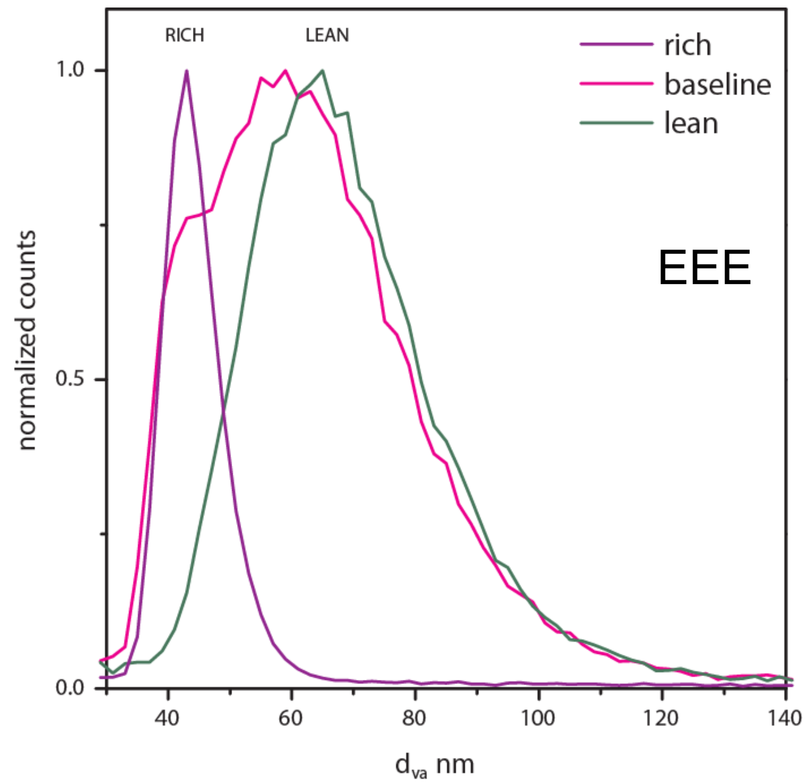


- Overall d_{va} distribution has two modes that can be separated
- Two modes mean either different chemical composition (not the case) or different primary spherule diameters.
- Two types of fractal agglomerates are present: d_p=18 nm and d_p=26 nm

DISI
Equivalence Ratio Sweep: E20 & EEE

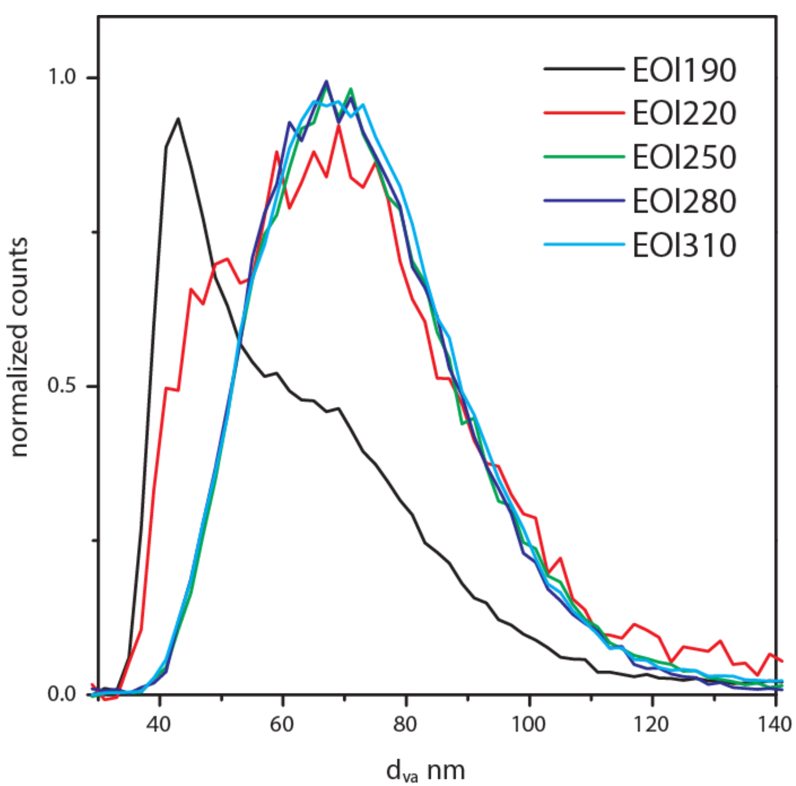
- E20 equivalence ratio sweep data provide an insight into bimodal distributions: the left mode is related to rich regions in the combustion chamber.
- Similar trend is observed for EEE.

