Detailed Characterization of Particulate Matter Emitted by Spark Ignition Direct Injection (SIDI) Gasoline Engine

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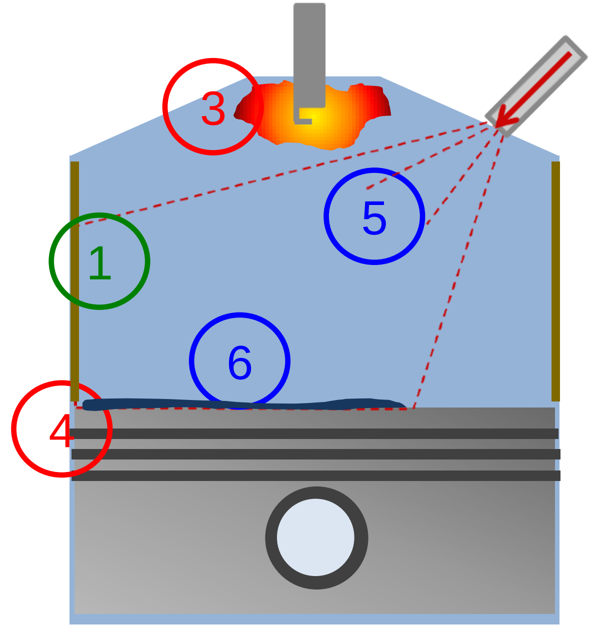
Relevance and Objectives

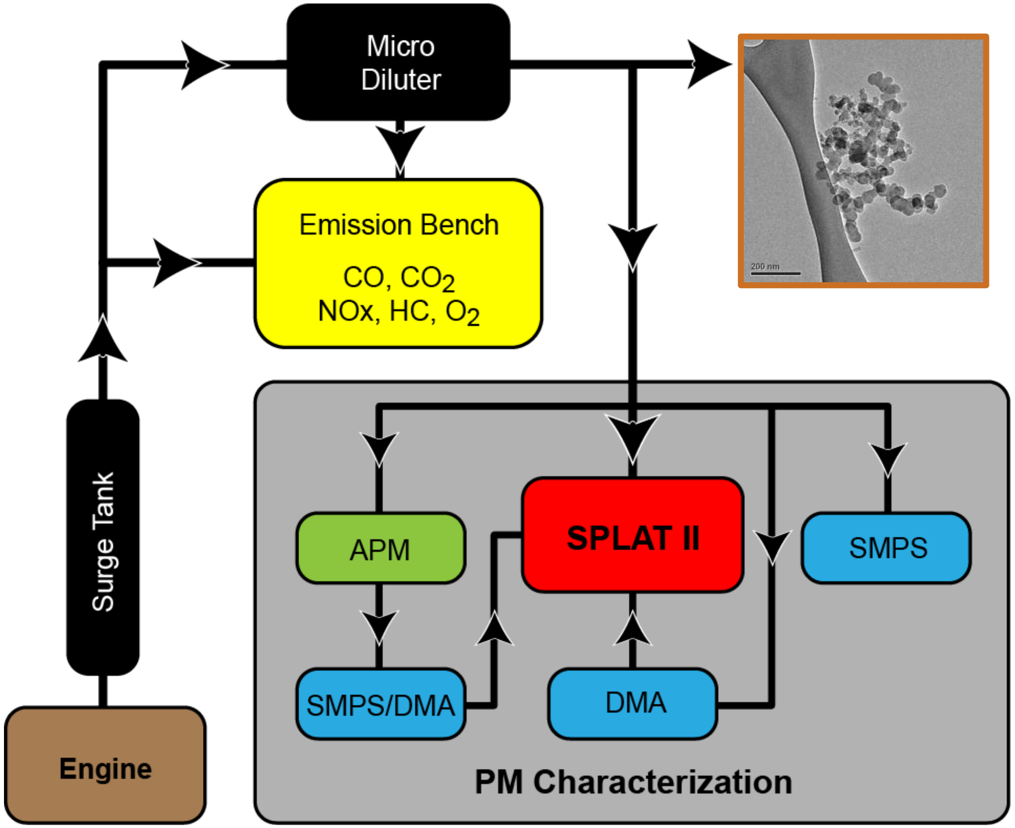
- SIDI is currently used in many light-duty passenger vehicles and offers increased fuel economy.
- Particulate number is higher with SIDI than traditional spark ignition engines, which presents a challenge.
- Particulate formation has been shown to be dependent on injection timing, most likely due to tradeoffs between mixing time and wall wetting.
- Equivalence ratio, load, oxygenated fuel, and fuel injection pressure have also been shown to affect particulates.
- Advanced aerosol analysis methods have been used to examine particulates from a 1.9 L single-cylinder test SIDI engine running on gasoline and ethanol blends.

- Non-fuel sources
  1. Engine oil
  2. Intake air and other engine particles
- Bulk-gas formation
  3. Inhomogeneous mixing
  4. Combustion of fuel from crevices and deposits
- Liquid-fuel sources
  5. Incomplete droplet vaporization
  6. Wall wetting (fuel films, pool fires)



Approach

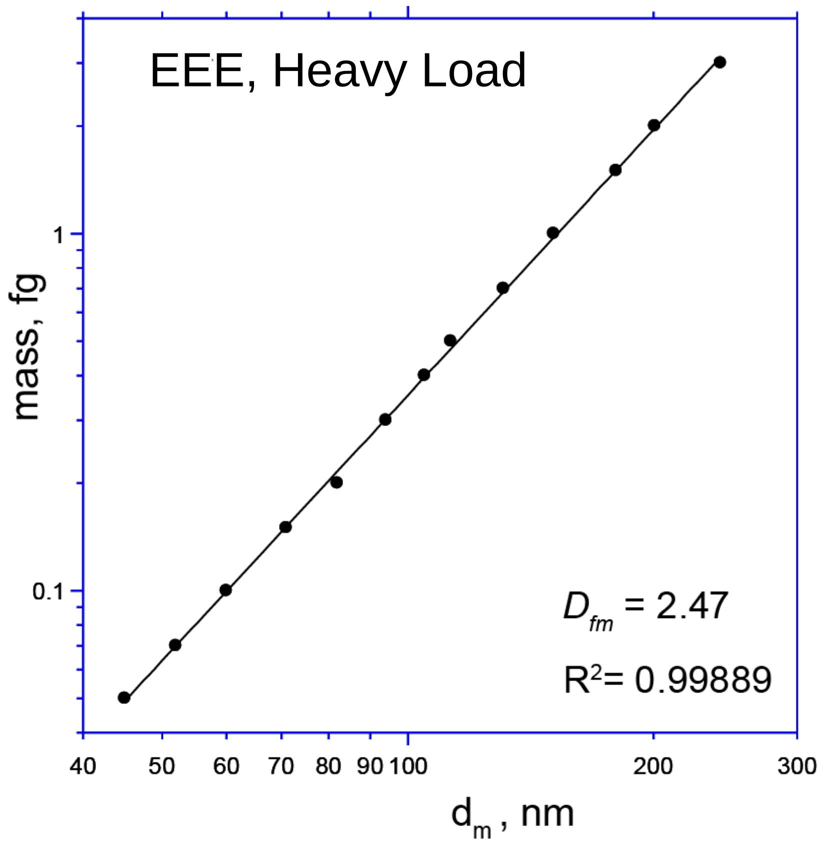
- Exhaust PM represents a complex mixture of particles with various sizes, shapes, morphologies, and compositions that can be identified and characterized as a function of engine operating condition and fuel
- Highly detailed PM characterization is enabled by an array of advanced instruments and methods

