Measurement and Characterization of Unregulated Emissions from Advanced Technologies

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Vehicle Technologies

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ACE045

U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY

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Overview

- Timeline
  - » Start: FY2009
  - » Finish: Ongoing
  - » % Complete:
- Budget
  - » FY09 Funding: $475k
  - » FY10 Funding: $450k
  - » FY11 Funding: $425k
- Barriers
  - » Lack of actual emissions data on pre-commercial and future combustion engines.
    - “Development of fuel-efficient technology complies with existing regulation and also considers unregulated emissions
- Partners
  - » CRC Emissions Working Group
    - PM Measurements Committee
    - On-Road Emissions Workshop
  - » University of Maryland
  - » GM (provided lean DISI vehicle)
  - » Delphi
  - » ACEC Tech Team Input
  - » Other ORNL-FEERC Projects:
    - Advanced Combustion
    - Advanced Fuels

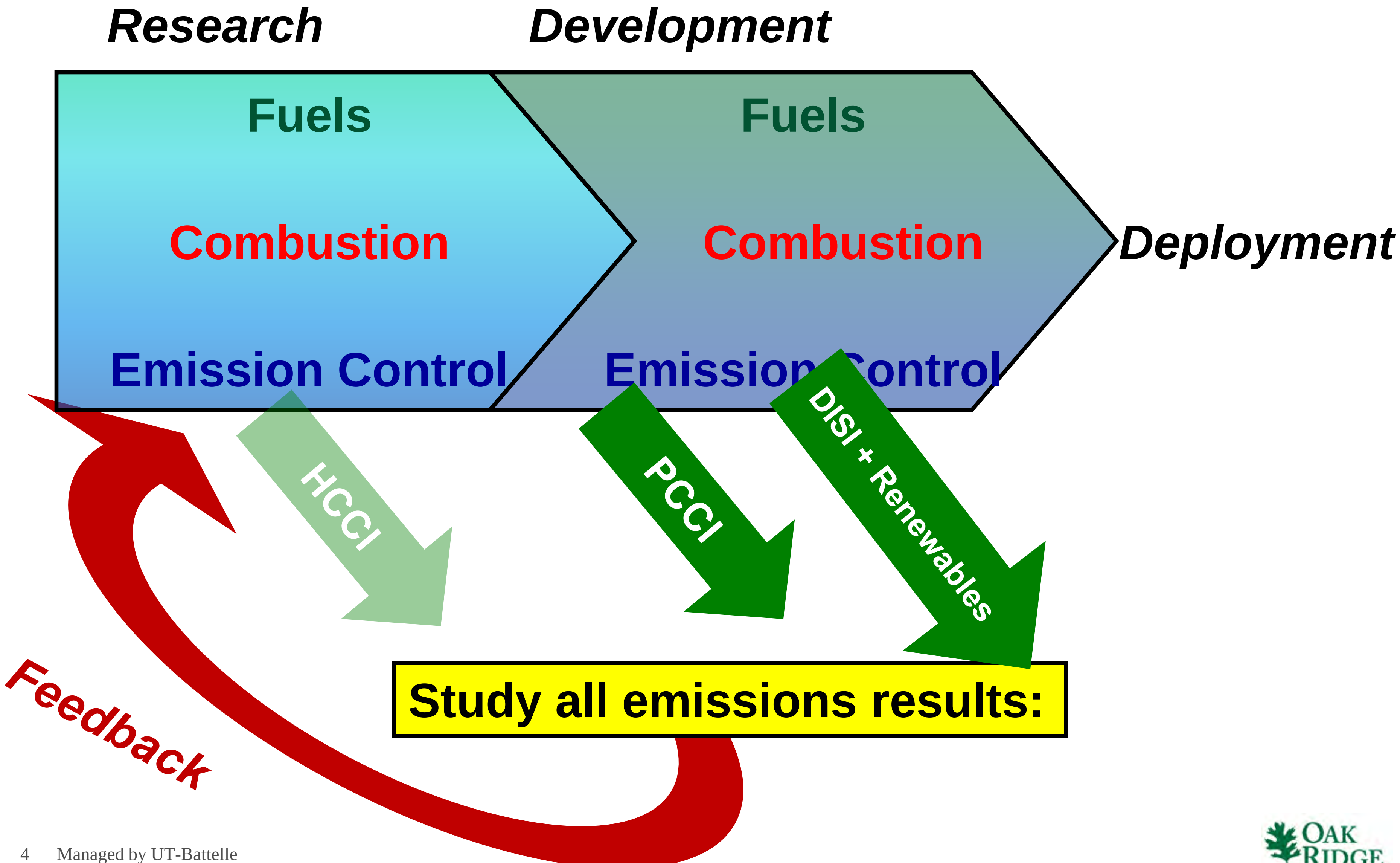
Objectives – continue from FY2009

- **Ensure that advanced petroleum-saving technologies "do no harm"**
  - » Characterize unregulated emissions from advanced engines with and without emissions control technologies
  - » Understand fuel substitution effects on emissions
    - E85, intermediate ethanol blends, biodiesel, other fuels

