

*Particle Mass and Number Emissions  
from a 2009 GDI Engine using Different  
U.S. Commercially Available Fuels*

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# Euro 6 and LEV III Light-Duty Particle Emission Regulations

- Euro 6 (2014)
  - Particle Mass: 4.5 mg/km
  - Particle Number:  $6 \times 10^{11}$  part./km ( $> 23$  nm, NEDC)
  - Number to Mass Ratio:  $1.33 \times 10^{11}$  (Part./mg)
- CARB Proposed LEV III (Light-Duty, 2014-2017)
  - Particle Mass (2014): 6 mg/mi (3.8 mg/km)
  - Particle Number (2014, Optional):  $3.8 \times 10^{12}$  part./km
  - Particle Mass (2017): 3 mg/mi ( $\sim 1.9$  mg/km)
  - Particle Number (2017, Optional):  $1.9 \times 10^{12}$  part./km
  - Number to Mass Ratio:  $1 \times 10^{12}$  (Part./mg)

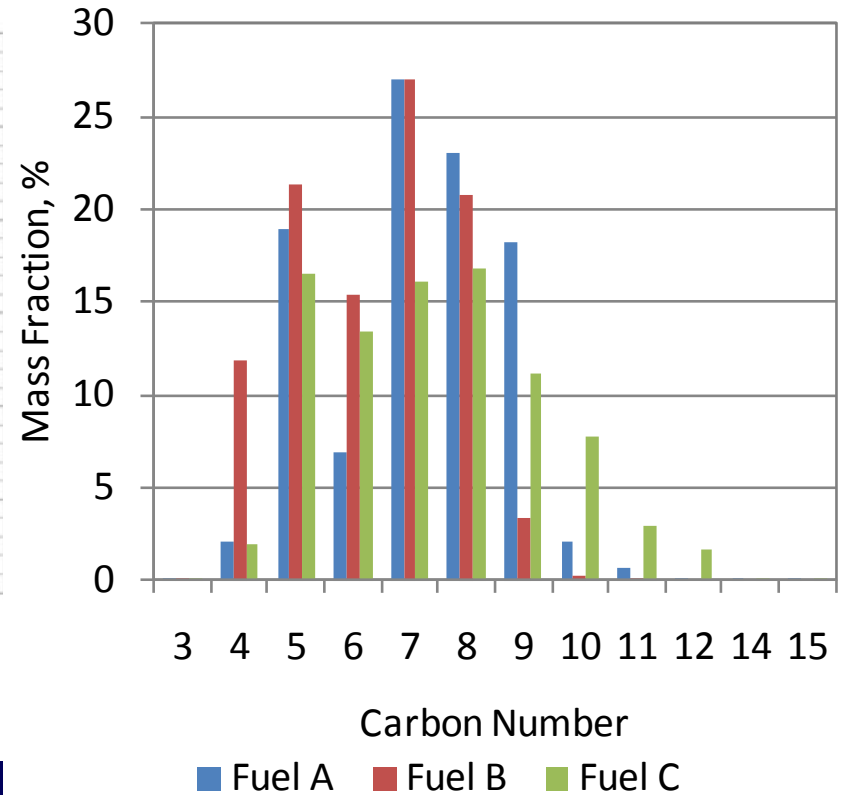
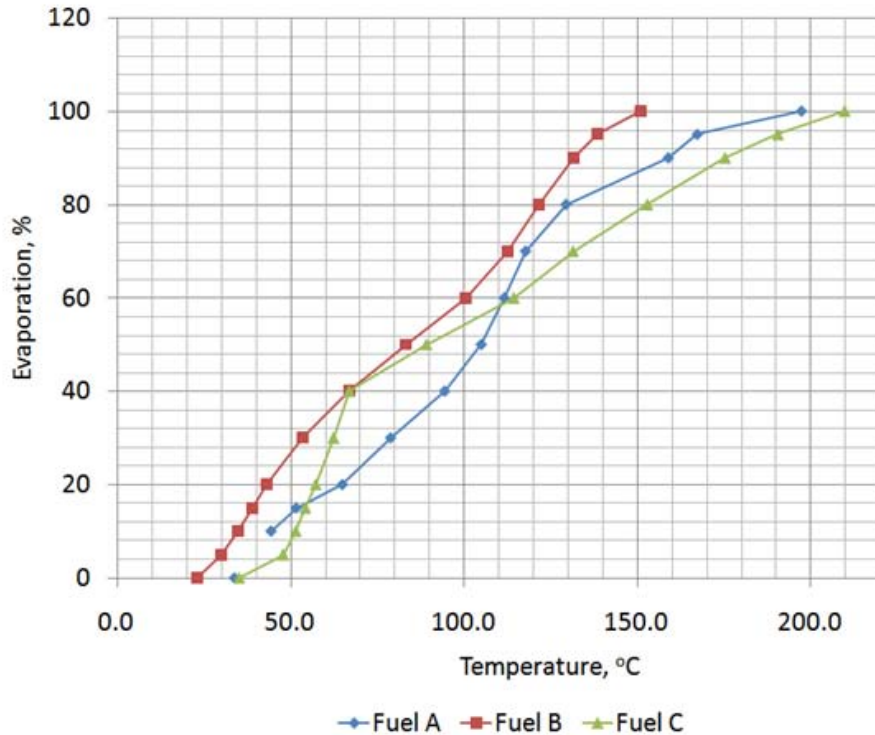
# Meeting Particle Emissions Regulations