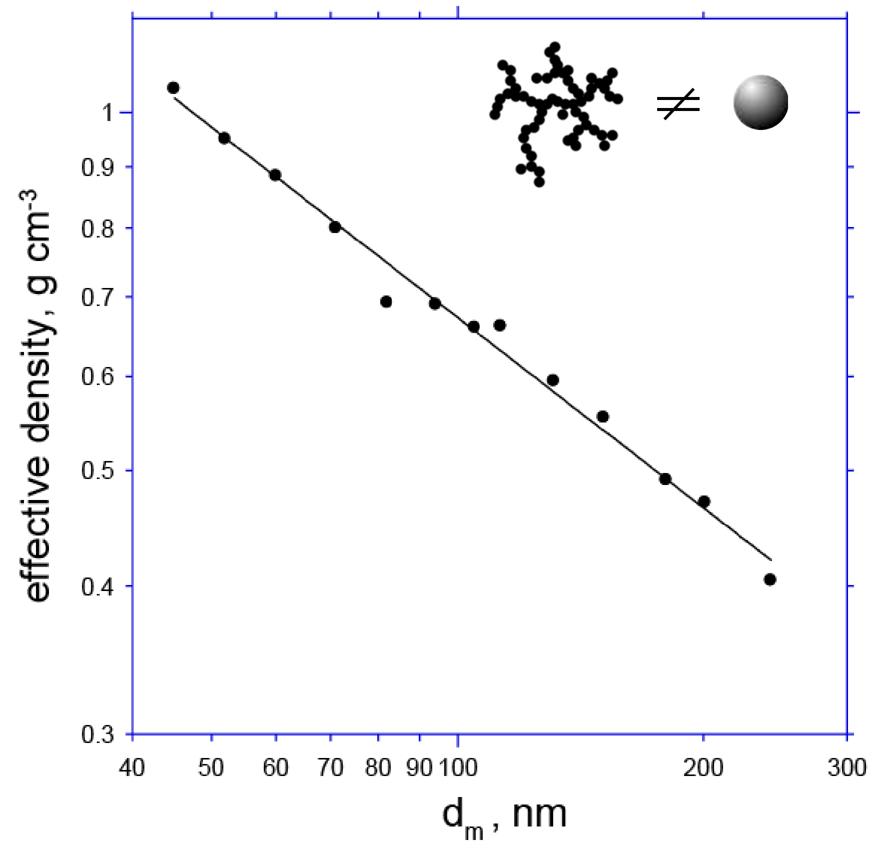


- **SMPS:**
  - ✓ size distributions, d_m
- **SPLAT II:**
  - ✓ single particle size, d_{va}
  - ✓ single particle composition, *MS*
- **DMA/SPLAT:**
  - ✓ effective density, ρ_{eff}
  - ✓ fractal dimension, D_{fa}
  - ✓ primary spherule diameter, d_p
- **APM/DMA/SPLAT:**
  - ✓ particle mass, m_p
  -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

Mass / Mobility Relationship

- Direct measurements of exhaust particulates mass represent significant challenge (complex composition, shapes, morphologies, large size-dependent void fractions).
- Selected particles with narrow distributions of masses using CPMA or APM and measured their mobility distributions using SMPS.
- Mass range from 0.005 fg to 5 fg.





Mass / Mobility Relationship

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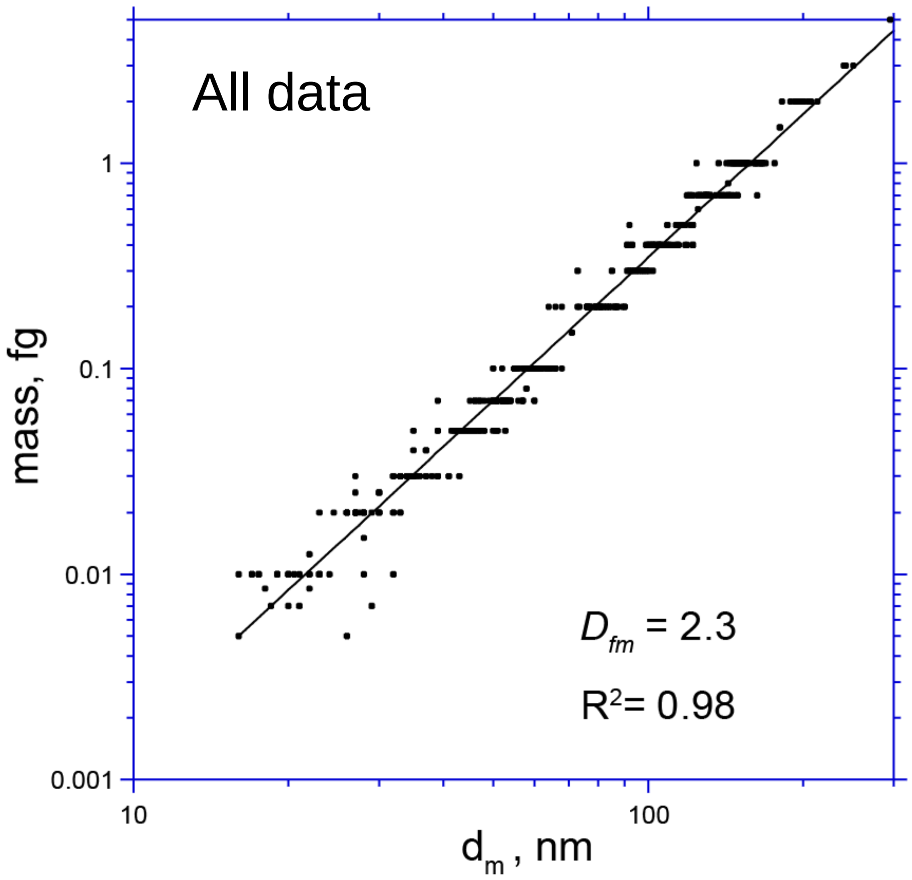

Average fractal dimension D_{fm} = 2.3
15% FWHM

- In addition to providing information on PM fractal dimension, effective density vs. size, average primary spherule diameter, number of spherules, etc. mass/mobility relationship can be used to quantify particle mass filtration efficiency with PM mass accumulation (filter state).
- Characterized mass vs. mobility relationship for ~60 different SIDI operating conditions/fuels.
- Most fuels/conditions showed a very similar mass/mobility relationship.
- A single relationship can be used to determine particle mass with good accuracy (±30% of true value) across all sizes and conditions.

Filtration Experiments – Effect of Particle Shape on Penetration Efficiency

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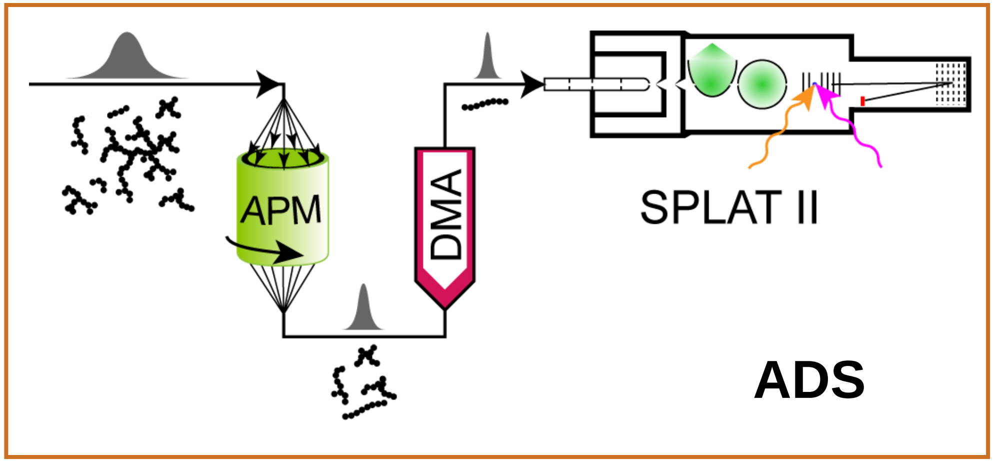
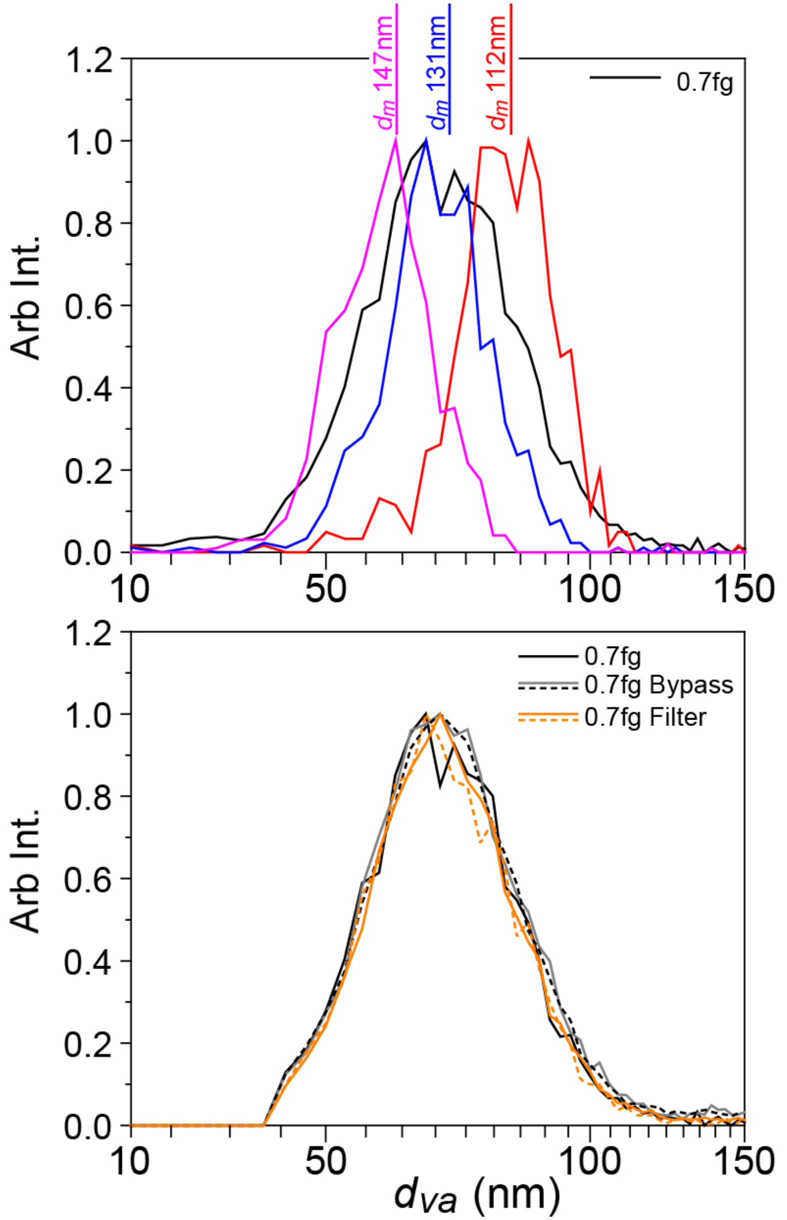