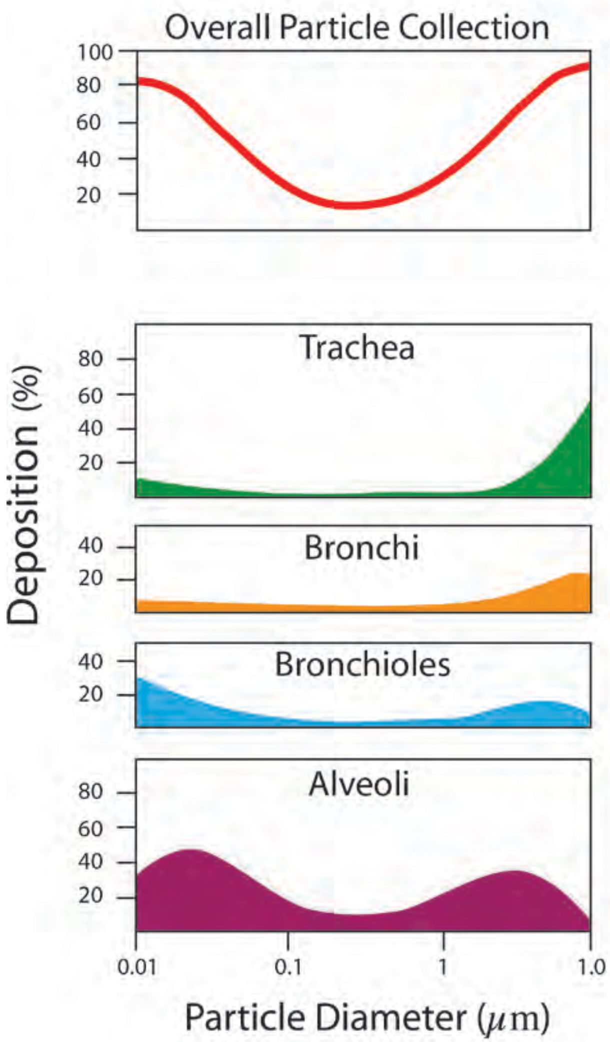
Milestones

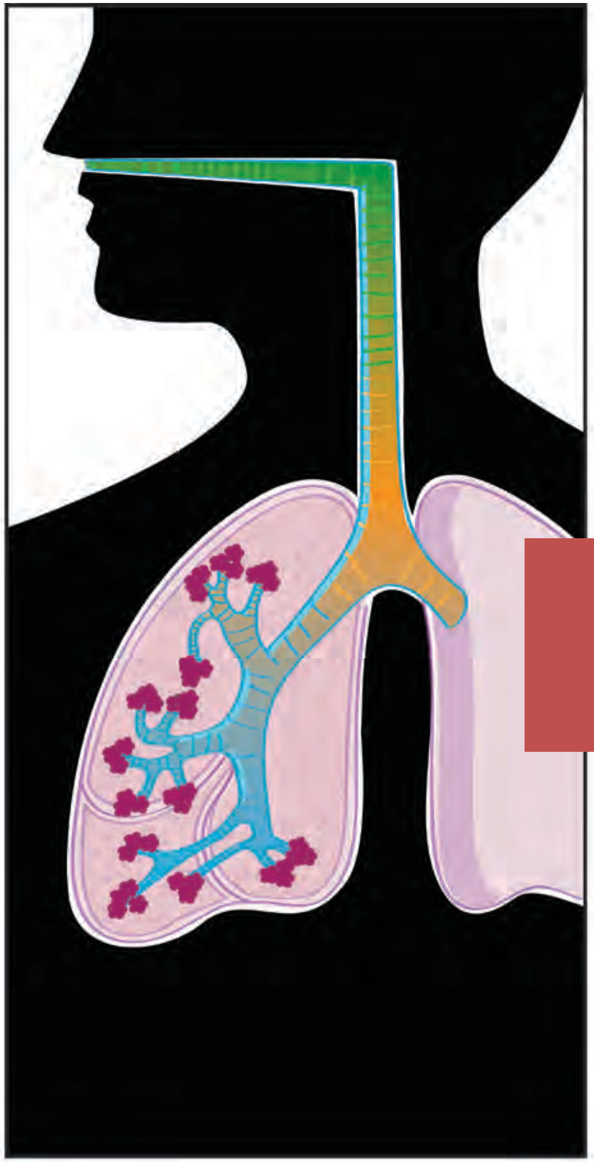
- **FY10:**
  - ➢ Characterize PM and mobile source air toxics from stoichiometric and lean DISI vehicles operating on blends of ethanol and gasoline (Sept. 30, 2010)
  - ➢ Status: Complete
- **FY11:**
  - » Characterization of PM emissions from start-stop activity (Sept. 30, 2011)
  - » Status: In progress (Ongoing work continuing)

Approach designed to address key barriers



Particle Size Influences Location of Deposition in Respiratory System





Nanoparticles can penetrate into alveolar region

- Data Source: Heyder (2004)

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Technical Accomplishments and Progress

Since last review (June 2010):

- **Completed data analysis from stoichiometric DISI vehicle experiments**
- **Finished lean DISI vehicle evaluation**
  - » E0, E10, and E20 fuels
- **Evaluated DISI engine PM emissions with E0, E20, and E85**
  - » Advanced controls on engine
  - » PM morphology and sizing
- **Measured PM emissions from RCCI engine**
  - » Reported by Jim Parks in ACE031

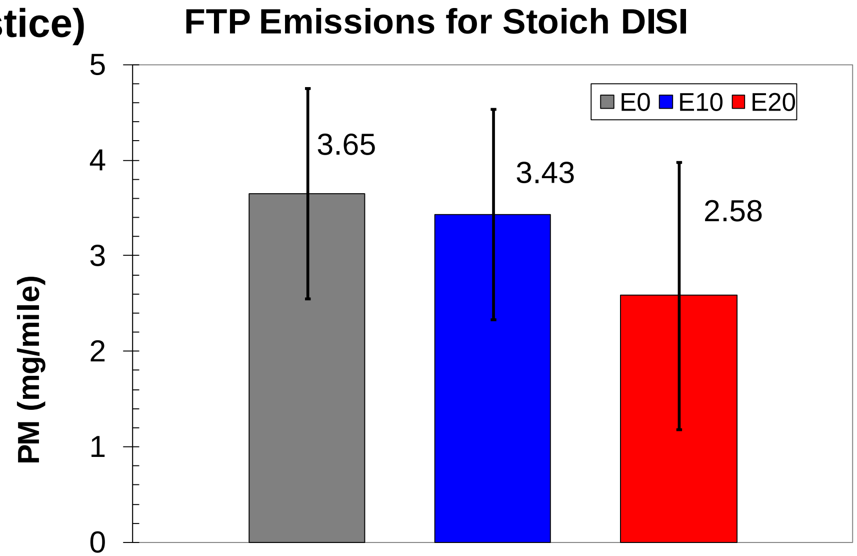
Leveraging existing ORNL-FEERC programs to acquire critical data for the Health Impacts activity

Stoichiometric DISI Platform

Lean DISI Platform

Technical Accomplishments: DISI vehicle emissions

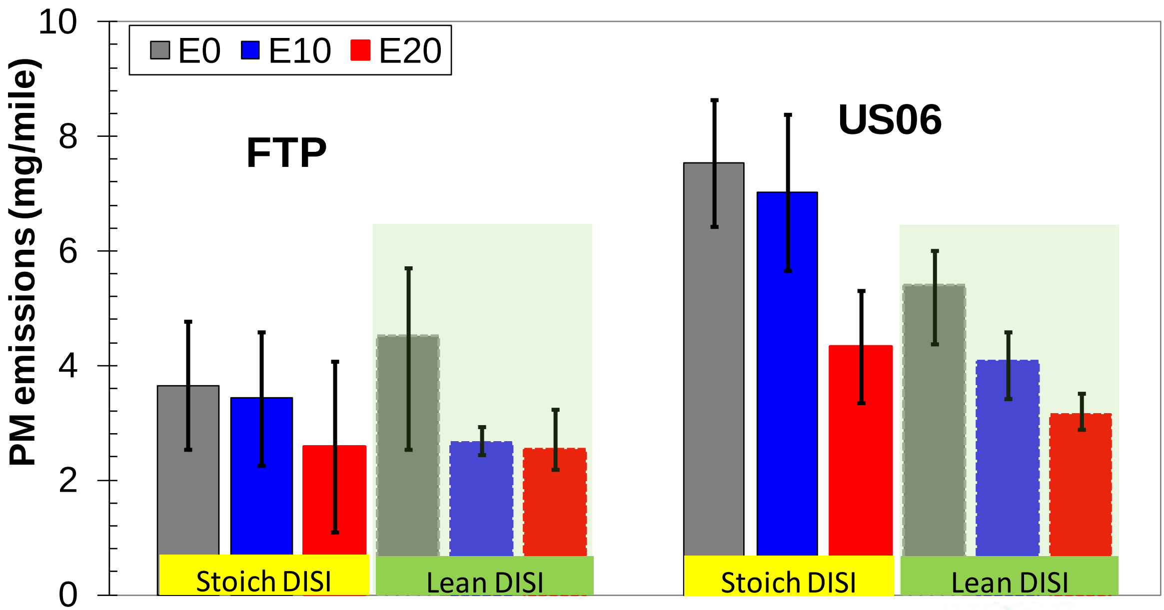
- **Last year, stoichiometric DISI vehicle (Pontiac Solstice) data presented and published (SAE 2010-01-2129)**
  - » E20 reduced particle mass (up to 40%) and number
- **Lean DISI BMW (Euro IV, lent by GM) acquired for investigations of lean NOx catalyst strategies**
  - » Leveraged efforts to get Health Impacts data
  - » E0, E10, and E20 with low S fuel
  - » Upstream three-way cat and downstream NOx trap
  - » *SAE 2010-01-2267* covers catalyst work