- Euro 6:
  - Diesel: High Efficiency DPF is required
  - Gasoline: Multi-Port Fuel Injection, TWC
  - Gasoline: GDI, TWC, with significant PM reduction via combustion optimization :
    - Higher Injection Pressure
    - Smaller Droplets
    - Better Transient Mixing
    - Improved Cold-Start
    - High Turbo Boost and EGR
    - Injector Location
    - Gasoline Particle Filter (GPF)?
    - Fuel Formulation?
- LEV III:
  - Diesel: DPF is required
  - Gasoline: Multi-Port Fuel Injection, TWC
  - Gasoline: GDI, TWC, with some PM reduction combustion optimization such as those used for Euro 6

# Objective

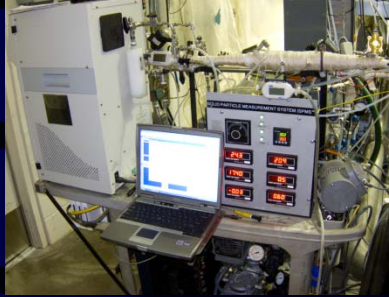
- To investigate the influence of three different U.S. commercially available fuels on particle mass and number emissions using:
  - 2009 Vehicle equipped with a GDI engine
  - FTP-75 and US06 Drive Cycles

# Volatility Profile and Carbon Number Distribution for Different Commercially Available Gasoline Fuels

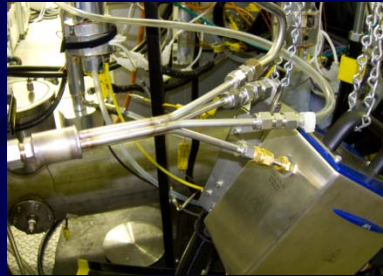


The Double Bond Equivalent is highest for Fuel C and Lowest for Fuel A, See [SAE Paper No. 2010-01-2115 on PM Index](#)

# Equipment Used



EEPS Plus SPSS (Real Time Solid Number and Size Distribution)



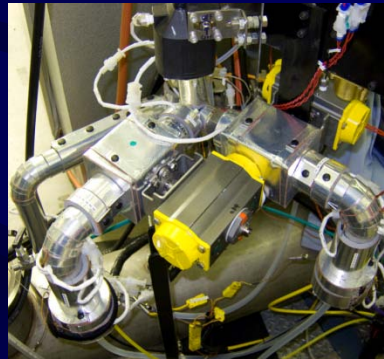
Sampling Probes



AVL MSS (Real Time Black Carbon Mass)



AVL Particle Counter (APC),  
(EU Solid Particle Number)