- Applied ADS to demonstrate the presence of particles with different shapes for mass-selected particles generated under heavy load condition.
- Separated particles with different shapes and characterized their dynamic shape factors in two different flow regimes.

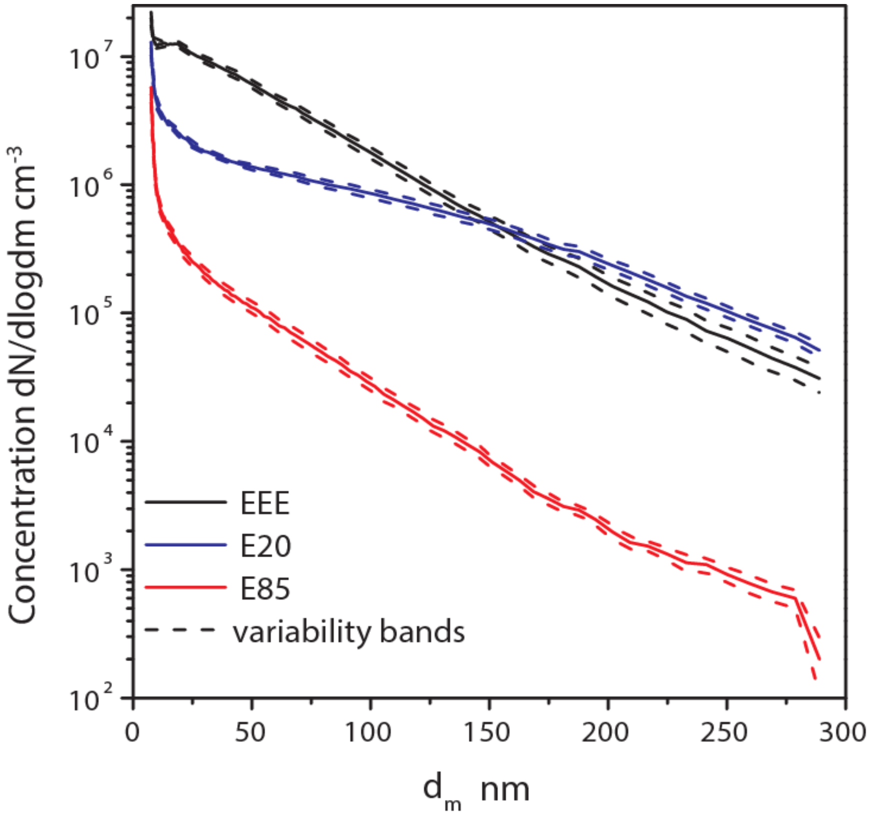
d_m, nm	147	131	112
χ_t	1.83	1.96	2.05
χ_v	2.62	2.83	3.17

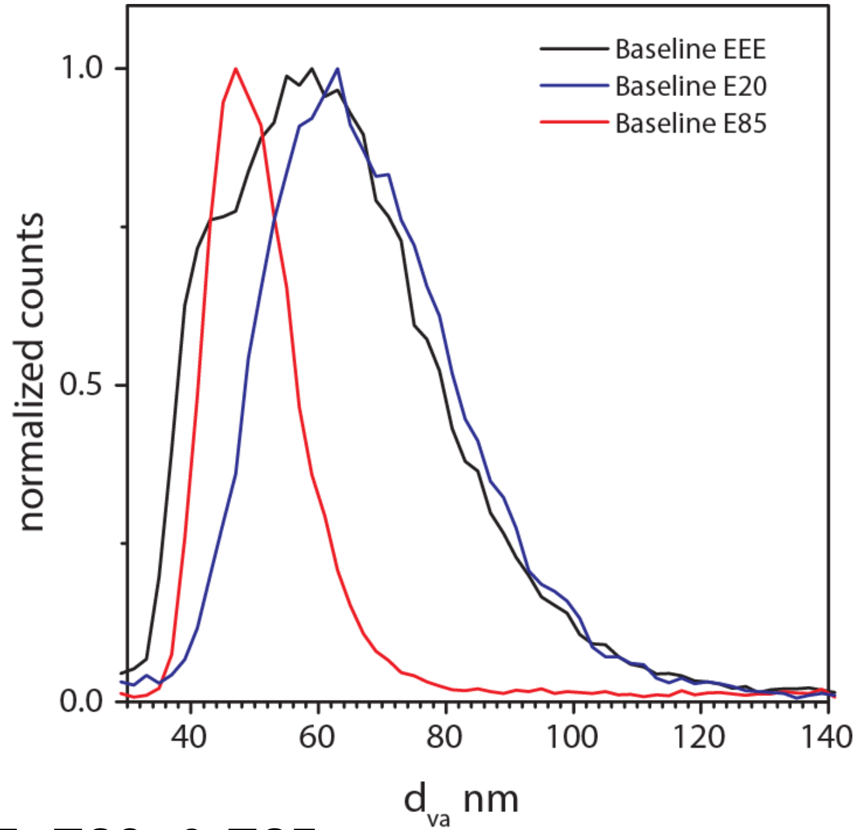
- Within the present distribution of shapes filter efficiency is *independent* of particle shape



Baseline Conditions: EEE, E20, E85

- Very large dataset: different fuel blends (EEE, E10, E20, E30, E50, E85, E100, TRF30, ISO), a wide range of engine operating conditions, including sweeps of equivalence ratio and injection timing, DI and premixed pre-evaporated (PMPV) operations.