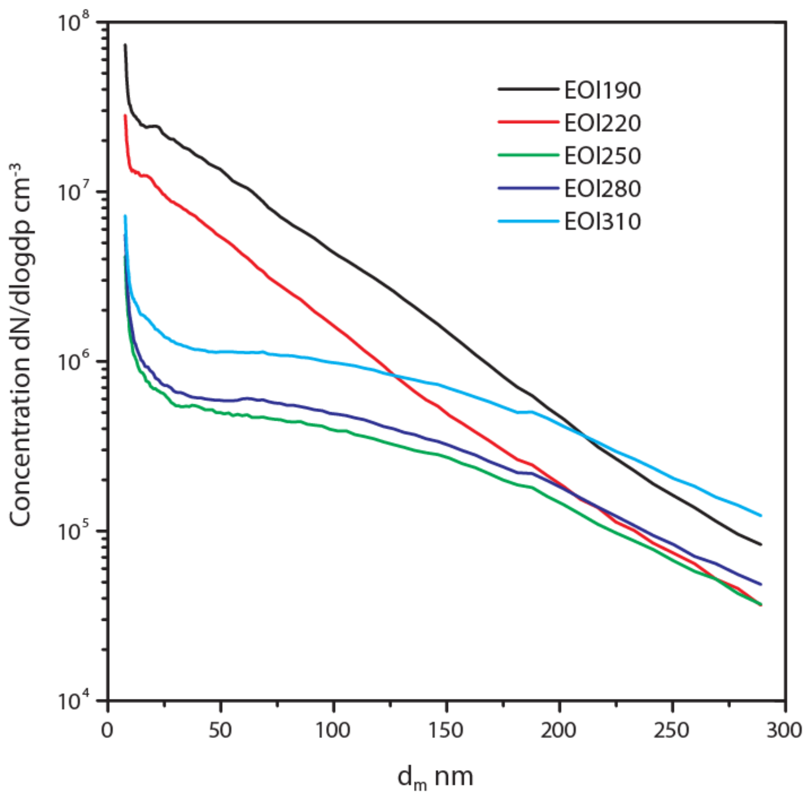




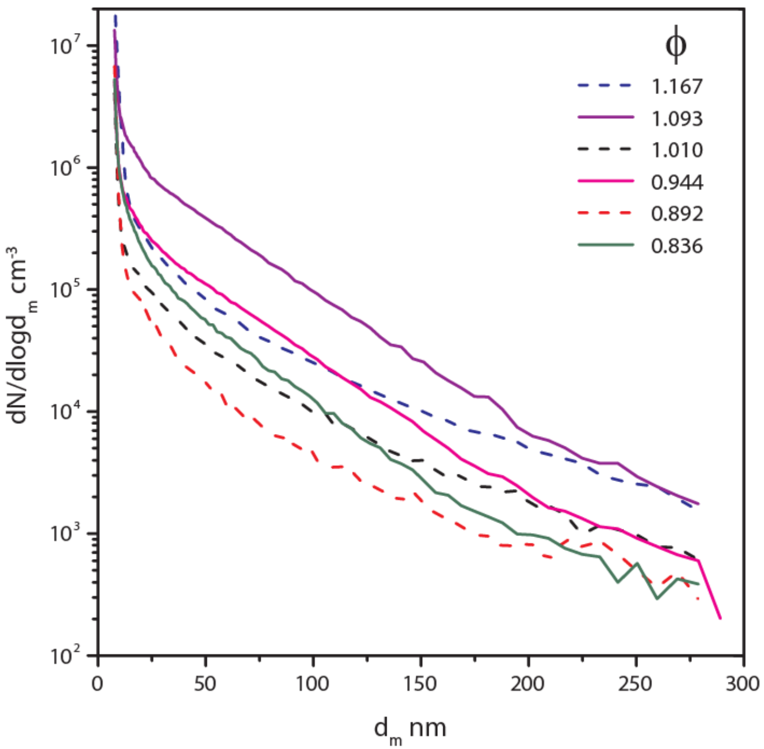
DISI
Injection Timing Sweep: EEE

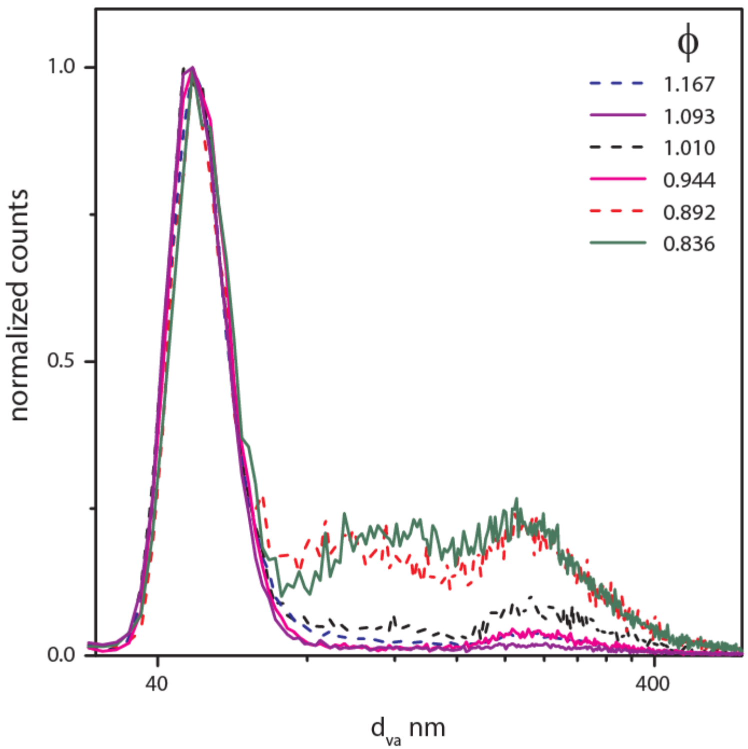
- E20 equivalence ratio sweep provided an insight into bimodal distributions: the left mode is related to rich regions in the combustion chamber.
- Similar trend is observed for EEE late injection (low mixing time) time





