Particle Number and Ash Emissions from a Heavy Duty Natural Gas and Diesel w/DPF Engine

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Background

- Solid particle number (PN) (> 23 nm) has become a regulatory metric in the EU, but not in the USA
  - The EU is also working to take into account PN below 23 nm down to 10 nm
- Solid PN limit is much more stringent than the PM mass limit
  - Meeting the PN limit typically results in PM mass 90% below the mass standard
- Engines without exhaust particle filters, regardless of engine technology and fuel, will have a difficult time competing with engines with filters relative to PN emissions in the real world

Objective

- The objective of this work is to characterize PN & Ash emissions from two different modern engine platforms (CNG with TWC & Diesel with SCRF/SCR) that both meet ultra-low NOx emissions at or below 0.02 g/hp-hr (90% below current heavy-duty NO_X limit in the USA)

- Note:
  - Both engine platforms have not been calibrated or optimized for PN reduction to meet the EU number standard
    - Both engines are intended to meet US PM Mass Standard

Test Articles

Diesel - 2014 Volvo MD13TC (Euro VI)

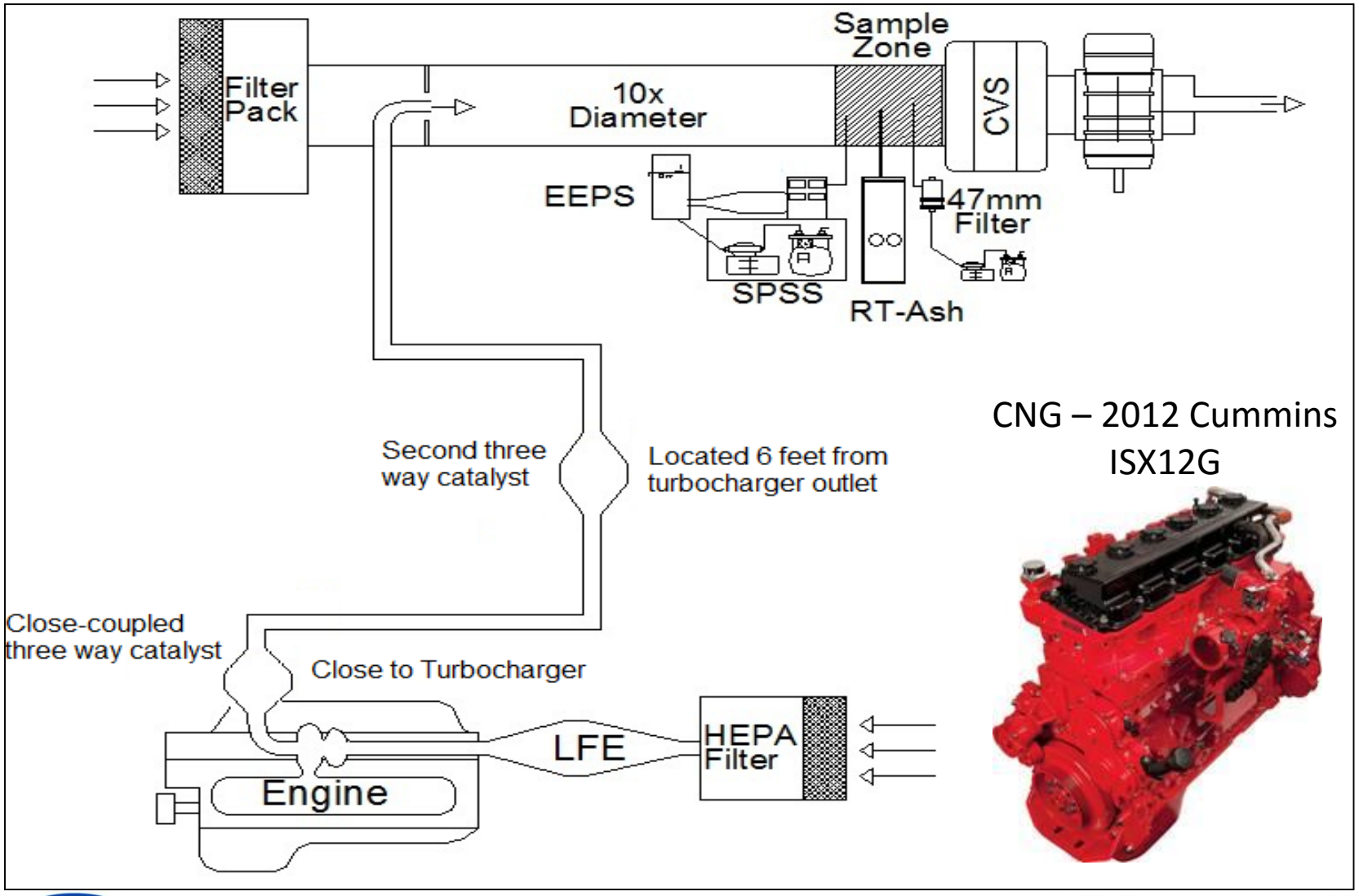
- A diesel engine with cooled EGR, DPF and SCR
  - 361kw @ 1477 rpm
  - 3050 Nm @ 1050 rpm
- Representative platform for future GHG standards for Tractor engines
- Incorporates waste heat recovery – turbo-compound (TC)