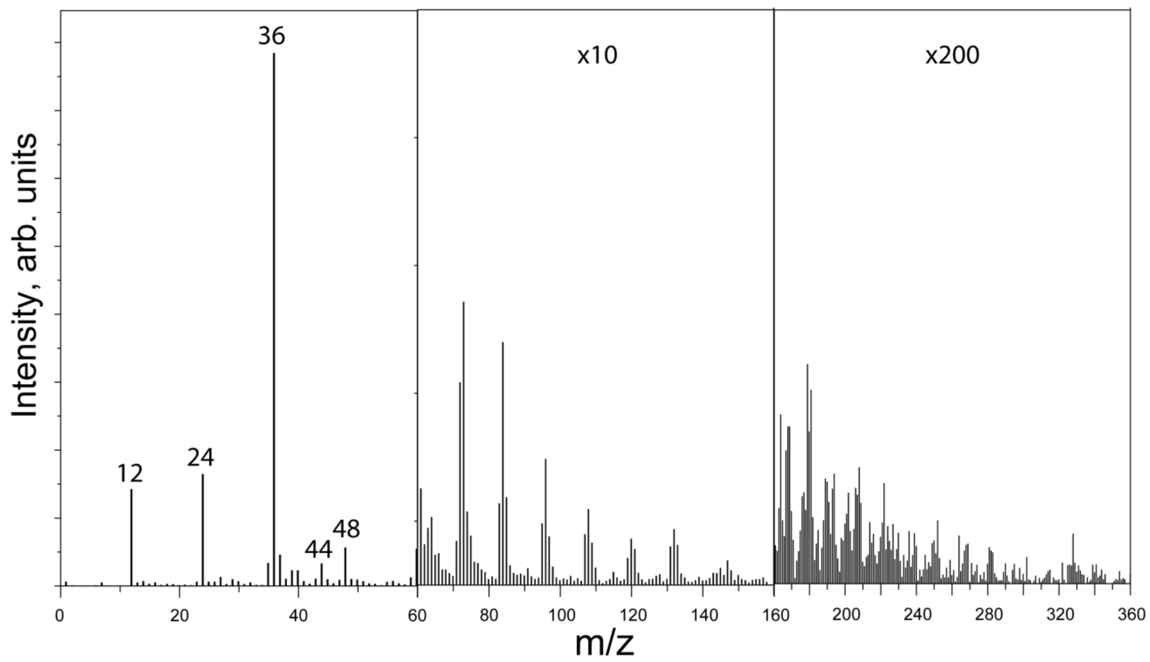


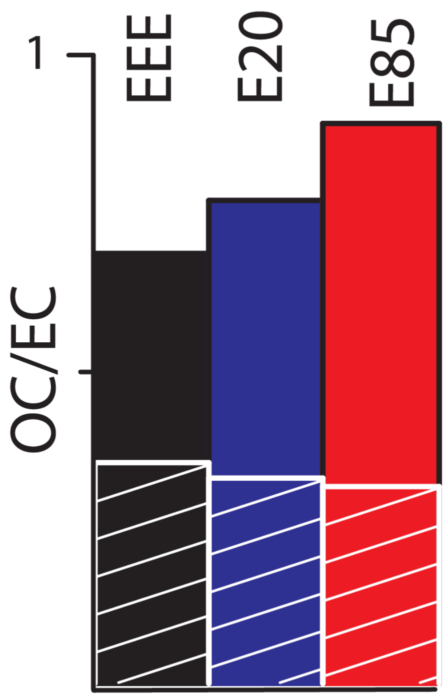


- Example: Baseline conditions for EEE, E20, & E85.
- Very different size distributions. E85 produces significantly fewer PM.

Baseline Conditions: EEE, E20, E85

- All particles contain large fraction of organics (OC).
- Example: Baseline conditions for EEE, E20, & E85.





- SIDI PM organic fraction is tightly integrated within primary soot spherules.
- It is extremely difficult to remove organics from the SIDI particles by volatile particulate removal (VPR).
- These findings were corroborated with SIDI PM analysis by XPS, FTIR/ATR, and HRTEM.

Volatile Particulate Removal (VPR)

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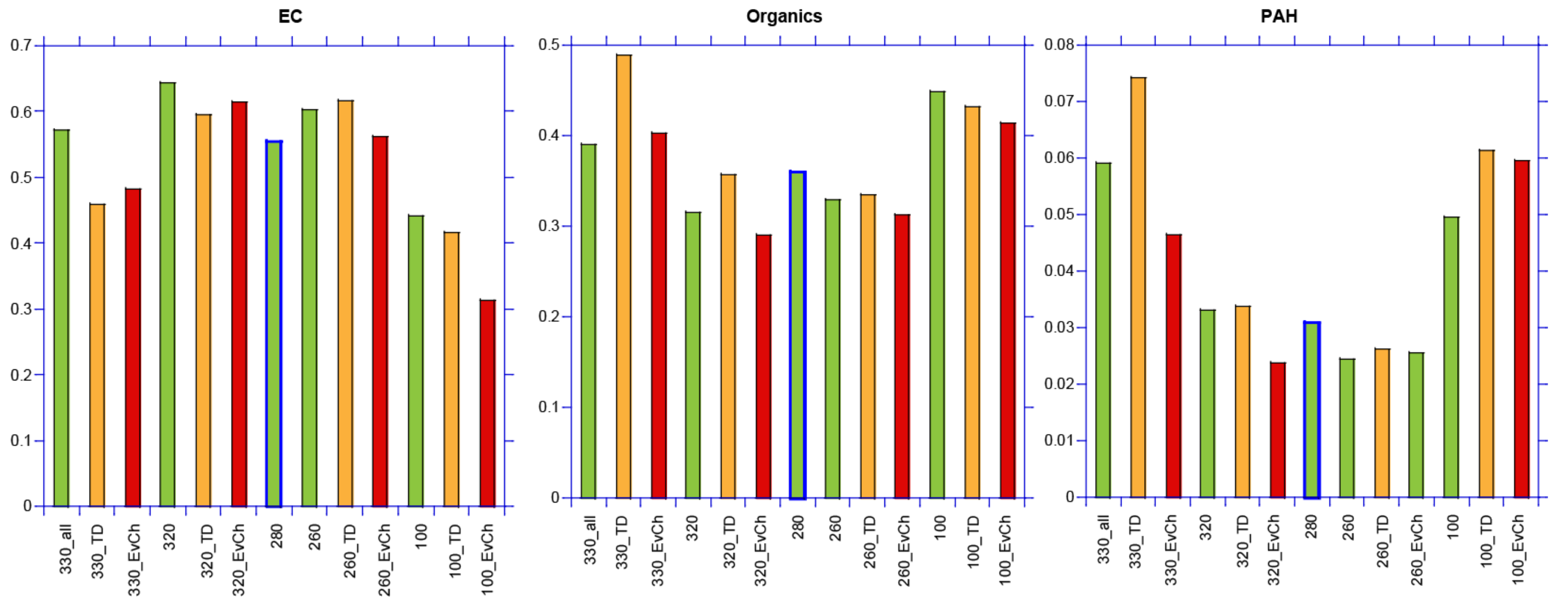
- It is extremely difficult to remove organics from the SIDI particles by VPR
- Example: Fractions of EC, OC, and PAHs for SIDI PM emitted under different operating conditions (EEE, EOI sweep)

  thermodenuder **(TD, yellow bars)**

  evaporative chamber **(EvCh, red bars)**



Volatile Particulate Removal (VPR)