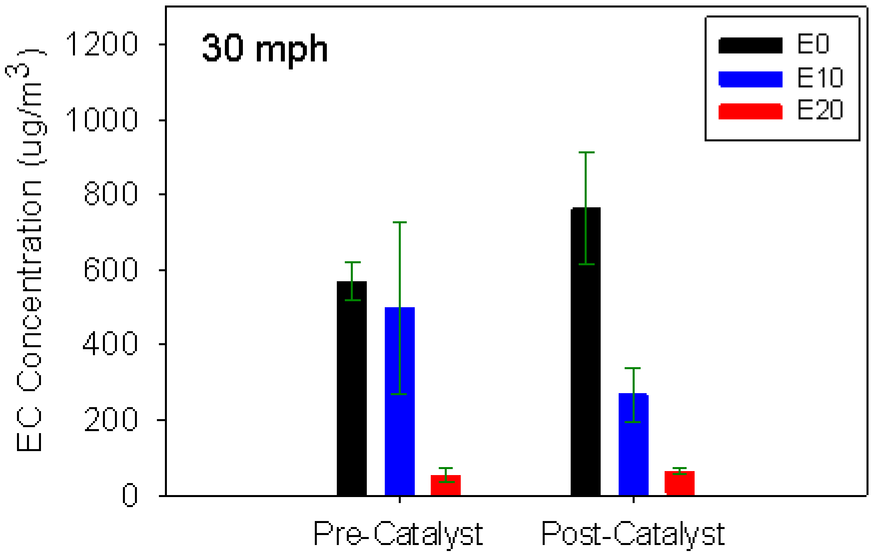
Lean DISI Platform:

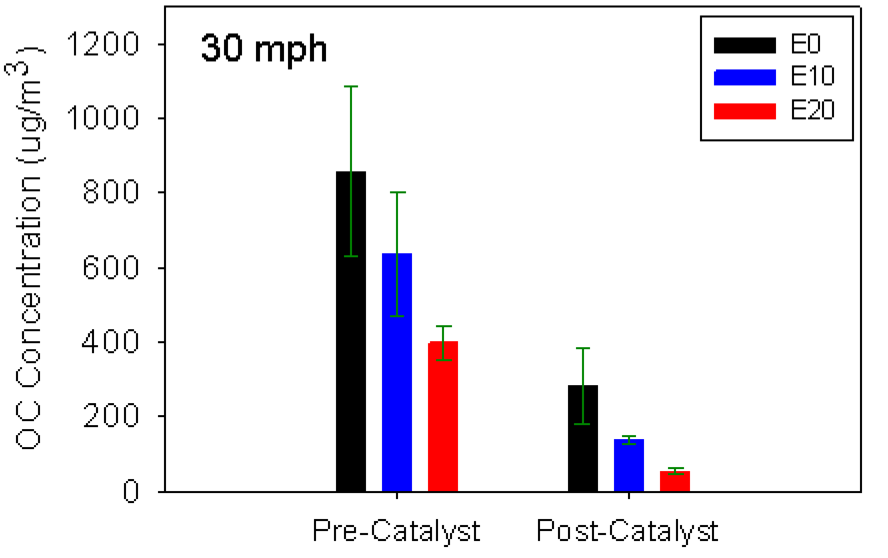
Euro V BMW, 2.0L, non-turbo

- *FTP – urban cycle*
  - *CO, CO_2,HC, NOx, PM mass, PM number*
  - *Aldehydes and ethanol*
- *US06 – harder accelerations*
  - *CO, CO_2, NOx, HC, PM mass, PM number*
- *Steady-state operation*
  - *OC/EC, PM size*



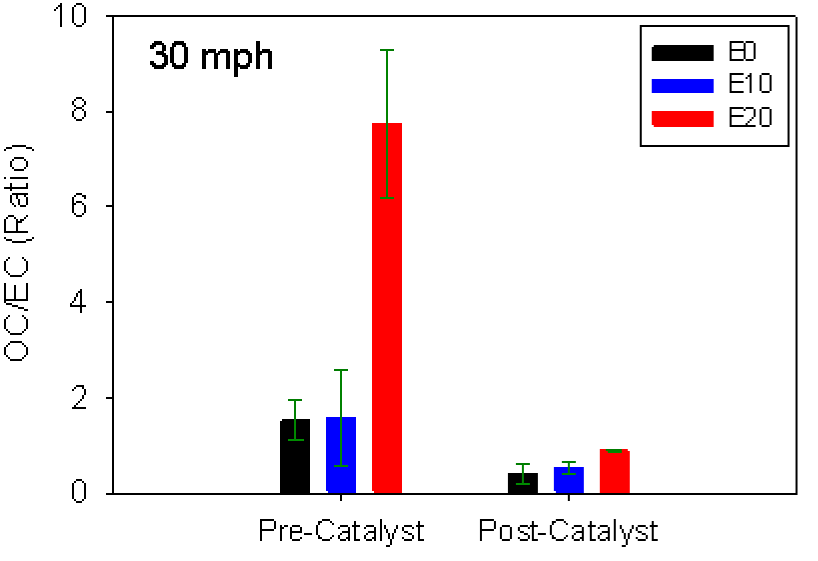
Lean DISI vehicle has lower pre-catalyst OC/EC ratios than stoich DISI





Stoich vehicle had much higher OC/EC: 5 to 50

- Less oxidation in-cylinder
- Difference in injection
- Three-way catalyst still effective at removal of OC