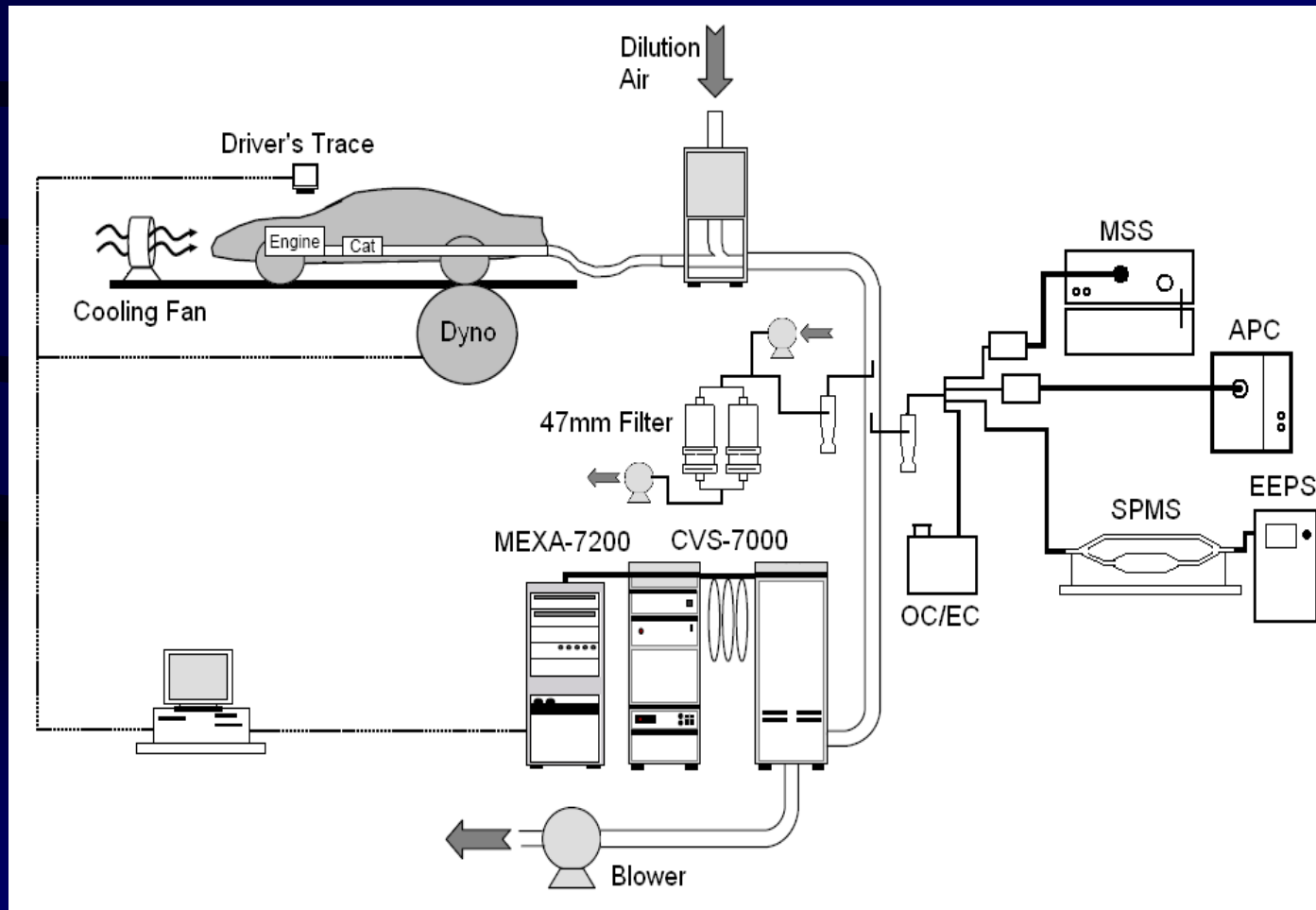
47 mm Filters  
(Integrated PM mass)



Integrated Organic and Elemental Carbon  
(OC/EC)

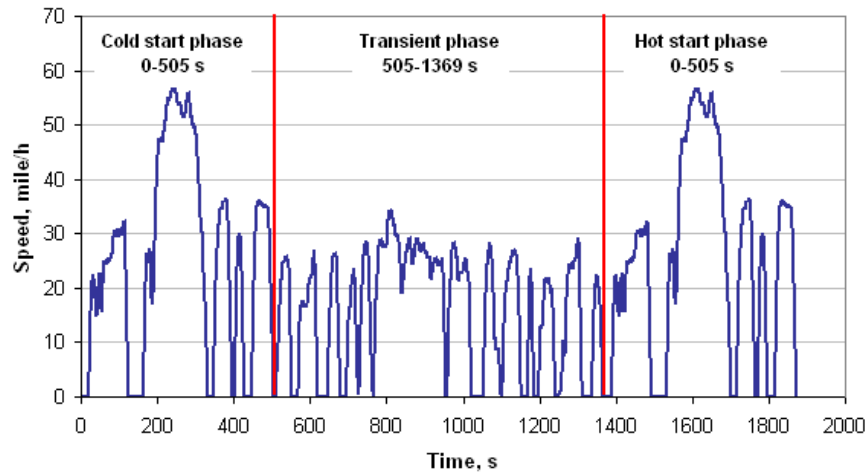
# Experimental Setup

(CFR Part 1065 Full Flow CVS was Used)