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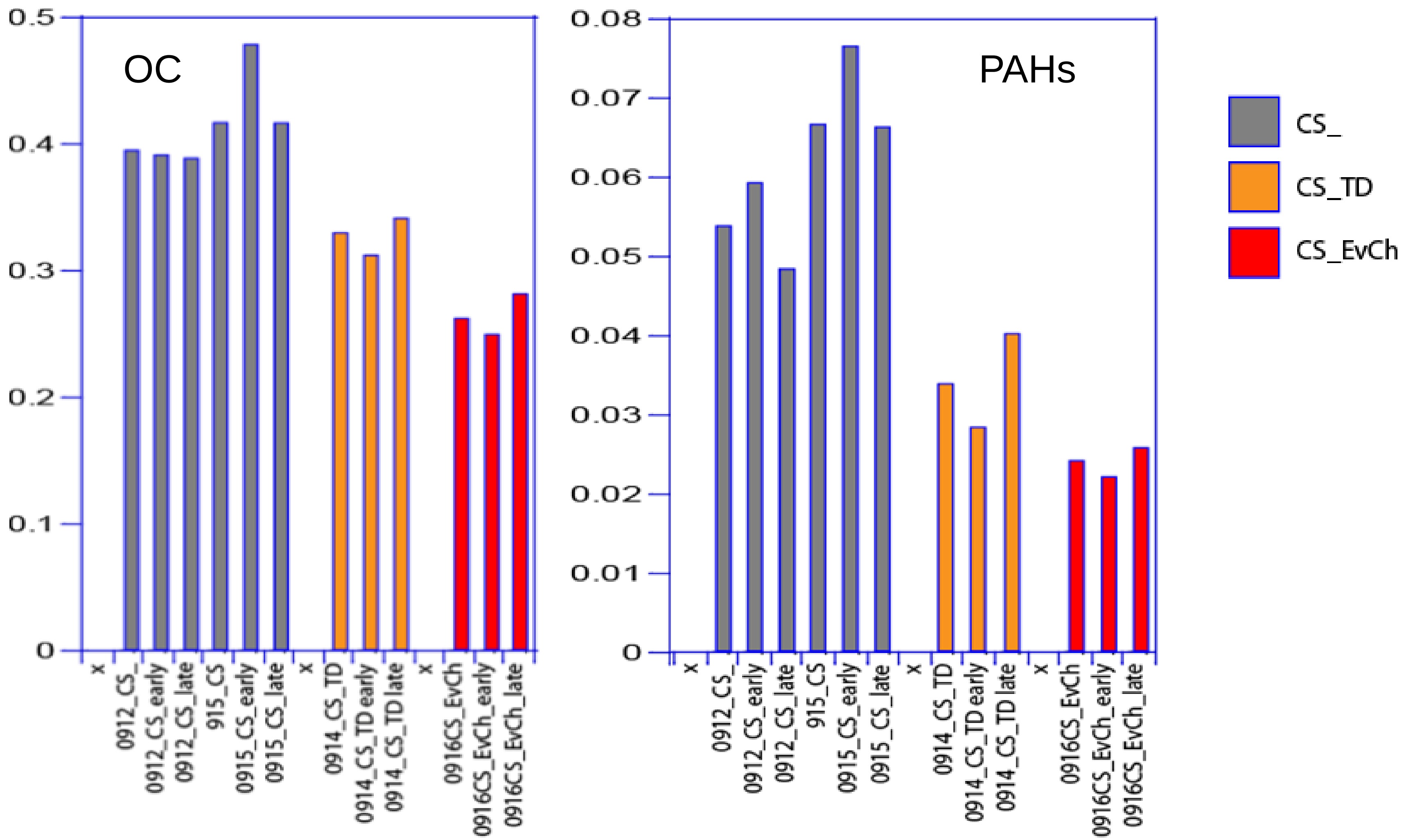
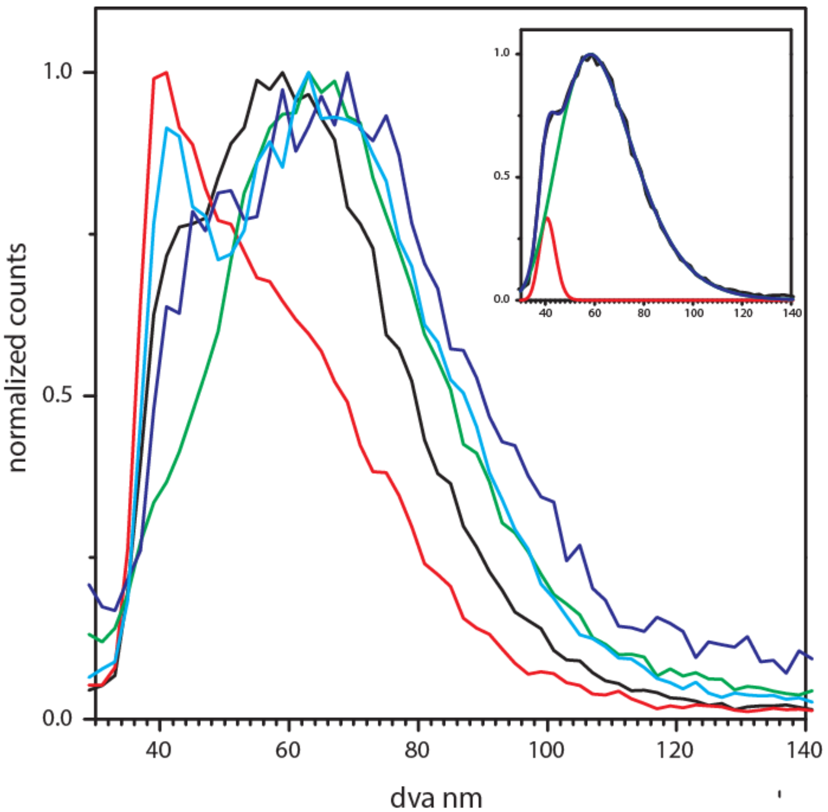
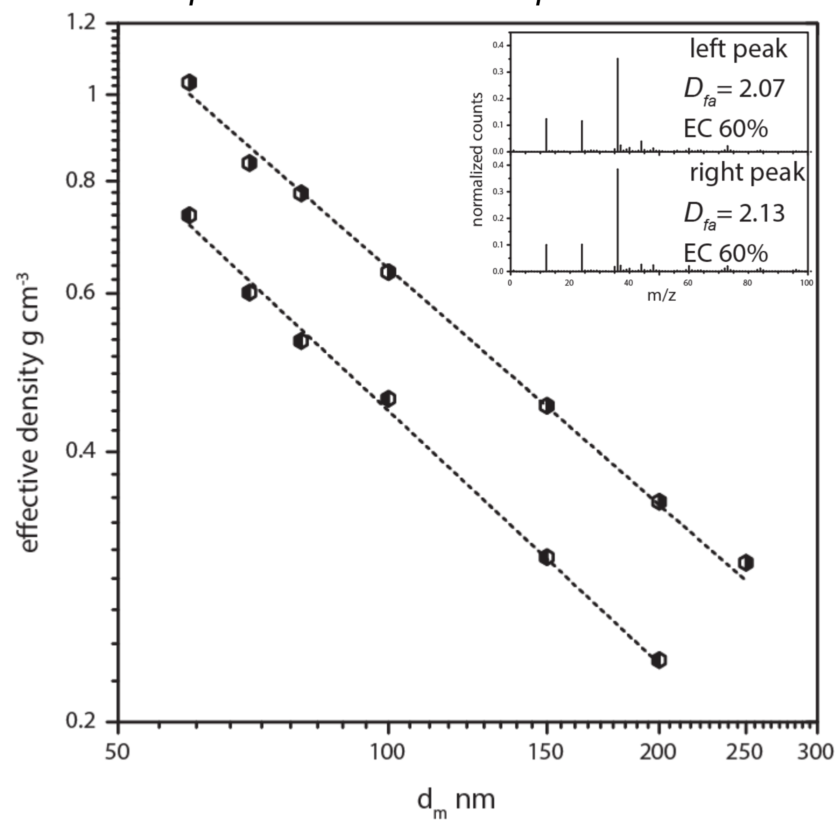
- VPRs *do* remove a significant amount of particle organic content, especially PAHs, for the Cold Start condition



Baseline Conditions: EEE

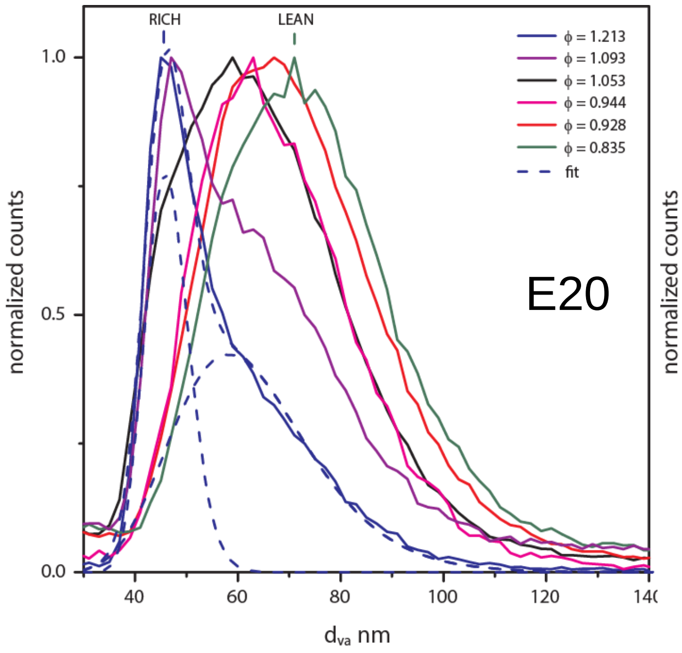
- Under some experimental conditions, overall d_{va} distribution has two distinct particle modes that can be separated.
- Two modes with different effective densities mean either different chemical composition (not the case) or different primary spherule diameters.
- Two types of fractal agglomerates are present: d_p=18 nm and d_p=26 nm