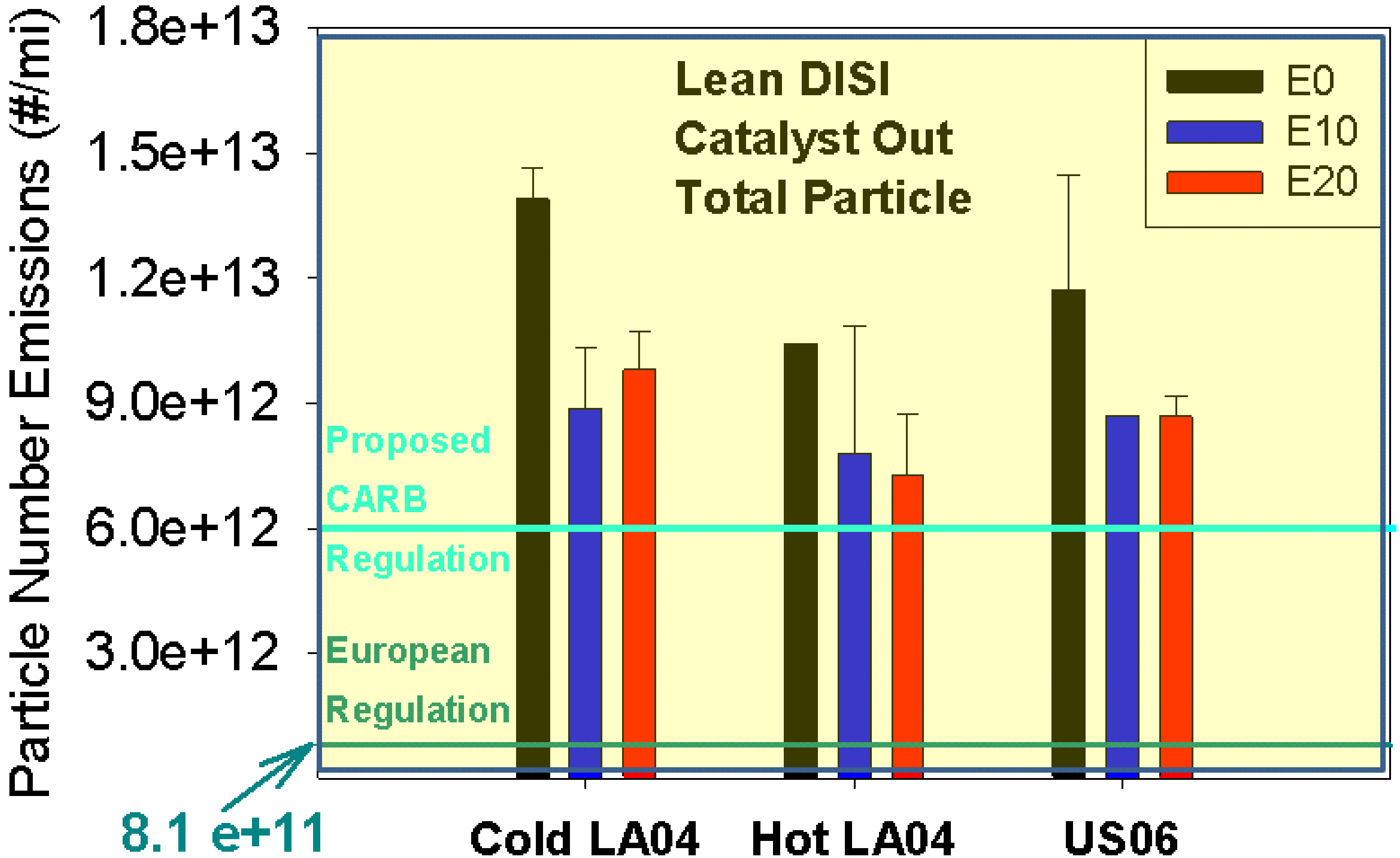
PM Number Regulation in US under consideration

- **Europeans use Particulate Measurement Programme (PMP) protocol**
  - Only PM > 23 nm is counted
- **March 2010 CRC On-Road Emissions Workshop, CARB presented DISI vehicle data**
  - Bag 1 emissions dominated
  - Many vehicles worse than our vehicles and higher than diesel + DPF or PFI gasoline
- **May 2010 CARB issues Preliminary Discussion Paper on future PM regulations**
  - *Goal* is to prevent additional PM burden due to DISI use
  - New PM regs for 2014 (6 mg/mi) 2017 (3 mg/mi)
    - Apply to all light-duty vehicles
  - Alternative: number measurement instead of mass
    - $6X10^{12}$ particles/mi in 2014 > European number standard ($9.6X10^{11}$)
  - EPA Tier 3?

Goal for this activity : Understand and mitigate PM from DISI vehicles and engines

Particle number emissions close to potential regulatory limits

- Important: includes particles < 23 nm



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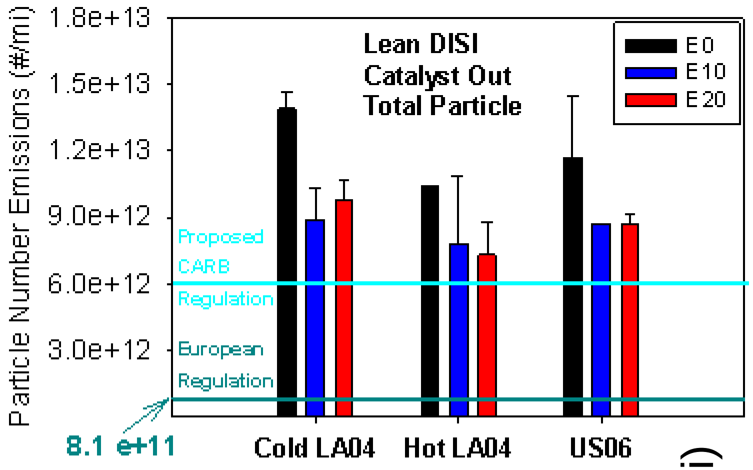
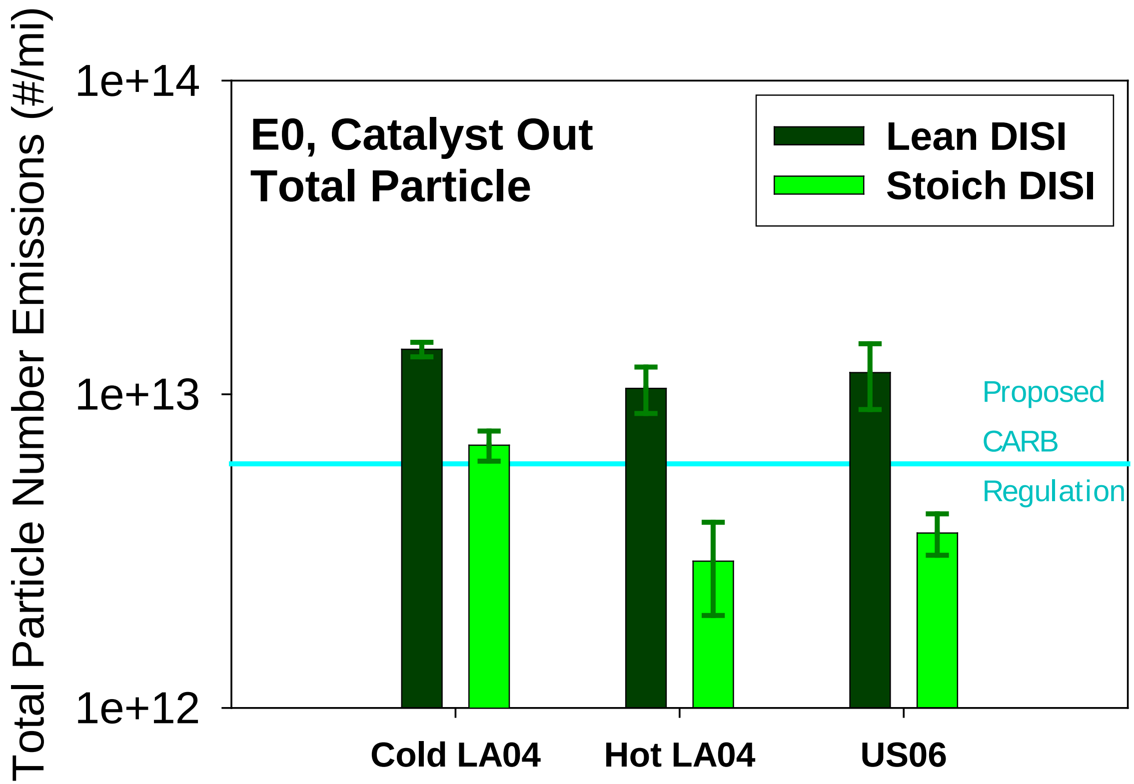
Particle number emissions below potential regulatory limits for stoichiometric DISI vehicle