CNG – 2012 Cummins ISX12G

- A stoichiometric engine with cooled EGR and TWC
  - 250 kw @ 2100 rpm
  - 1700 Nm @ 1300 rpm
- Suitable for a variety of vocation types

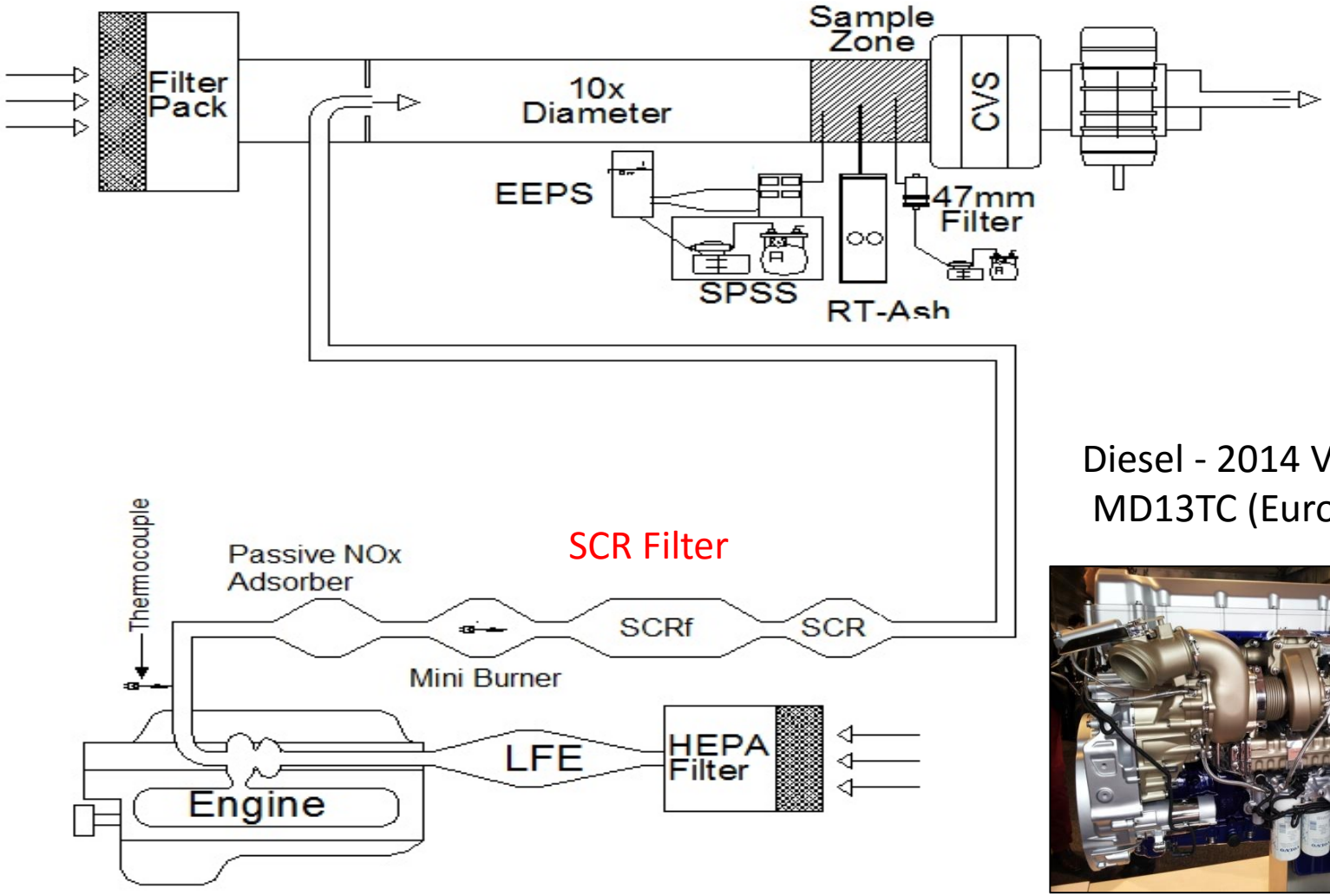
Gas Species	Concentration (vol. %)
Methane (CH_4)	90.0 ± 1.0
Ethane (C_2H_6)	4.0 ± 0.5
C_3 and Higher	2.0 ± 0.3
C_6 and Higher	0.2 max
Oxygen (O_2)	0.5 max
Inert Components (CO_2 and N_2)	3.5 ± 0.5
Hydrogen (H_2)	0.1 max
Carbon Monoxide (CO)	0.1 max
Sulfur (S)	16 ppm max