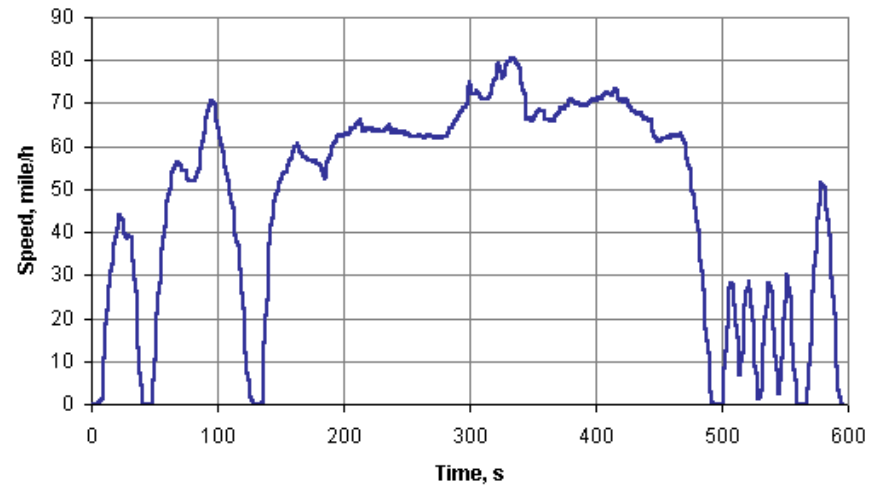


# Cycles Used

## FTP-75



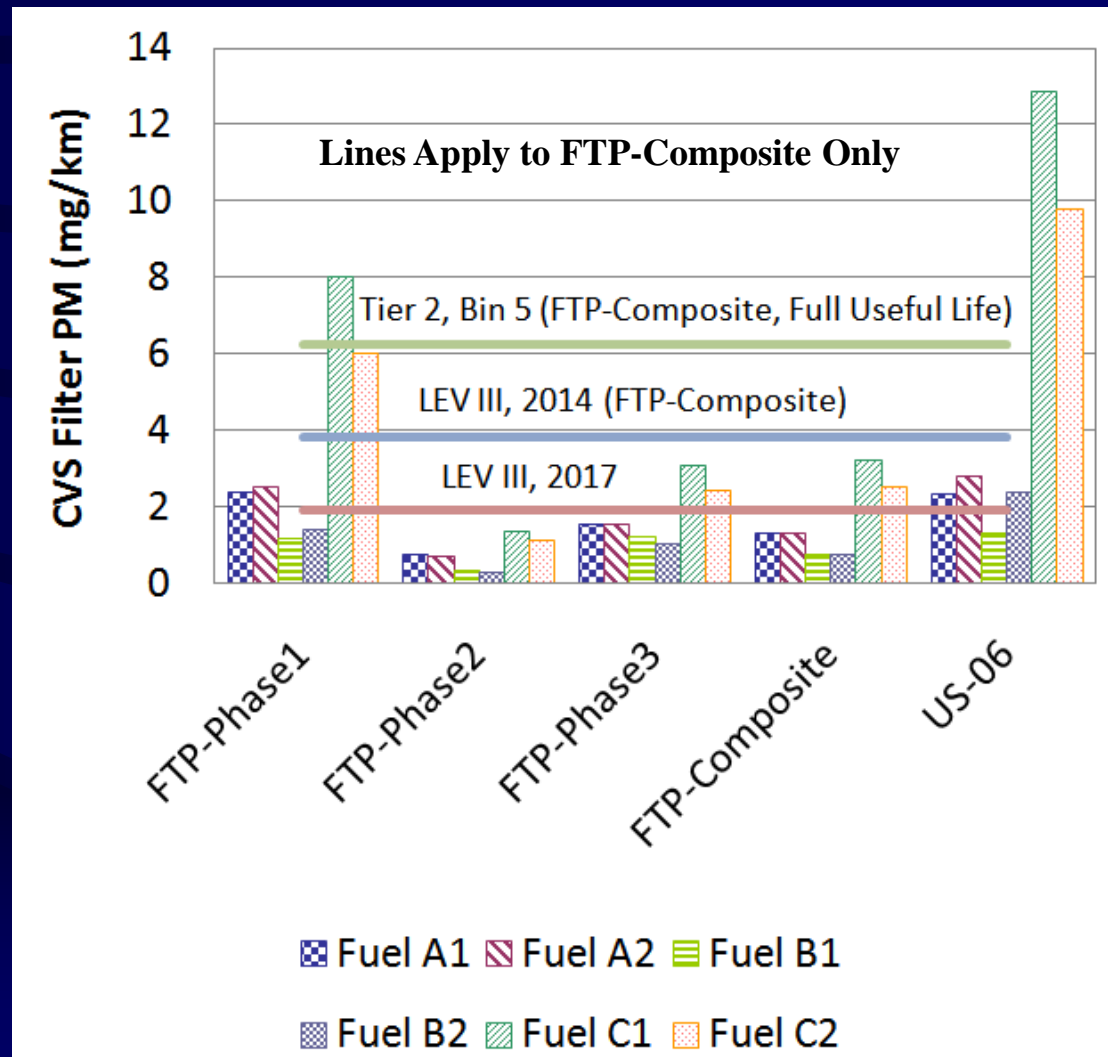
## US06





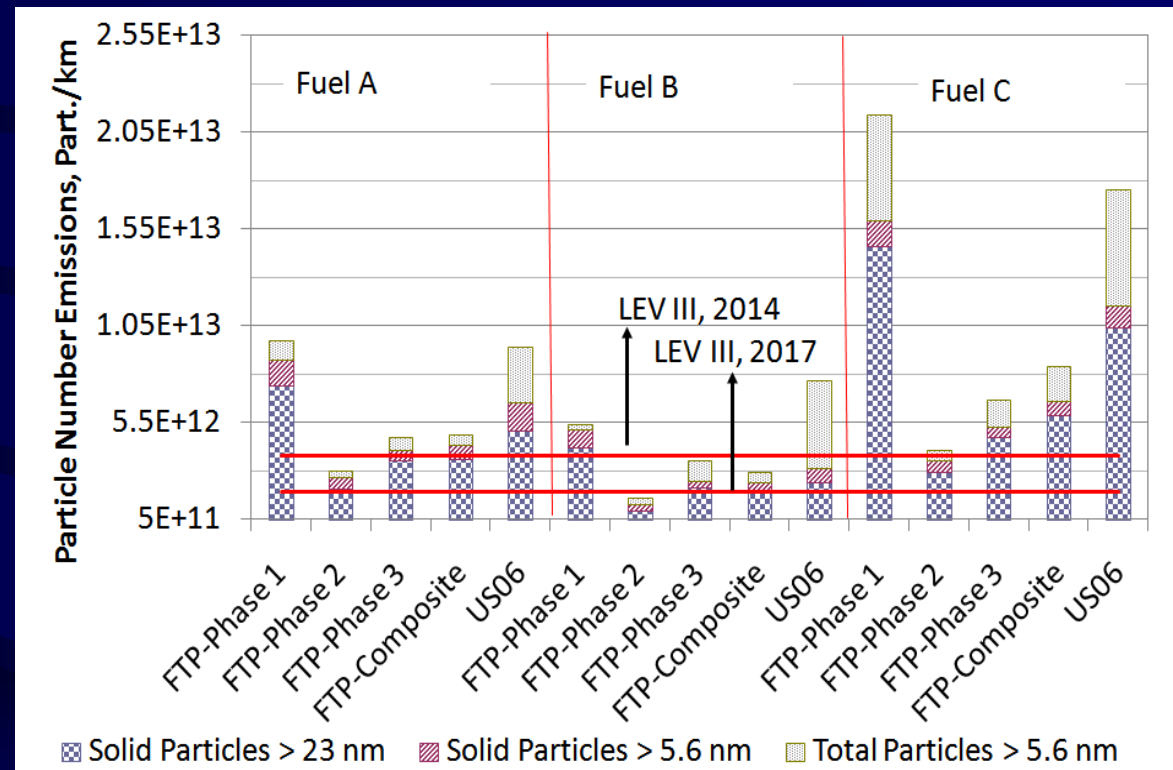
# Total Particle Mass Emissions from a 2009 GDI using Different Fuels

- FTP-Composite met EPA Tier 2, Bin 5, with all fuels