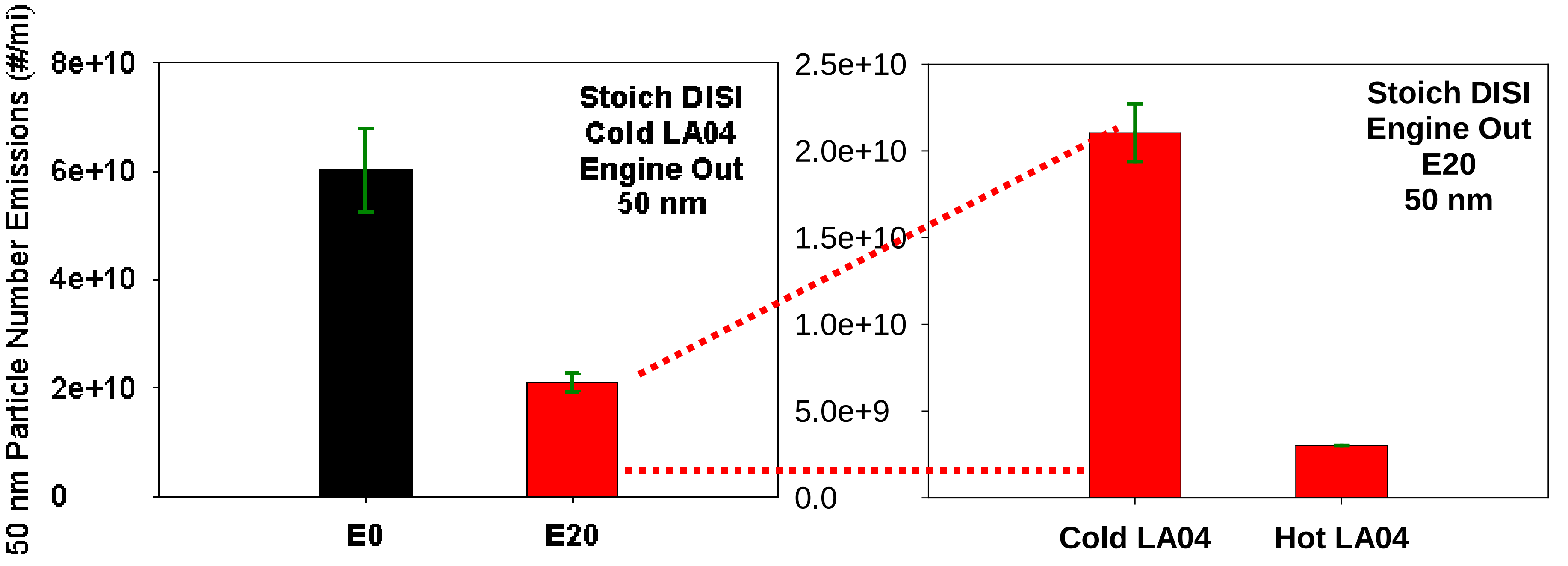


- Stoichiometric vehicle has lower number emissions
- Cold start biggest problem for stoich DISI



We observed higher particle number concentrations for the lean DISI vehicle over all cycles and the different e-blends.

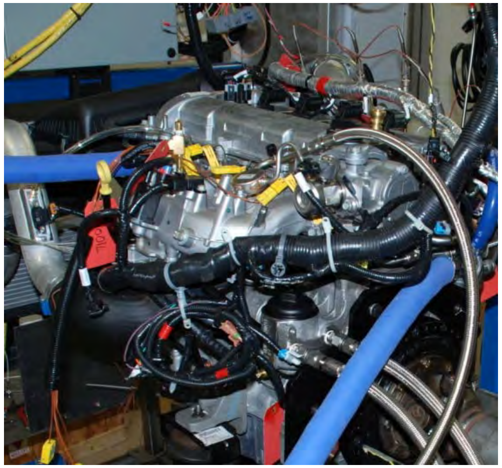
Particles per mile decrease with ethanol content, T



As more manufacturers adopt DISI platforms, vehicle PM emissions to the environment may increase. Understanding of PM formation processes in DISI combustion can help mitigate problem and avoid an aftertreatment solution

Technical Accomplishments: DISI engine with full controls

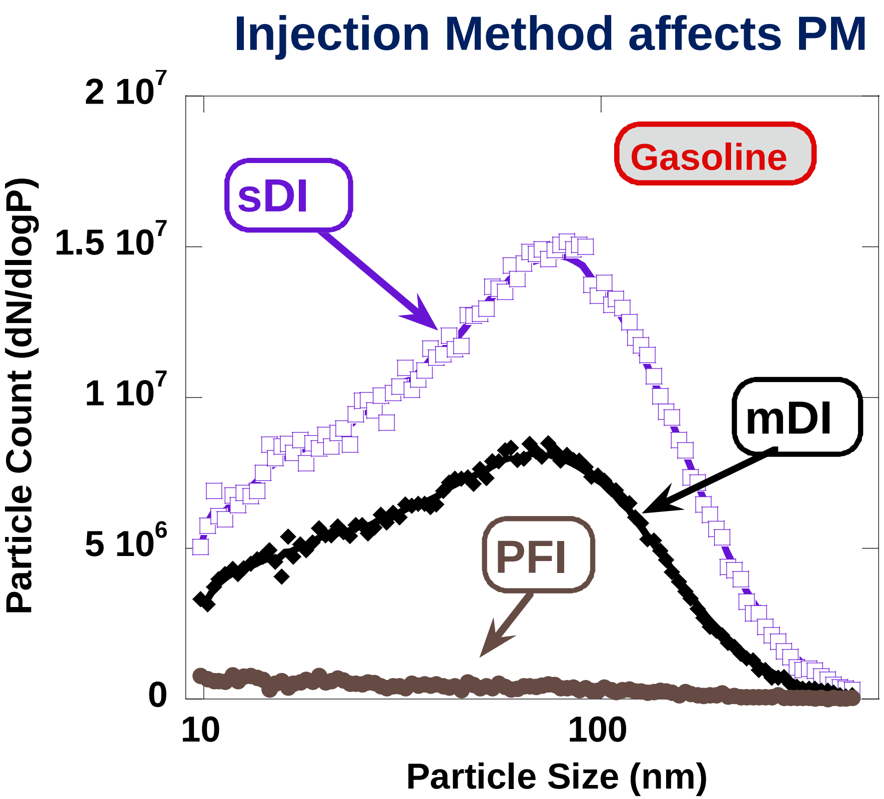
- **Engine provided by Delphi for CRADA on Ethanol Optimization**
  - » Turbocharged 2.0 L DISI with additional PFI capability
  - » Full pass engine control, variable valve timing
- **Engine-based experiments conducted to identify effects of fuels, injection, and breathing on PM emissions**
  - » Smoke (FSN), PM size and morphology
  - » More details given by Jim Szybist in FT008
- **Morphology studies can give insight into origins of PM**
  - » New capability: particle sampler for microscopy
  - » Uniform collection across substrate
  - » Sampling efficiency vs. particle size