Test Cell Configuration – Natural Gas Engine Platform



CNG – 2012 Cummins ISX12G

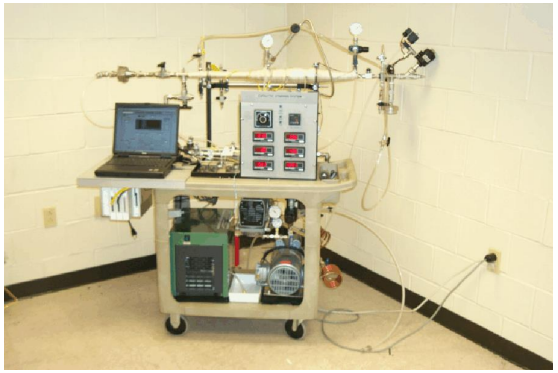
Test Cell Schematic – Diesel Engine



Diesel - 2014 Volvo MD13TC (Euro VI)

Particle Instruments

SwRI SPSS



Facilitate Solid Particle Measurement
(Used Upstream of EEPS)

TSI EEPS

Real time Size distribution and Number Concentration Measurement

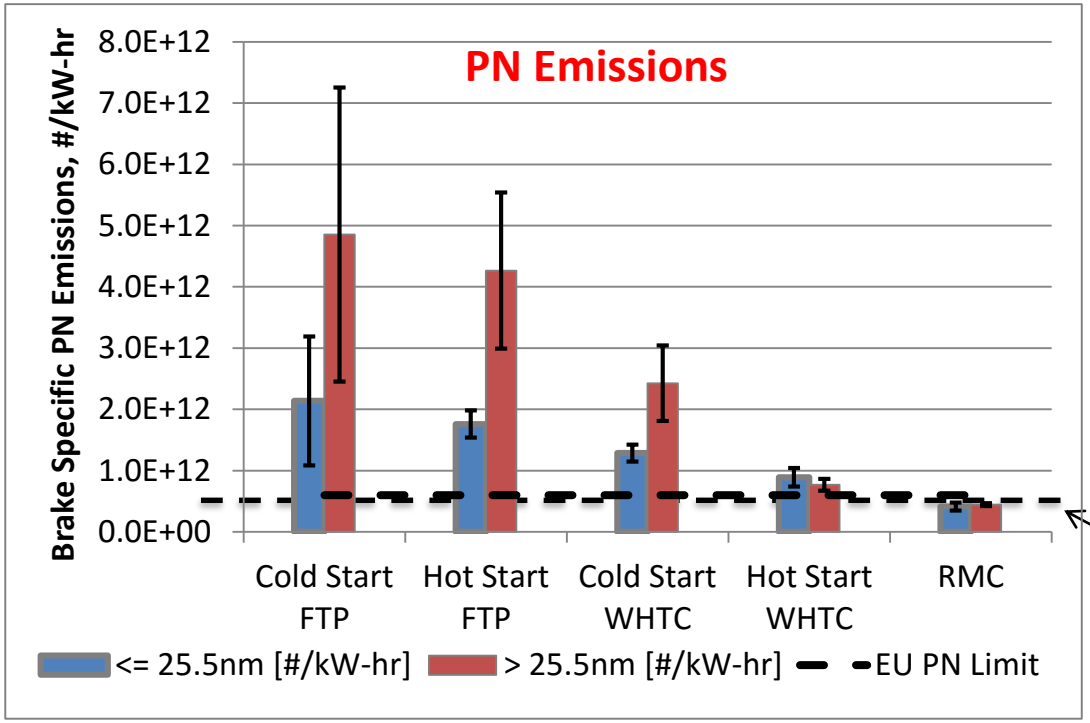
RT-Ash

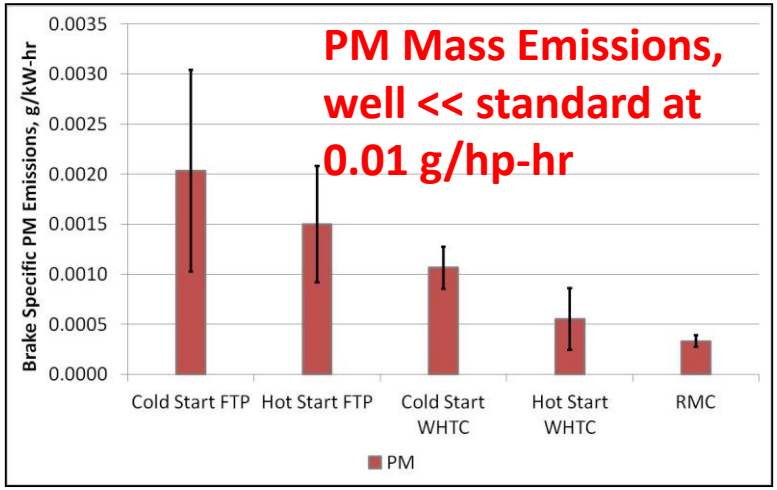
Real time Ash Number Concentration Measurement

CPC 3025
50% detection at 3 nm
90% detection at 5 nm

Full Flow CVS and Part 1065 PM Filter measurement

Results – Solid PN Emissions (Natural Gas Engine)