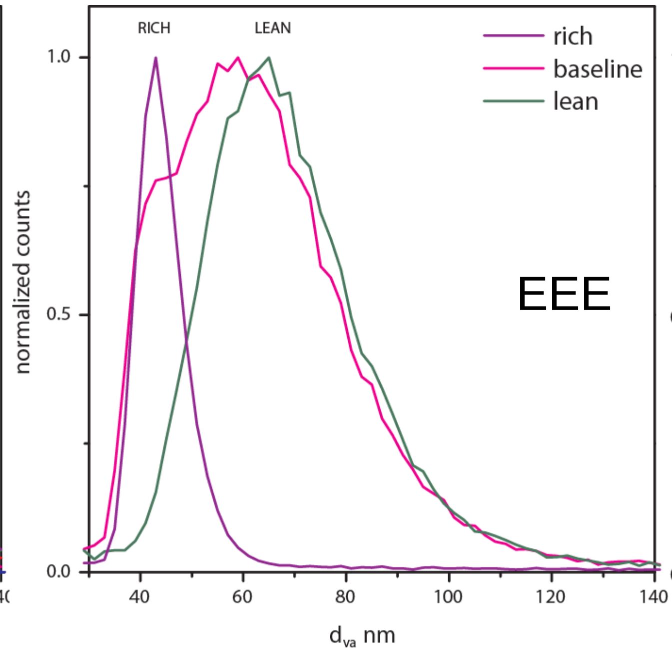


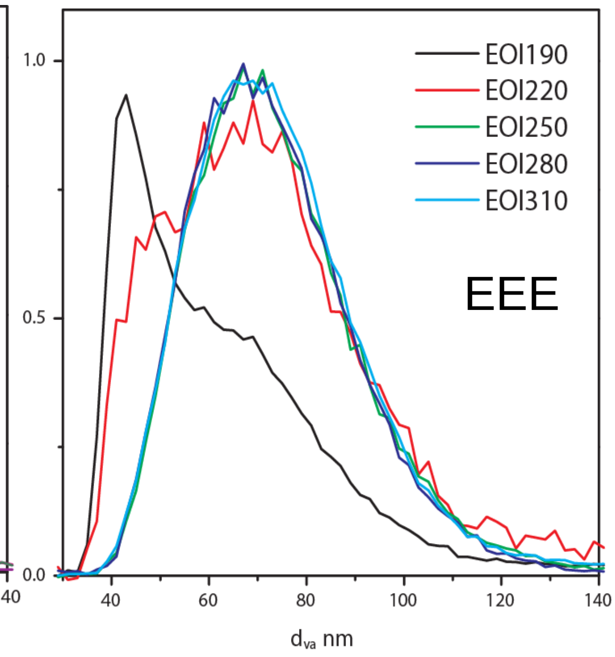


Equivalence Ratio Sweep: E20 & EEE
Injection Timing Sweep: EEE

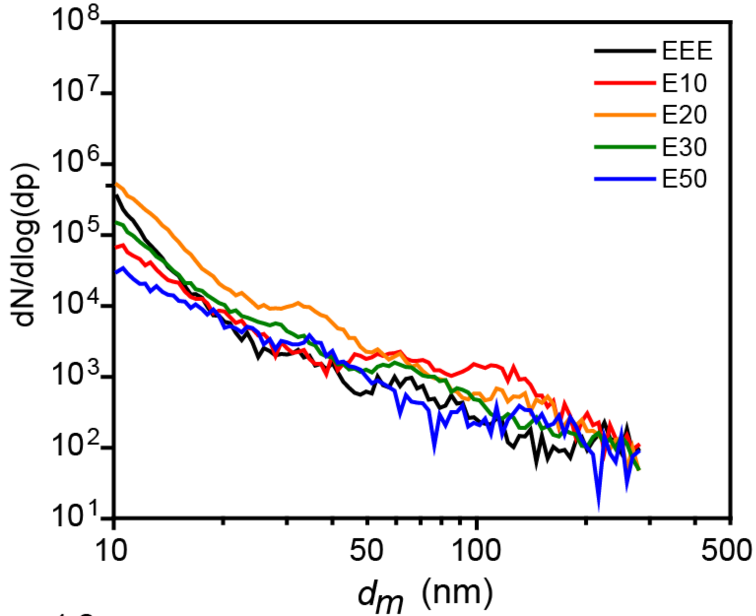
- Two particle modes of fractal soot particles were also observed when varying the equivalence ratio and injection timing.
- Examination of the engine operating conditions under which the two modes appear suggests the presence of multiple mechanisms for in-cylinder soot formation. One possible mechanism could involve relatively rich pockets due to incomplete air/fuel mixing. Soot formation could also be facilitated by pools of liquid fuel caused by wall or piston impingement.

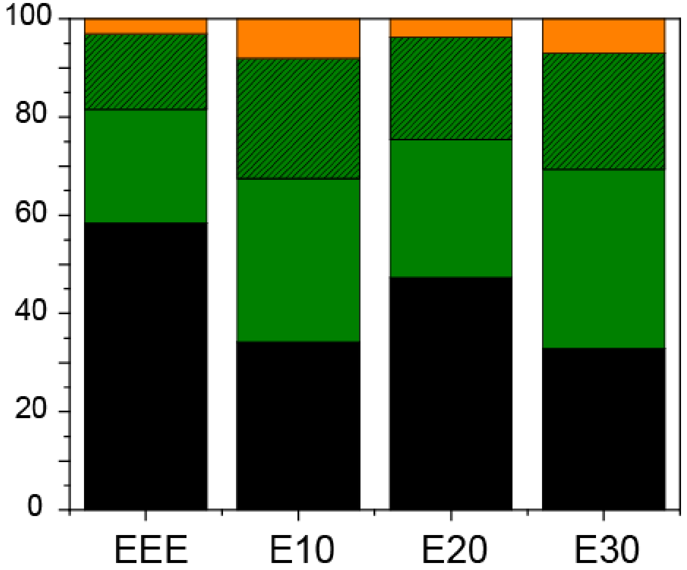


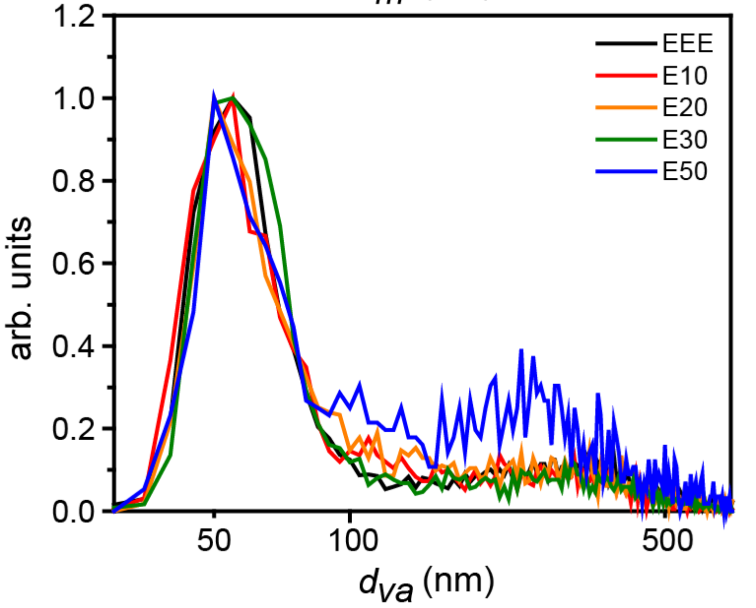




PMPV Fuel Chemistry Study: NFB Condition for Different Fuels Blends







- Compared size distributions and compositions of a non-fuel-related baseline (NFB) PM generated under PMPV operations for different fuels.
- Number concentrations under all NFB conditions are extremely low.
- Both d_{va} and d_m size distributions are all very similar.
- All d_{va} size distributions are bimodal.
- E50 produces slightly fewer particulates, has larger fraction of compact OC-rich particles.

PMPV Fuel Chemistry Study: EEE, Φ Sweep

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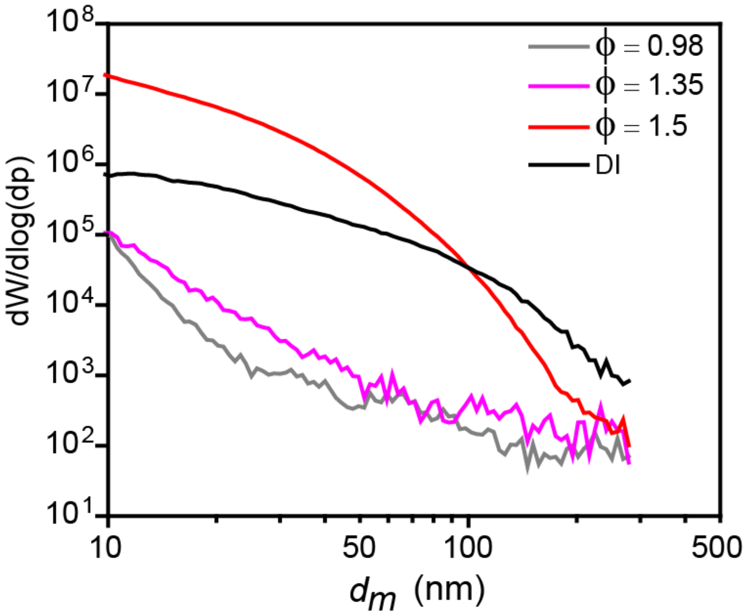
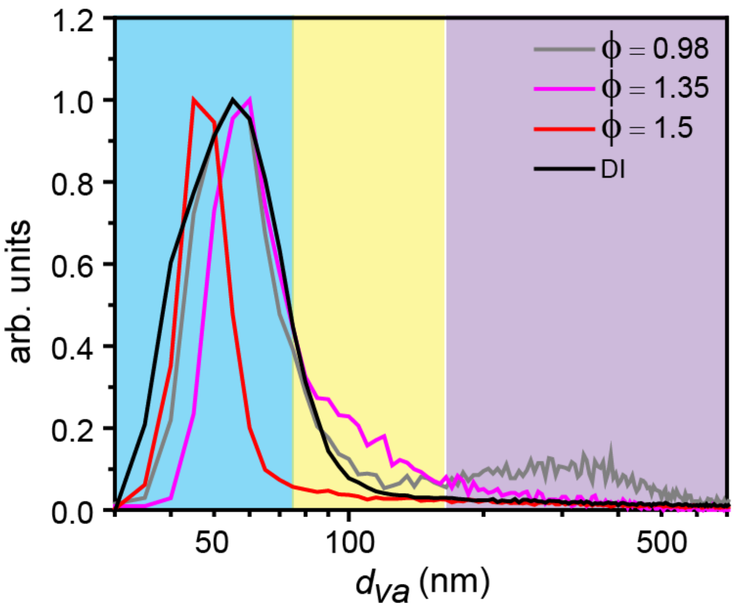
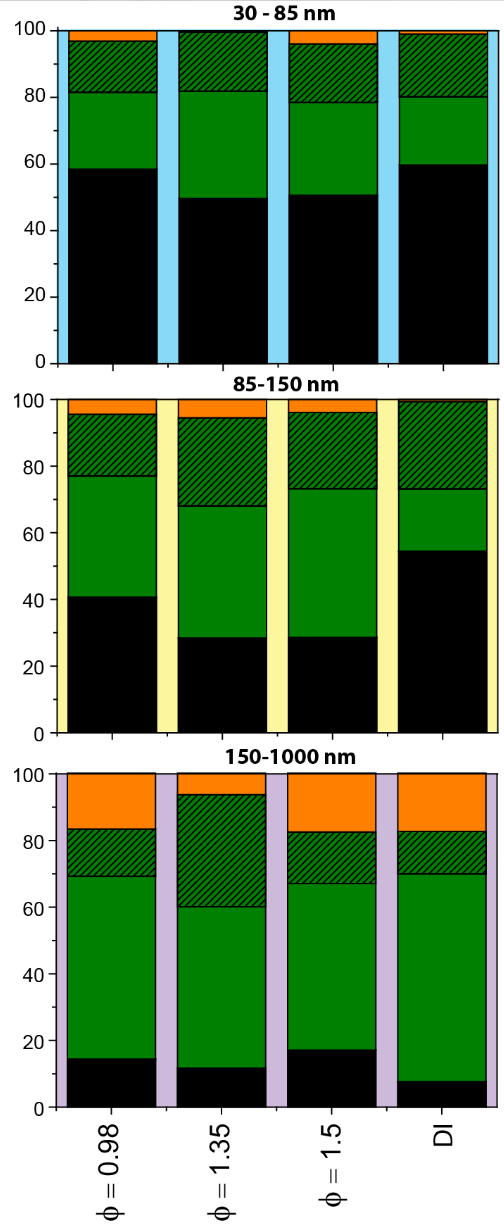