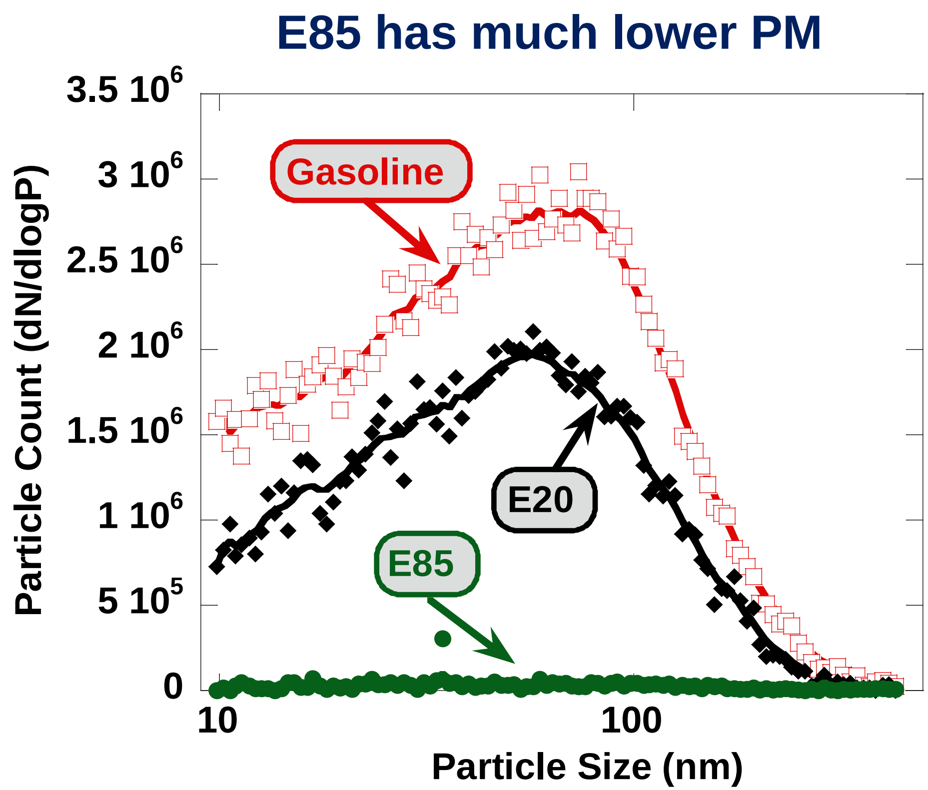


N/W Particle Sampler for TEM

Flexibility of engine platform enables a more systematic investigation of DISI PM formation mechanisms

DISI engine enables investigation of PM formation



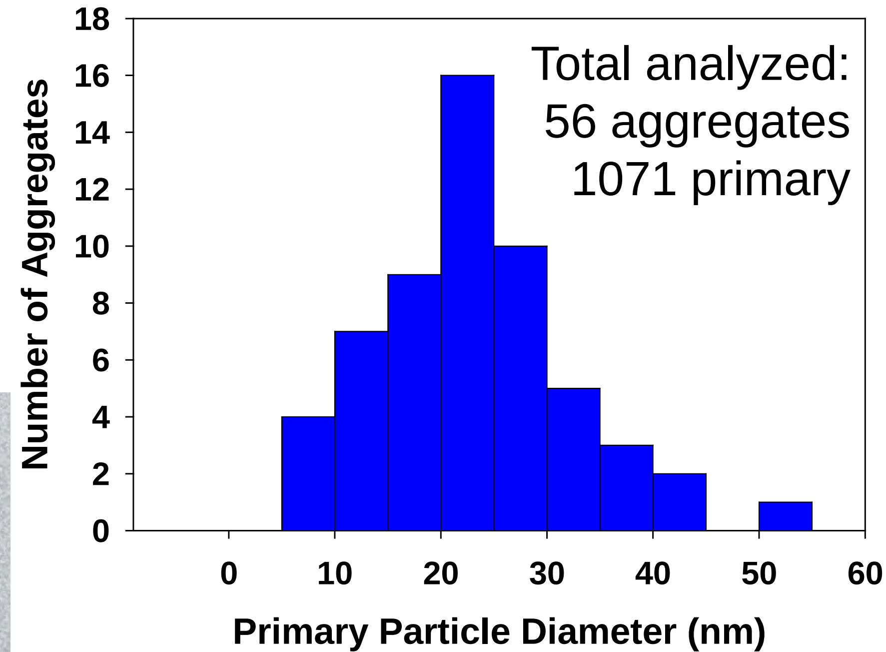


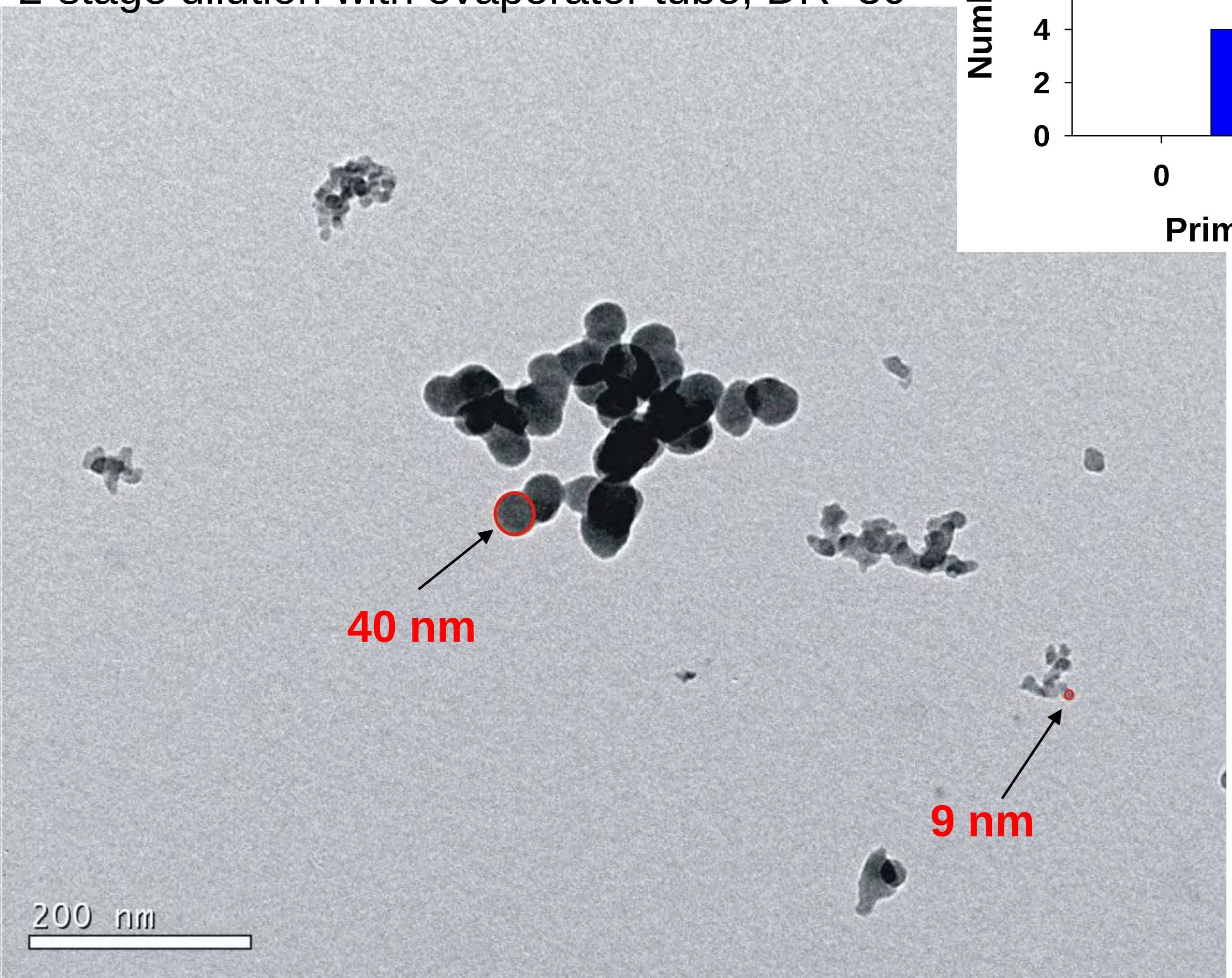
Injection timing, injection method, and fuel ethanol content all had significant effects on PM formation; e.g. advancing injection can lead to wall impingement and crevice burning