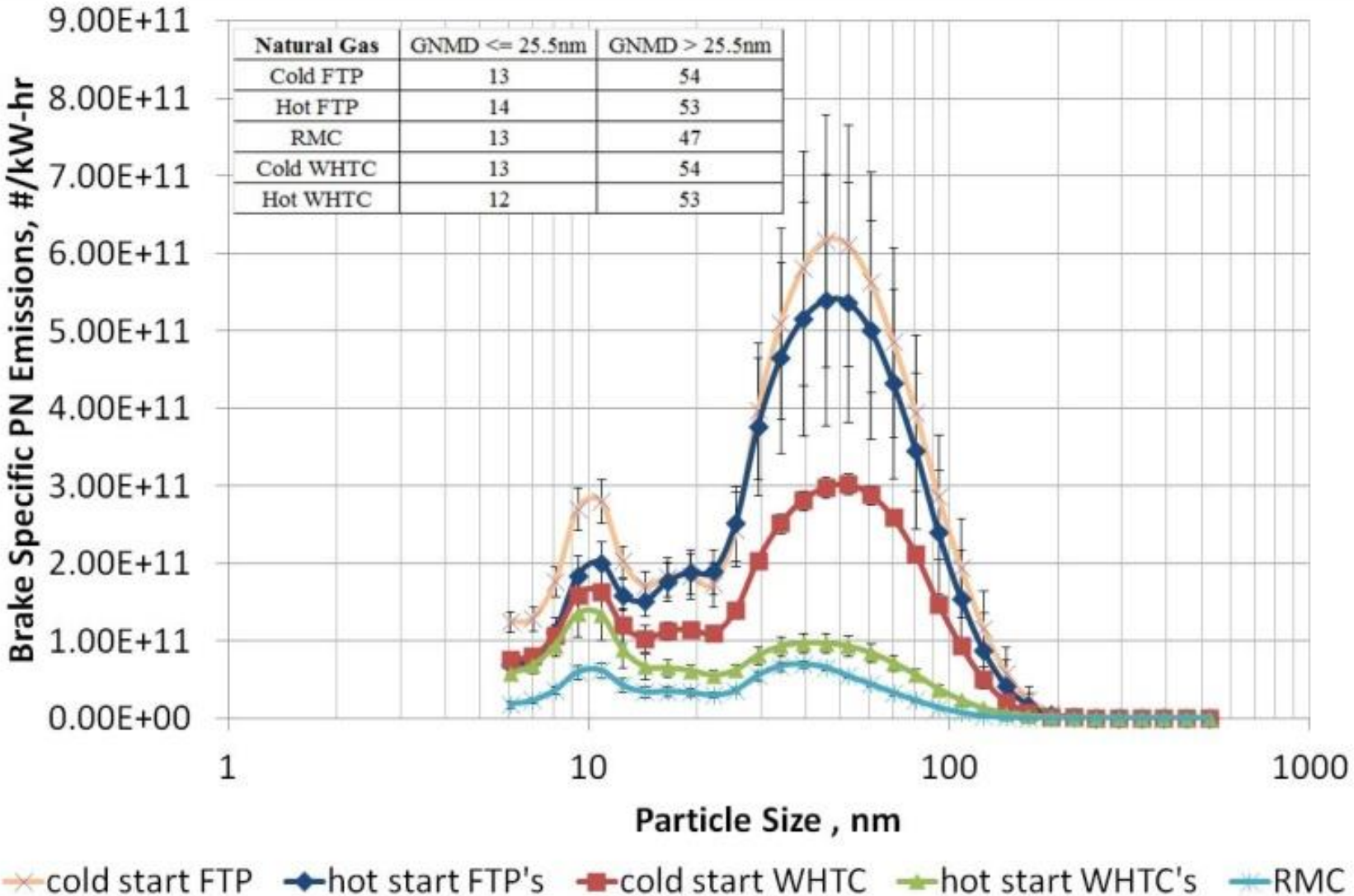


Eu PN Limit $6x10^{11}$ #/kW-hr (particles > 23nm)

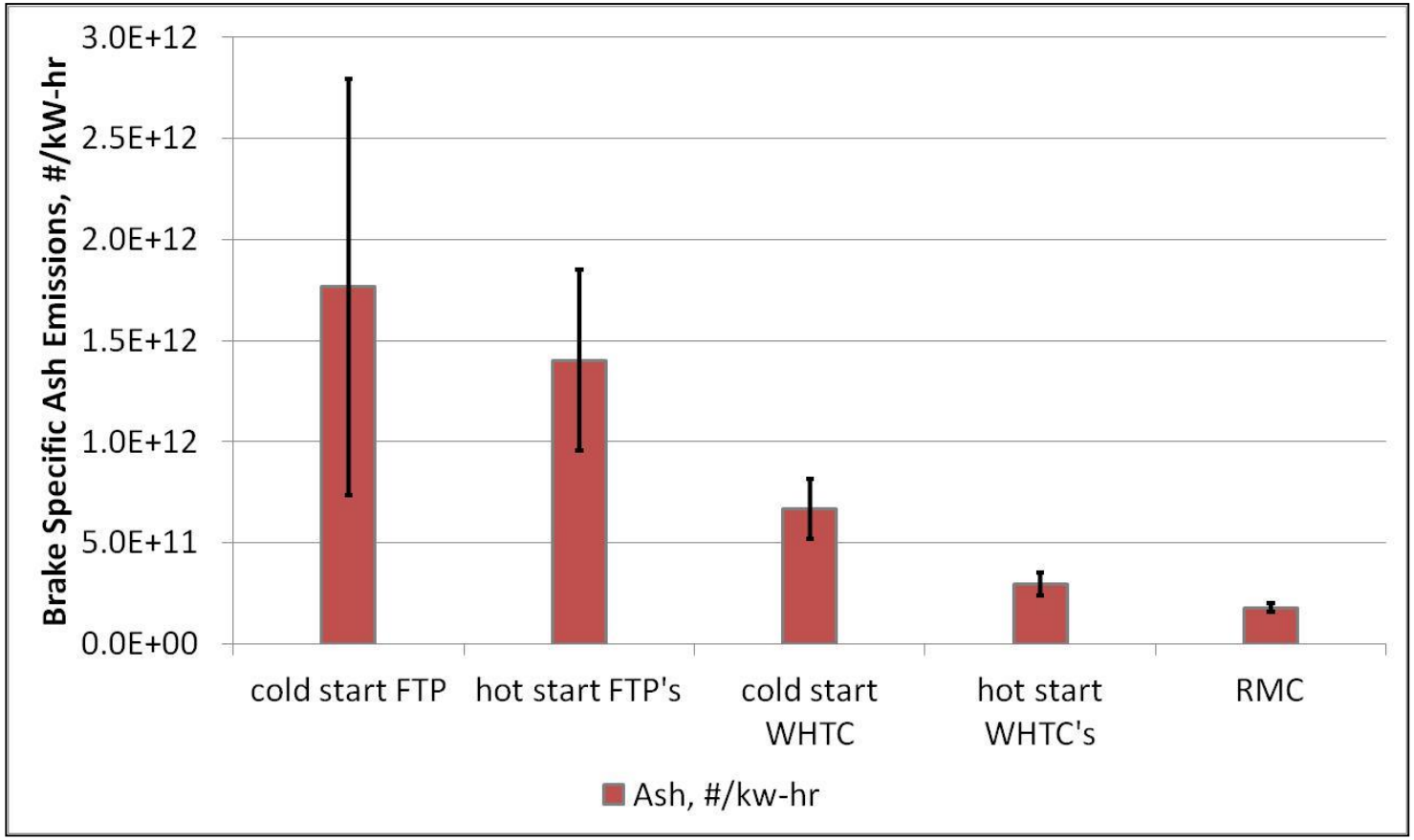
- Cold Start FTP indicated highest emissions of particles >25 nm
- Sub 25 nm particle emissions were comparable between cold and hot start FTPs
- Sub 25 nm particles constitute ~ 30% of total number emissions for both cold-start and hot-start FTPs
- Sub 25 nm particle emissions was more than >25 nm particle emissions for WHTC Hot-Start