- FTP-Composite met CARB 2014 and 2017 LEV III, except for Fuel C for 2017
- The high volatility fuel, Fuel B showed the lowest PM emissions



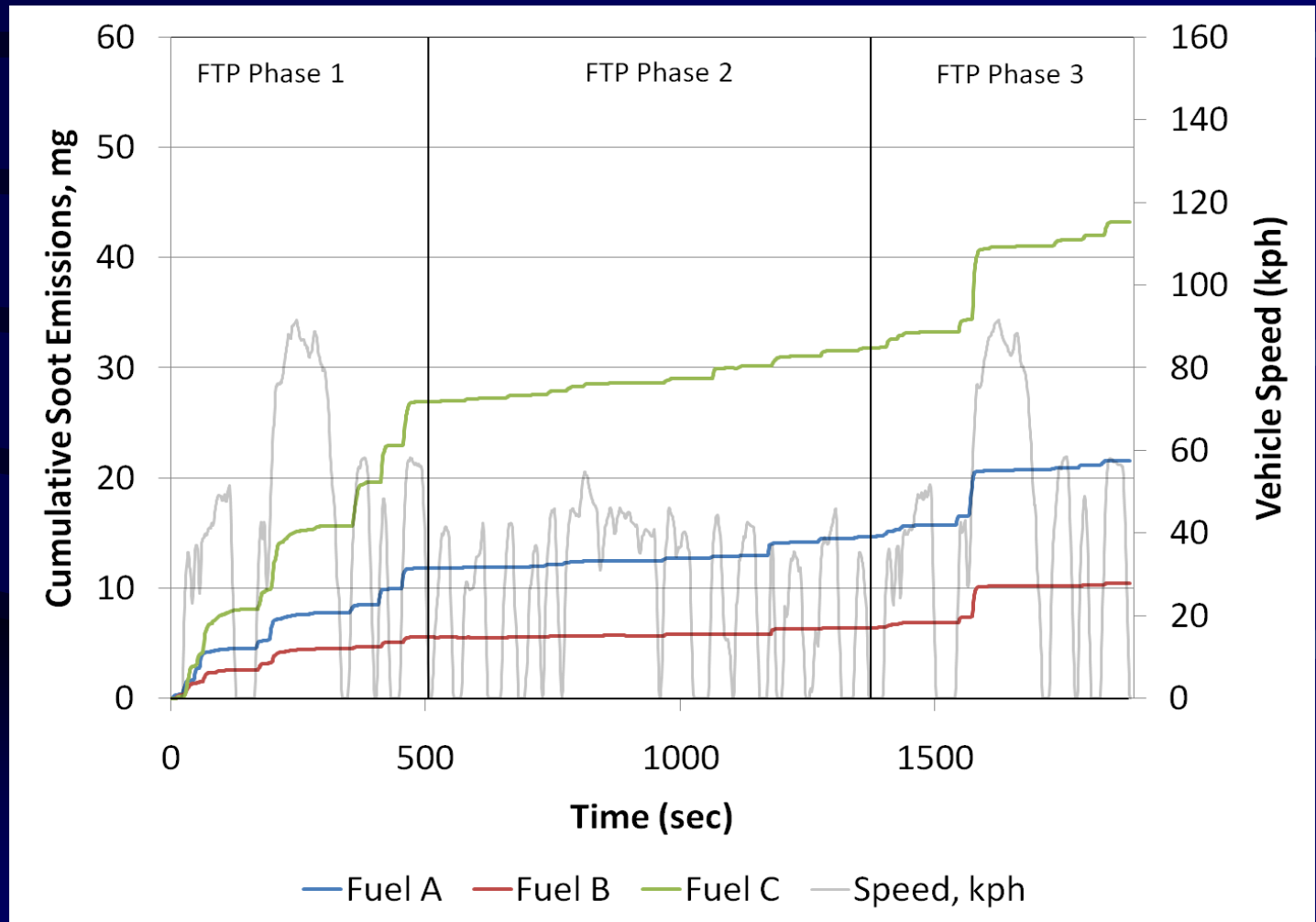
# Solid and Total Particle Number Emissions from a 2009 GDI using Different Fuels