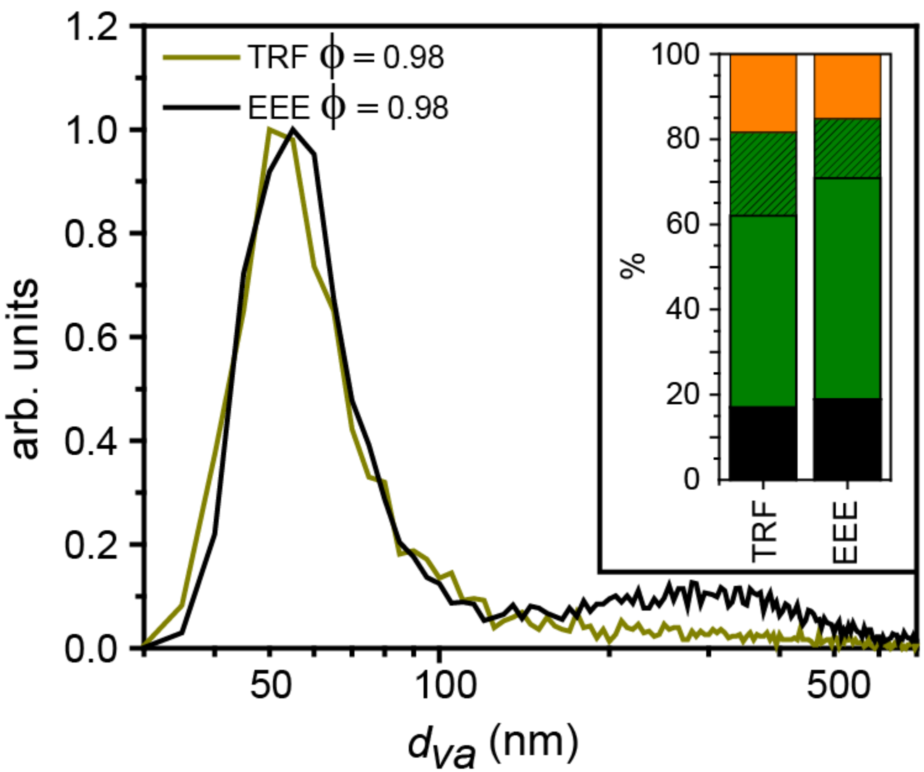


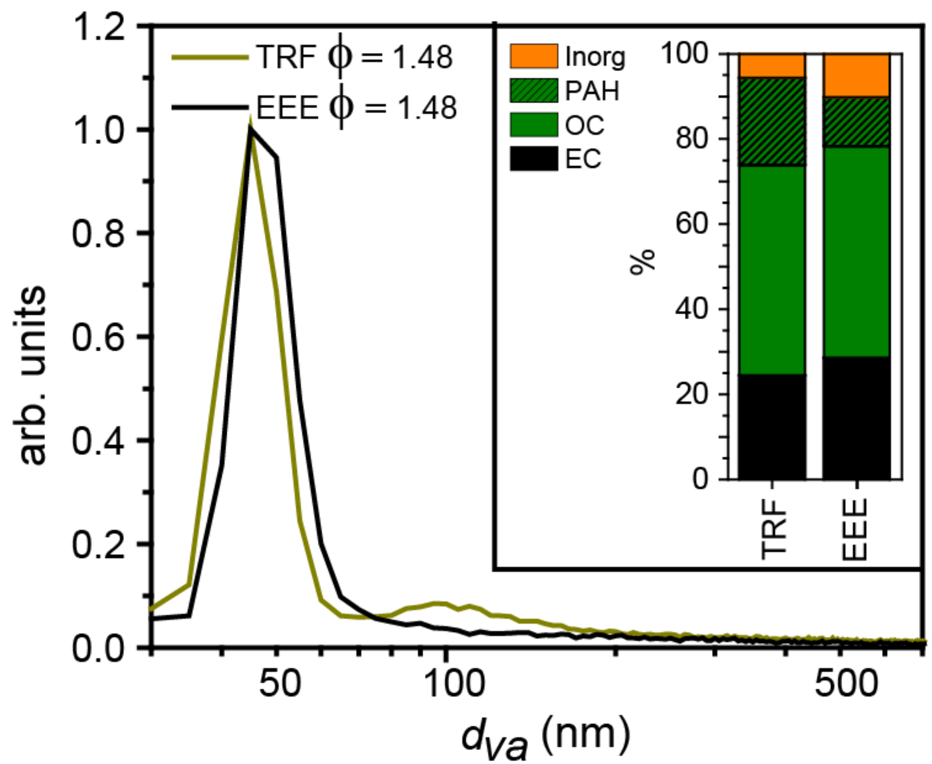


- Compared size distributions and compositions of PM generated under PMPV operations at different Φ for different fuels.
- Example: EEE.
- Similar to DI EEE and E20, increase in Φ results in higher number concentrations of fractal agglomerates that are comprised of smaller primary spherules and contain slightly large OC fraction.
- Larger non-fractal particles have larger fraction of organics and metals.

PMPV Fuel Chemistry Study: Comparison of EEE and TRF30

- Compared size distributions, composition, and morphology of PM generated by EEE and TRF30 fuel, formulated to match chemical properties of EEE.
- PM generated EEE and TRF30 fuels under PMPV operation at matched Φ exhibit similar d_{va} and d_m size distributions, compositions, and morphology (TRF D_{fm}=2.37; EEE D_{fm}=2.42), suggesting that TRF30 can serve as an adequate chemical surrogate fuel for EEE.