Results - Size Distribution (Natural Gas Engine)

Natural Gas	GNMD <= 25.5nm	GNMD > 25.5nm
Cold FTP	13	54
Hot FTP	14	53
RMC	13	47
Cold WHTC	13	54
Hot WHTC	12	53

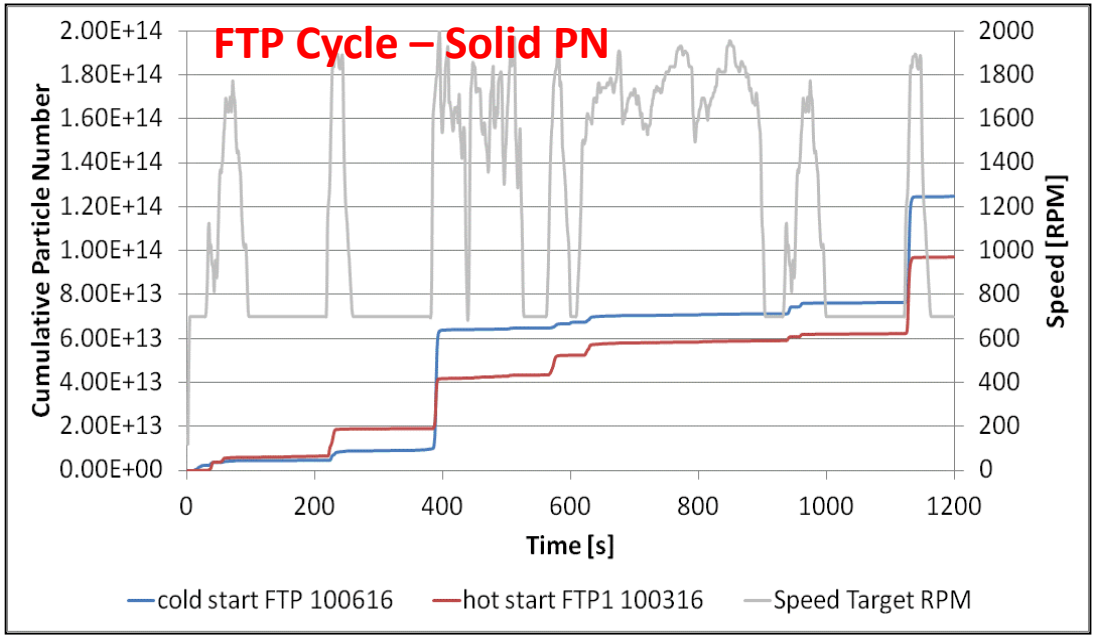


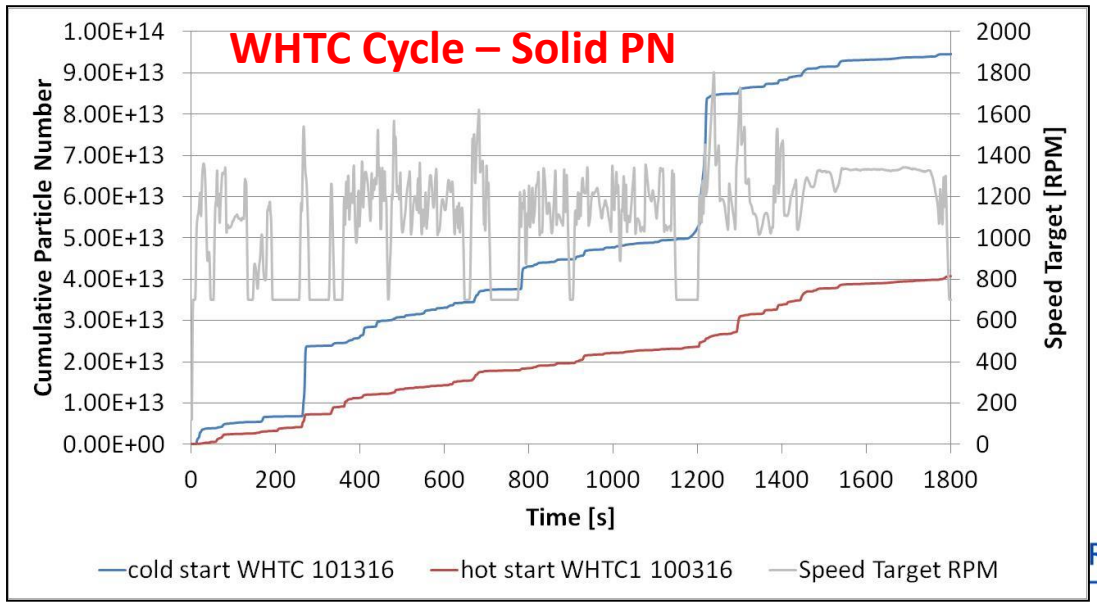
Results - Ash Emissions (Natural Gas Engine)