DISI Engine Particle Morphology (1)

E20, DI320 BTDC, 1500 rpm/8 bar, Engine-out

2-stage dilution with evaporator tube, DR=30





Large variation primary particle diameter

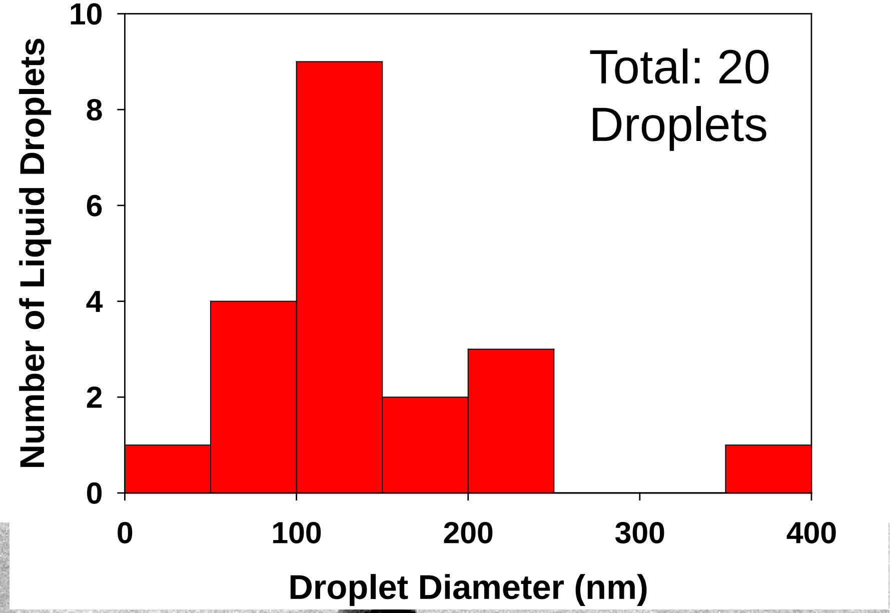
– Greater range than for diesel aggregates