DI Fuel Chemistry Study: Comparison of EEE and TRF30

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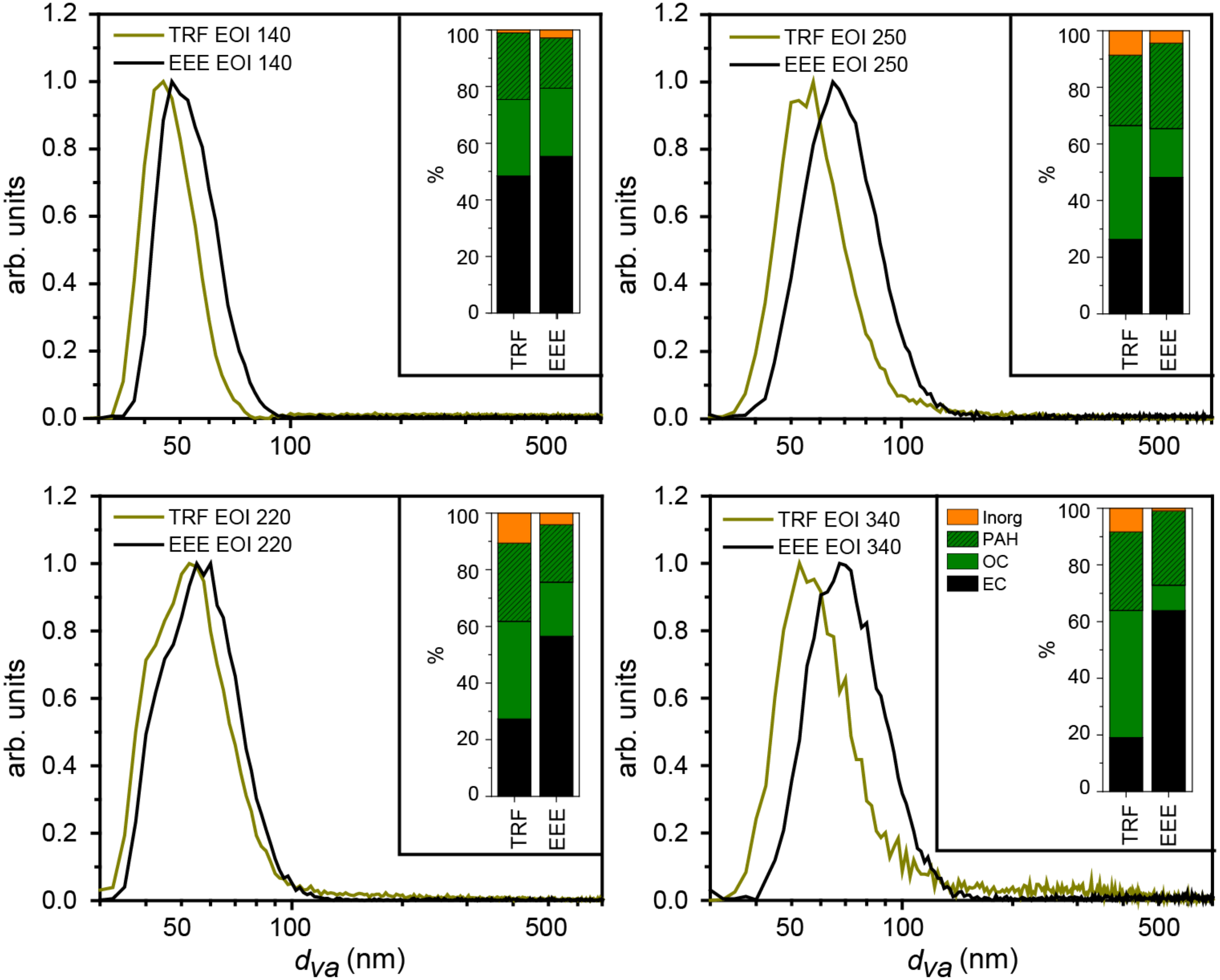

- Compared composition and morphology of PM generated by EEE and TRF30 fuels for DI EOI sweep
- There are clear differences in morphology and composition of particles generated by EEE and TRF30 fuels under PMPV operation at matched Φ
- EEE produces more EC, larger primary spherules

DI PM for different fuel blends: EEE, EOI 250, E10, E20, E30, E50, E100

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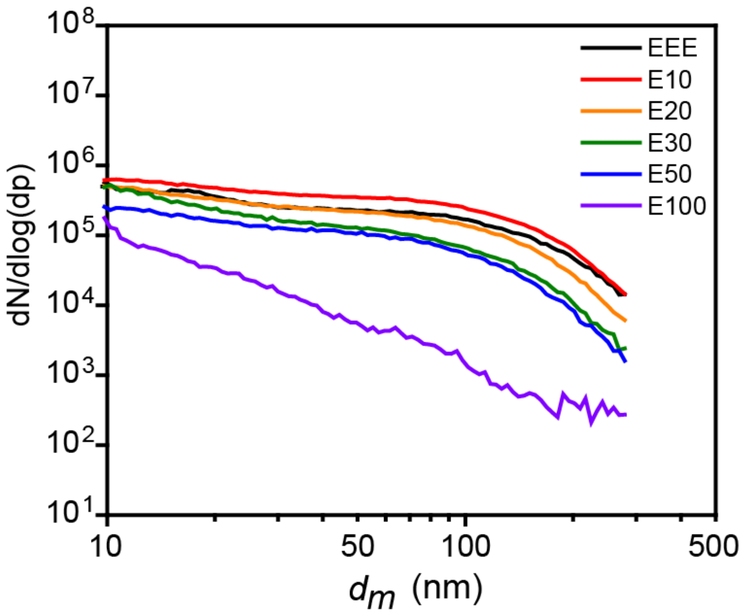

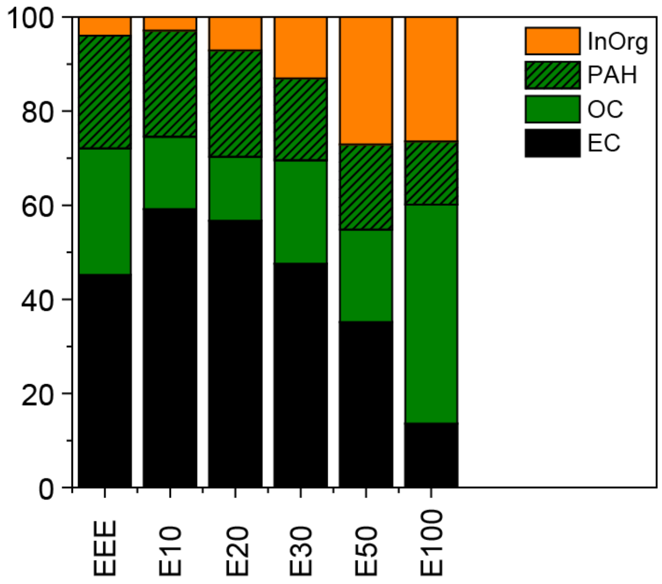

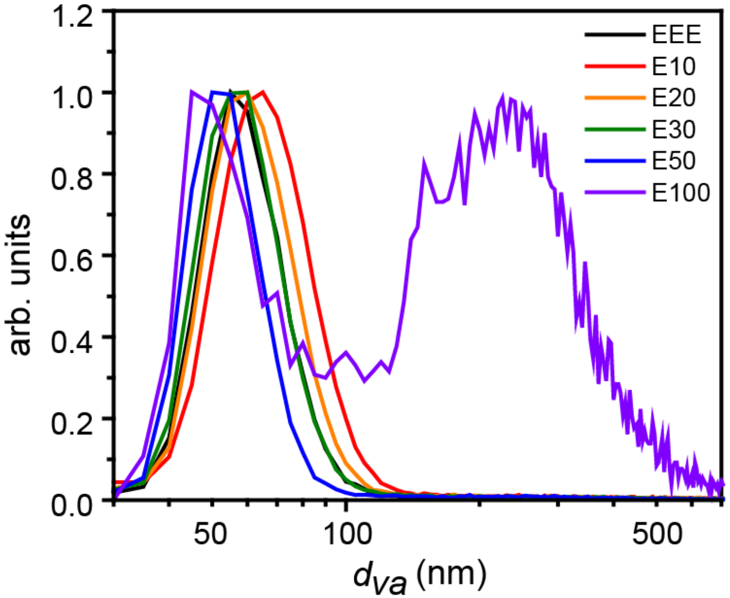

- E100 produces significantly fewer particulates. As a result, larger non-fractal particles (engine wear & tear, lubricating oil) represent significant fraction.
- SIDI PM exhibited high organic content, which depends on fuel blend and engine operating condition.
- Primary spherule size was observed to vary dramatically in SIDI soot.

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 SIDI engine as function of fuel blend and operating conditions, including DI and PMPV.
- A single mass/mobility relationship can be used to determine PM mass with good accuracy (±30% of true value) across all sizes and conditions
- Separated particles with different shapes and investigated the effect of particle shape on filtration efficiency. Within the present distribution of shapes filter efficiency is *independent* of particle shape.
- SIDI PM exhibited high OC content (40-60%) that was tightly bound with EC within the primary spherules, making is impossible to remove by TD or in evaporative chamber. The morphological distribution of OC in SIDI PM has important implications on soot oxidation and PM after-treatment.
- Primary spherule size was observed to vary dramatically in SIDI soot, which is a marked contrast with diesel.
- Two distinct modes observed in under some conditions result from different primary spherule sizes indicate presence of multiple mechanisms for in-cylinder soot formation, e.g. heterogeneity due to incomplete air/fuel mixing.