- Ash emissions was ~ 20 to 30% of total PN, but represents a higher fraction of sub 25 nm particles
- Cold-start cycles resulted in more ash emissions compared to hot-start cycles
- FTP ash emissions was twice that of WHTC ash emissions

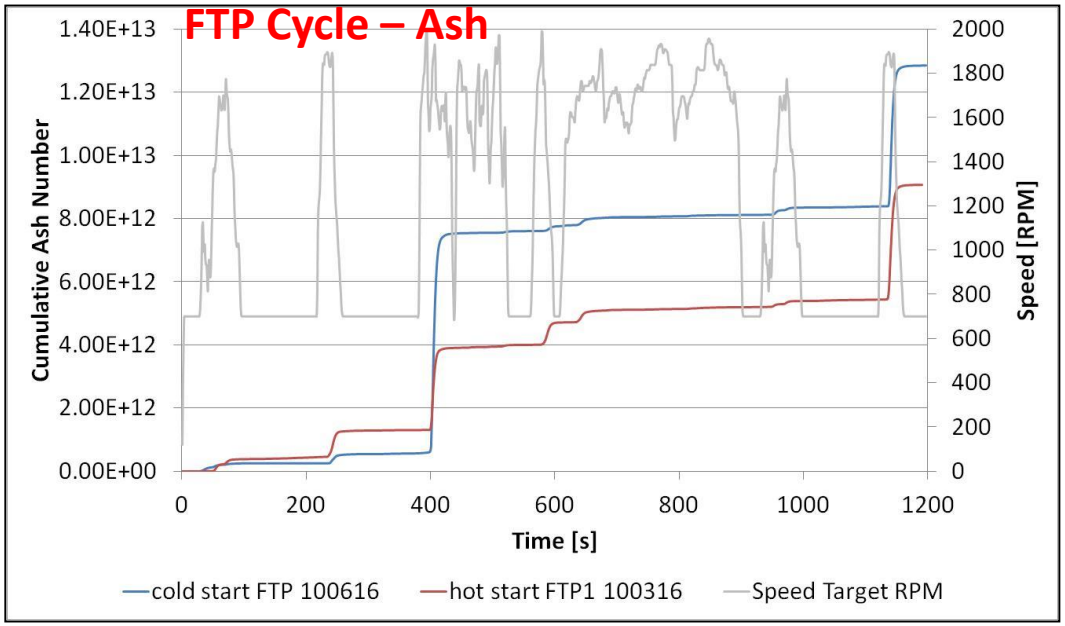
Results - PN Emissions Profile (Natural Gas Engine)