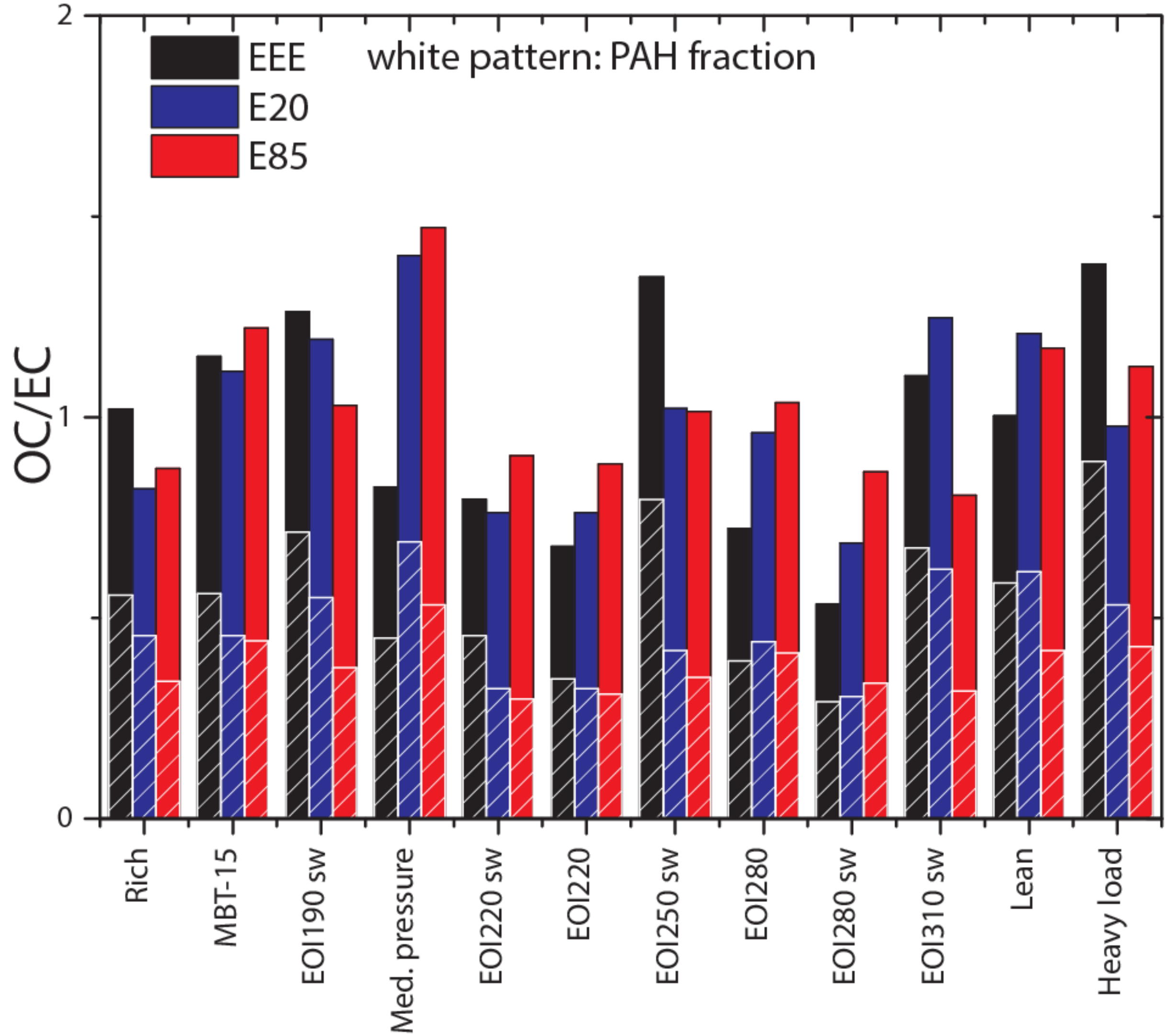
DISI
Equivalence Ratio Sweep: E85





- E85 produces significantly fewer particulates.
- As a result, larger non-fractal particles that contain large OC content, engine wear & tear, and lubricating oil represent significant fraction
- Composition analysis includes fractal particles only

DISI
Particle Composition



Conclusions

- Characterized in detail properties (*d_m, d_{va}, MS, ρ_{eff}, D_{fa}, D_{fm}, D_{pr}, m_p, d_p, N_p, Φ, χ_t, χ_v*) of particles emitted by pre-commercial gasoline GDICI and DISI engines as function of fuel blend and operating conditions.
- GDICI PM varied significantly in character depending upon engine load. Under low load conditions PM is dominated by compact organic particles with smaller (~30%) contribution of fractal soot particles (d_p=40 nm). Under high load conditions, PM consist of fractal soot agglomerates with nearly identical fractal dimension but smaller spherule diameter (d_p=26 nm).
- DISI PM exhibited high organic content (40-60%) that was tightly bound with inorganic carbon within the primary spherules, making is impossible to remove by TD or in evaporative chamber.
- Primary spherule size was observed to vary dramatically in SIDI soot, which is a marked contrast with diesel.
- Two distinct modes observed in d_{va} distributions during equivalence ratio and injection timing sweeps result from different primary spherule sizes, since compositions and fractal dimensions are similar. The left mode is dominant for conditions known to produce particles from rich mixtures, while the right mode appears to be linked to wall/piston impingement.