- None of the fuels met LEV III, 2017
- Fuels A and B met LEV III, 2014
- Cold-start and US06 were the dominant contributor of solid particles
- Sub-23 nm solid fraction was 17 to 20%



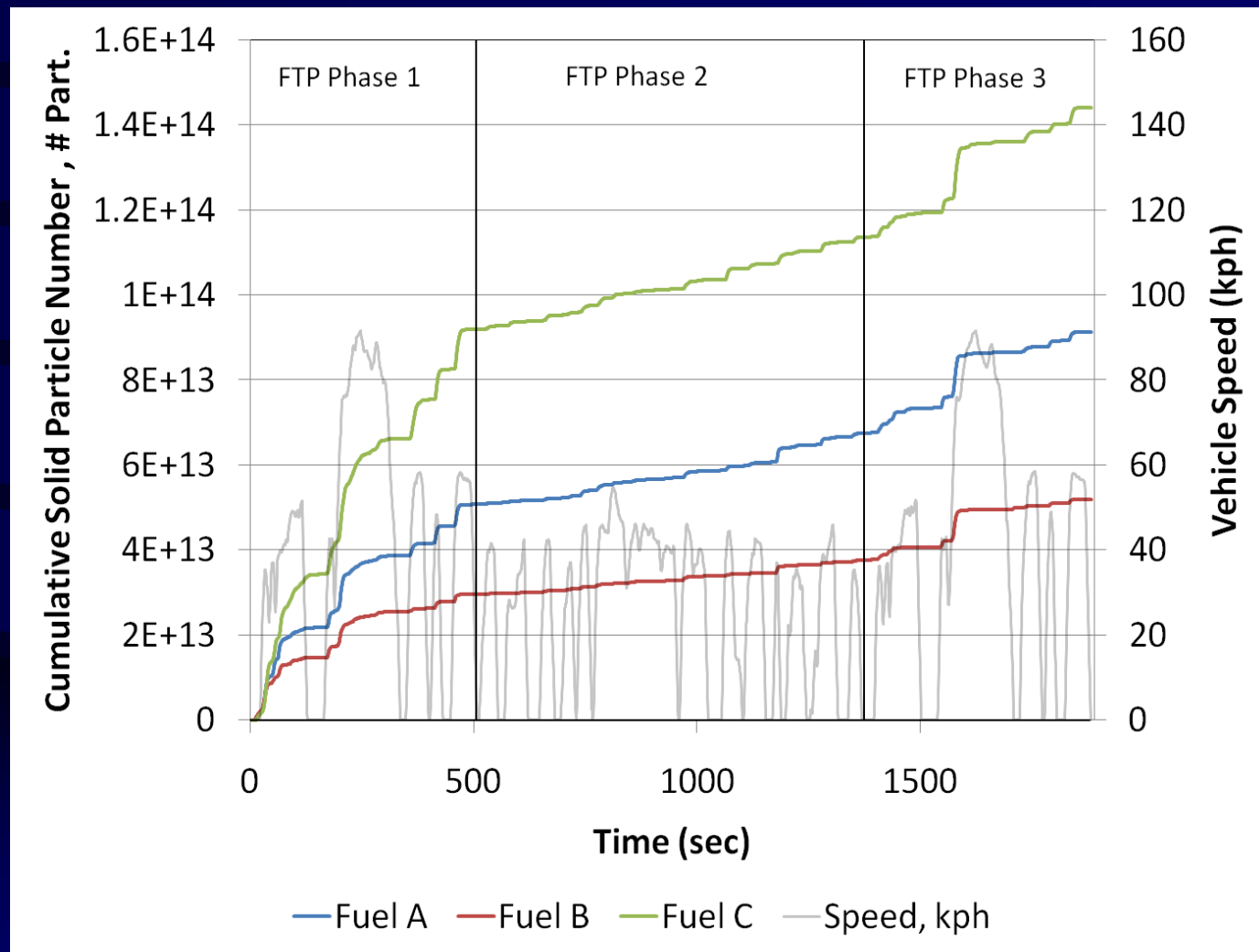
# FTP Cumulative Soot Mass Emissions

- Acceleration events to high vehicle speed dominate soot Mass emissions
- Fuel B reduces soot drastically, compared to Fuel C