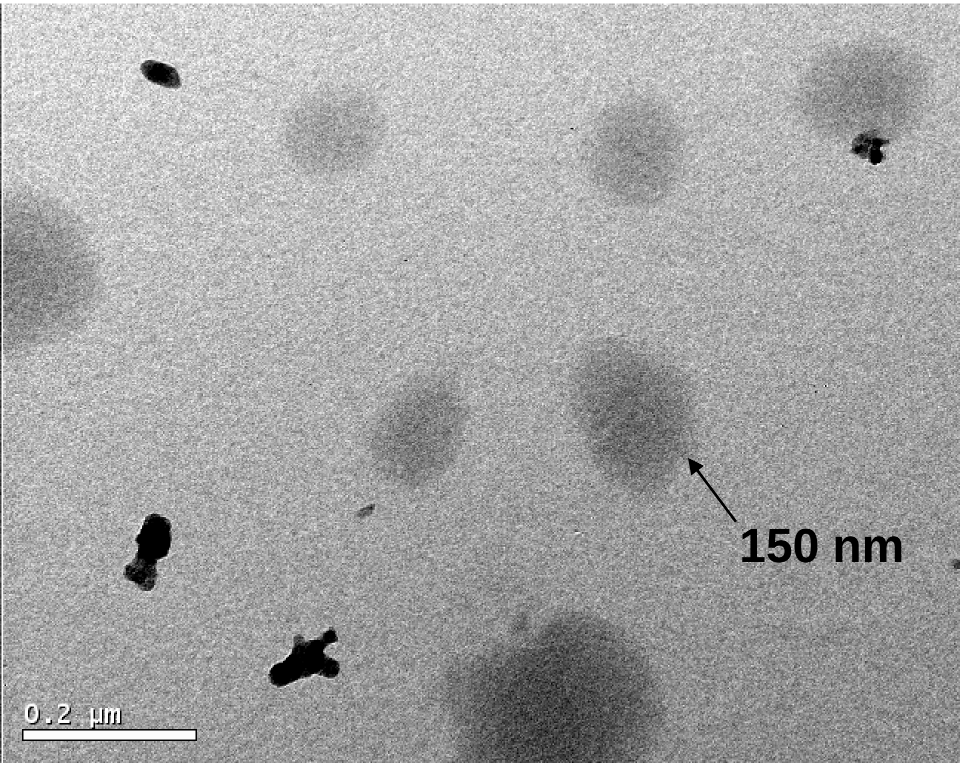
– Heterogeneous fuel/air mixing

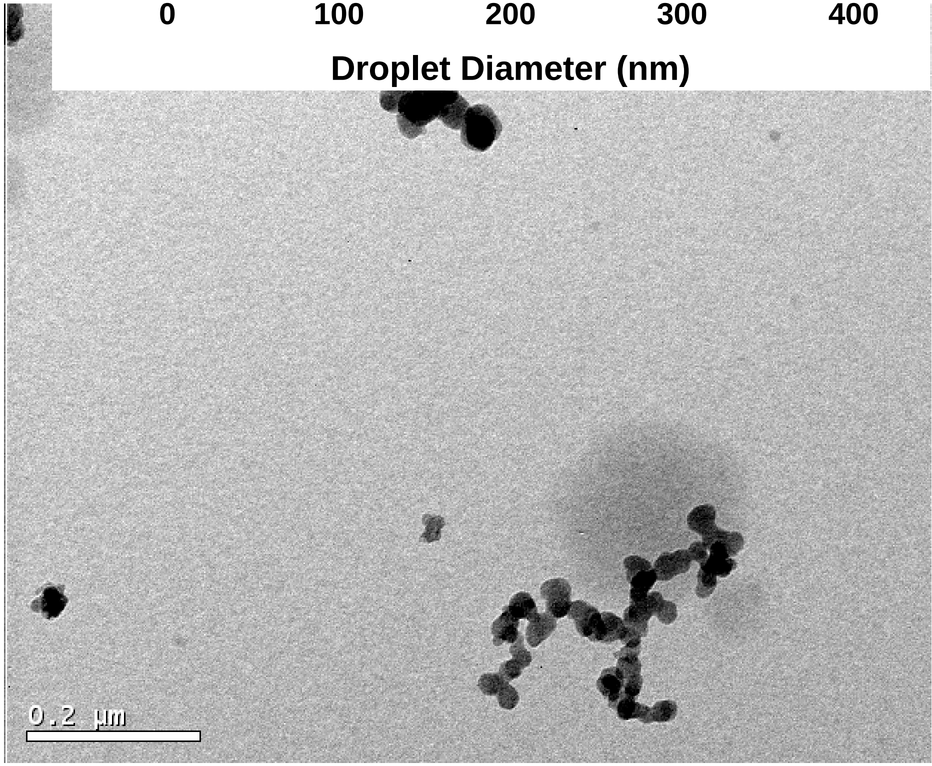
Scale bar 200 nm

DISI Engine Particle Morphology (2)

- Liquid droplets abundant
  - Condensation of unburned HC and lube
  - Possible fuel impingement from early injection







E20, DI320 BTDC, 1500 rpm/8 bar, Engine-out

2-stage dilution with evaporator tube, DR=30

Scale bar 200 nm

Idealized Aggregate Theory relates primary particle diameter to on-line measurements

- **d_{pp} = primary particle diameter**
  - » Aerodynamic Diameter (d_a)

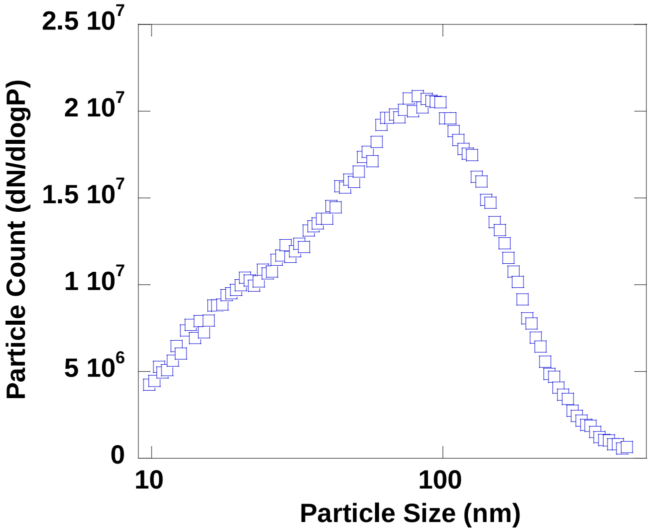
$$d_a = \left(\frac{6\pi}{(A_1 + A_2)c^*} \right) \left(\frac{\rho_p}{\rho_0} \right) d_{pp}$$

Barone et al. (2006)

  - » Electrical Mobility Diameter (d_m)

$$\frac{d_m}{C(d_m)} = \frac{c^* N_p d_{pp}^2}{12\pi\lambda}$$

Lall and Friedlander (2006)



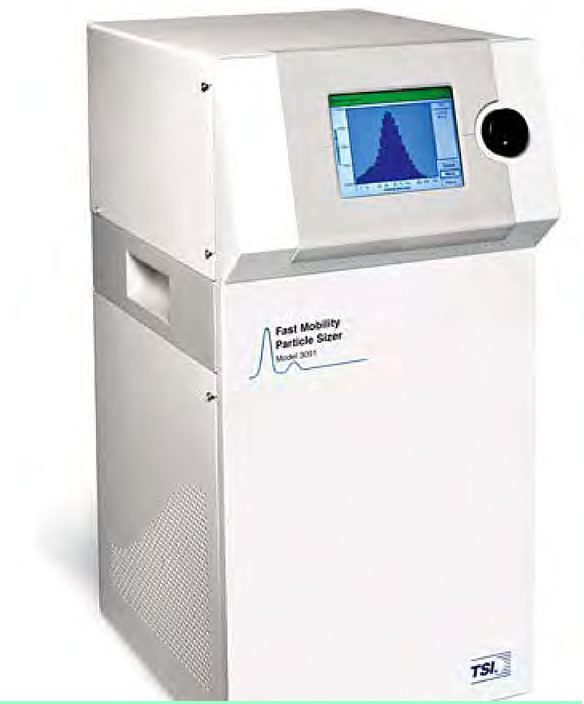
Enables comparison of TEM measurements with SMPS and impactor data

Collaborations

- **Engine/Combustion and Emissions and Catalysts (ACE)**
  - » Worked internally with ORNL emissions control team on lean DISI vehicle
  - » Working internally with ORNL combustion team on RCCI measurements as reported in ACE031
  - » CRC Emissions Working Group
  - » ACEC tech team provided feedback
- **Fuels Technology**
  - » Working internally with ORNL fuels team on DISI engine PM
    - Leveraged Delphi CRADA engine
- **Particle Morphology**
  - » Working internally with ORNL-HTML on microscopes
  - » Univ. of Maryland for Aggregate Theory
    - Barone *et al.* “Size-Resolved Density Measurements of Particulate Emissions from an Advanced Combustion Diesel Engine: Effect of Aggregate Morphology “ accepted for publication in *Aerosol Science & Technology,* 2011.

Future Work

- **Remainder of FY2011**
  - » Data analysis on DISI engine results
    - Compare Idealized Aggregate Theory to actual PM measurements
  - » Examine start-stop effects on DISI vehicle PM
    - Highest PM emissions from cold start
    - Implications for hybrid vehicles with DISI engines
    - Real-time PM sizing available (arrived January 2011)
- **Support of ACES Project**
  - » ORNL developed methods for urea-SCR byproducts
  - » Analyze filters from Phase III engine (2010 spec)
- **Beyond FY2011**
  - » RCCI PM characterization and HC speciation
  - » Additional fuel blending components



Engine Exhaust Particle Sizer

Summary

- **<u>Relevance</u>: Targets the measurement of PM and unregulated emissions for advanced engine technologies and alternative fuels (DOE Technical Barrier)**
- **<u>Approach</u>: Incorporate PM and unregulated emissions measurement into advanced engine system and alternative fuels studies in the ORNL program**
  - » Feedback from these measurements can then be used to identify pathways for mitigation of these pollutants
- **<u>Collaborations</u>: Industry stakeholder groups and universities are being used to maximize the impact of this work.**
- **<u>Technical Accomplishments</u>:**
  - » Particle size, number, and mass emissions characterized for stoichiometric and lean-burn DISI vehicles with ethanol blends
  - » PM speciation (organic carbon/elemental carbon – OC/EC) demonstrated large soot component
  - » Studies with an advanced DISI engine identified conditions which minimized PM emissions
  - » Morphological studies of PM showed that the broad size distribution of DISI PM derives from differences in primary particle size.
- **<u>Future Work</u>:**
  - » Near future: support of ACES with analysis of urea byproducts
  - » Start-stop PM emissions and ongoing morphological studies