Extra Slides

DISI: EEE Matrix

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EEE	Speed	Injection Timing	Fuel Quantity	AF	Φ	Spark Advance	Injection Press.	Intake Temp.	Oil Temp.	Coolant Temp.	Intake Manifold Press.
	[RPM]	[°bTDC]	[mg/cyc]	[-]	[-]	[°bTDC]	[MPa]	[°C]	[°C]	[°C]	[kPa]
EOI 220	2100	220	11	15	0.975	25	11	45	90	90	40
EOI 280	2100	**280**	11	15	0.975	25	11	45	90	90	40
Heavy Load	2100	220	**21**	15	0.975	**18**	11	45	90	90	66
Rich	2100	220	11	**13**	**1.125**	25	11	45	90	90	36
MBT-15	2100	220	11	15	0.975	**10**	11	45	90	90	39
Lean	2100	220	11	**17**	**0.860**	25	11	45	90	90	53
Medium Press.	2100	220	11	15	0.975	25	**8**	45	90	90	38
Cold Start	2100	**80**	11	15	0.975	25	11	**30**	**30**	**30**	38

DISI: E20 Matrix

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E20	Speed	Injection Timing	Calc. Fuel Quantity	AF	Φ	Spark Advance	Injection Press.	Intake Temp.	Oil Temp.	Coolant Temp.	Intake Manifold Press.
	[RPM]	[°bTDC]	[mg/cyc]	[-]	[-]	[°bTDC]	[MPa]	[°C]	[°C]	[°C]	[kPa]
EOI 220	2100	220	11.94	13.83	0.969	25	11	45	90	90	39
EOI 280	2100	**280**	11.94	13.83	0.969	25	11	45	90	90	39
Heavy Load	2100	220	**22.8**	13.83	0.969	**18**	11	45	90	90	65
Rich	2100	220	11.94	**11.98**	**1.118**	25	11	45	90	90	35
MBT-15	2100	220	11.94	13.83	0.969	**10**	11	45	90	90	44
Lean	2100	220	11.94	**15.67**	**0.855**	25	11	45	90	90	44
Medium Press.	2100	220	11.94	13.83	0.969	25	**8**	45	90	90	38
Cold Start	2100	**80**	11.94	13.83	0.969	25	11	**30**	**30**	**30**	39

DISI: E85 Matrix

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E85	Speed	Injection Timing	Calc. Fuel Quantity	AF	Φ	Spark Advance	Injection Press.	Intake Temp.	Oil Temp.	Coolant Temp.	Intake Manifold Press.
	[RPM]	[°bTDC]	[mg/cyc]	[-]	[-]	[°bTDC]	[MPa]	[°C]	[°C]	[°C]	[kPa]
EOI 220	2100	220	16.23	10.2	0.958	25	11	45	90	90	37
EOI 280	2100	**280**	16.23	10.2	0.958	25	11	45	90	90	37
Heavy Load	2100	220	**32.55**	10.2	0.958	**18**	11	45	90	90	61
Rich	2100	220	16.23	**8.84**	**1.106**	25	11	45	90	90	33
MBT-15	2100	220	16.23	10.2	0.958	**10**	11	45	90	90	35
Lean	2100	220	16.23	**8.83**	**0.846**	25	11	45	90	90	41
Medium Press.	2100	220	16.23	10.2	0.958	25	**8**	45	90	90	37
Cold Start	2100	**80**	16.23	10.2	0.958	25	11	**30**	**30**	**30**	36

Effect of EOI: Possible Piston/Wall Wetting

Fuel	EEE	E20	E85
SOI [ºbTDC]	324.8	325.4	328.8
EOI [ºbTDC]	310	310	310
Injection Duration [ºCA]	14.8	15.4	18.8
Injection duration [ms]	1.23	1.28	1.57

EOI 310 shows potential for piston and wall wetting