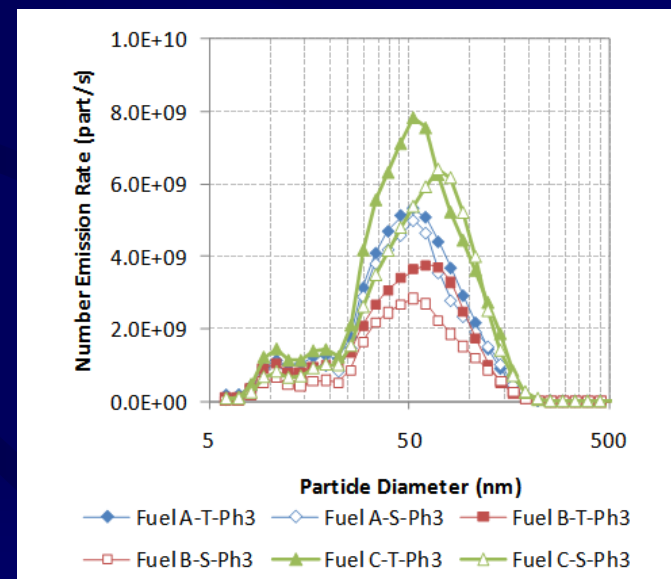
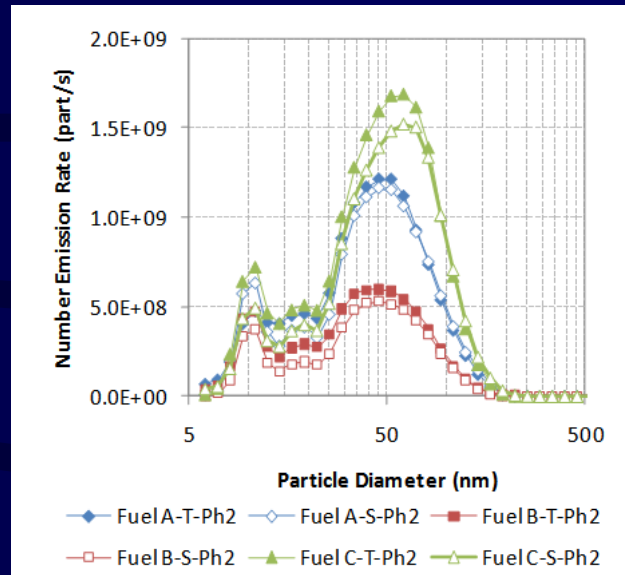
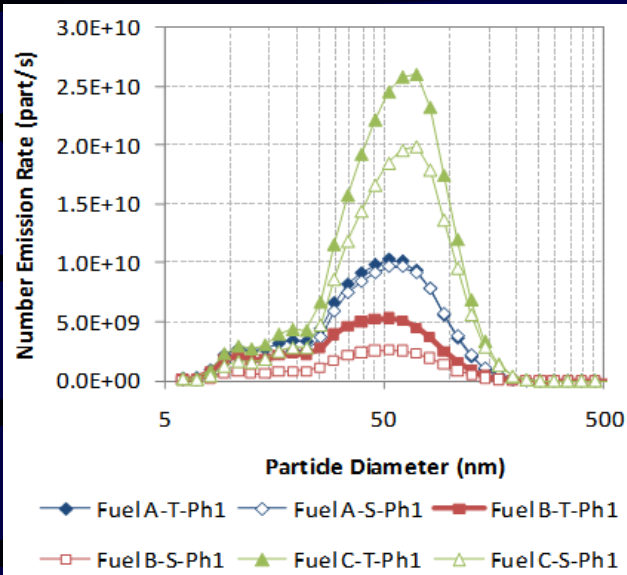


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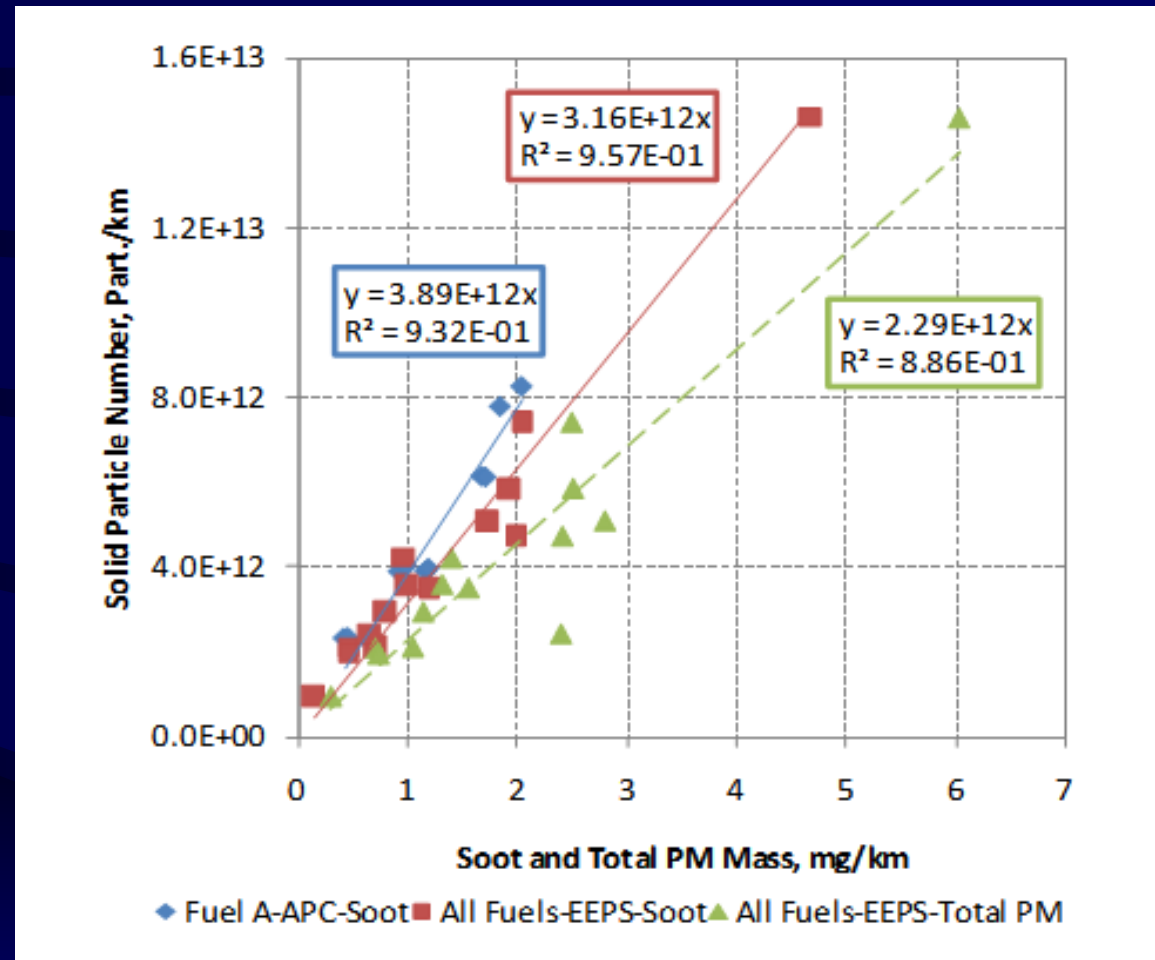
# Typical Size Distribution for Phases 1, 2, and 3 of the FTP Drive Cycle



Number Mean Diameter:  
 Accumulation Mode: 40 nm to 60 nm  
 Nuclei Mode: ~10 nm for volatile and solid nuclei

# Correlation Between Solid Number and Particle Mass

- Slope for soot was a factor of 1.5 to 2 higher than that reported by Kirchner, Vogt, & Maricq (SAE Paper No. 2010-01-0789) for Diesel with DPF
- Slope for Total PM was a factor of 2.3 higher than CARB LEV III, and a factor of 17 higher than Euro 6



# Summary

- The 2009 GDI engine shown in this work is able to meet CARB LEV III particle mass regulation proposed for 2014 and 2017 using all fuel tested, except fuel C for 2017
- PM formation is very sensitive to fuel properties, mainly fuel volatility and double bond equivalent (See SAE Paper (2010-01-2115))
- Most of the PM is formed in the cold-start Phase 1 of the FTP
- Hard acceleration to high speed is a significant contributor to solid particle number and mass emissions.
- Synergy exists between solid particle number standard and total PM standard as proposed by the CARB LEV III, although some tuning is recommended for a more appropriate ratio between solid number and total PM.
  - Two of the fuels met LEV III, 2017, total particle mass
  - None of the fuels met LEV III, 2017, solid particle number
- As for the Euro 6, there is a disconnect between solid number standard and total PM standard. E.g.
  - Total Particle Mass Emissions using Fuel B: 84 % below Euro 6 standard (based on FTP-Composite instead of NEDC)
  - Solid particle Number Emissions using Fuel B: a factor of 3.3 higher than Euro 6 standard (based on FTP-Composite instead of NEDC)

# Acknowledgements

- This work was funded by Honda R&D North America
- For more details, please see SAE Paper No. 2010-01-2117, approved for publication for the October 2010 SAE Powertrains, Fuels and Lubricants Meeting, San Diego, California