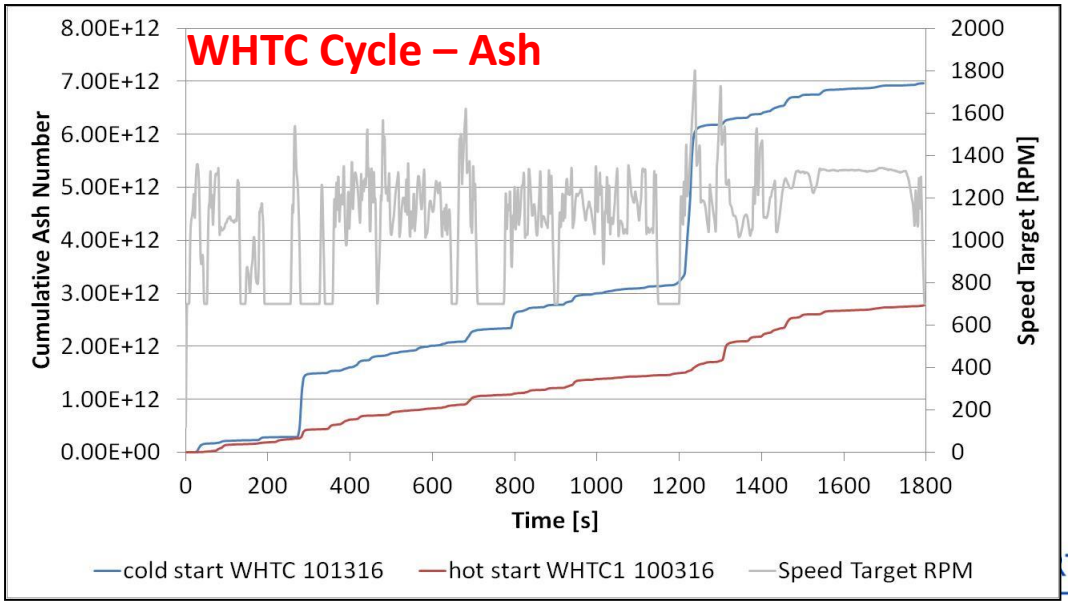




PN is produced during high acceleration events, most likely due to lack of good mixing between fuel and air

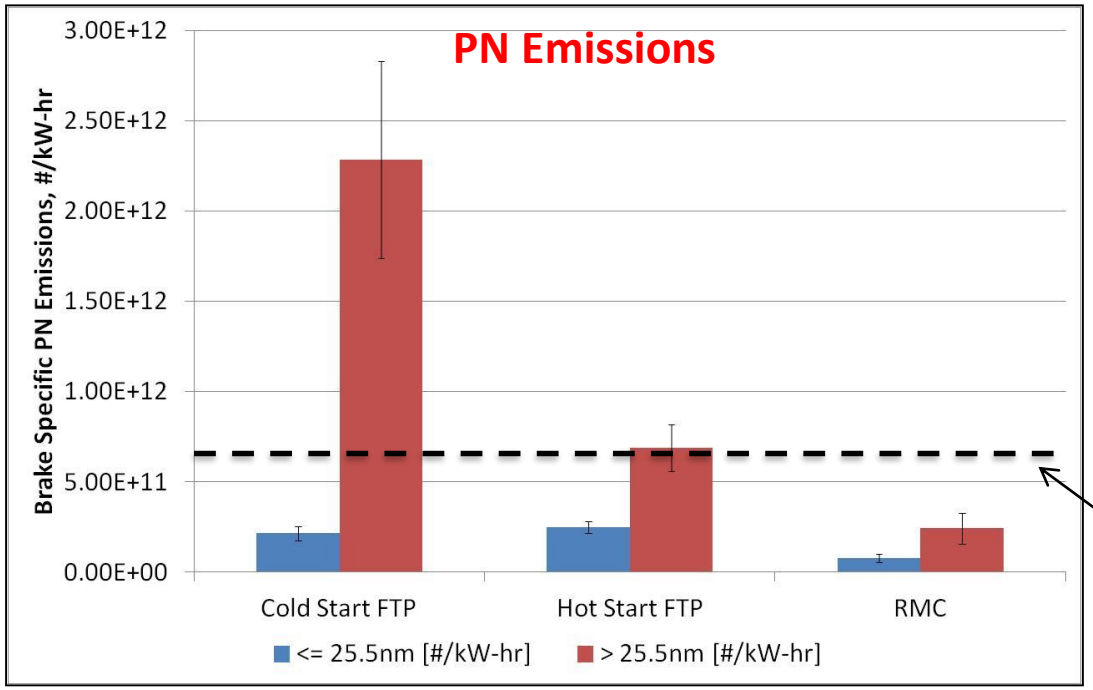
Results - Ash Emissions Profile (Natural Gas Engine)

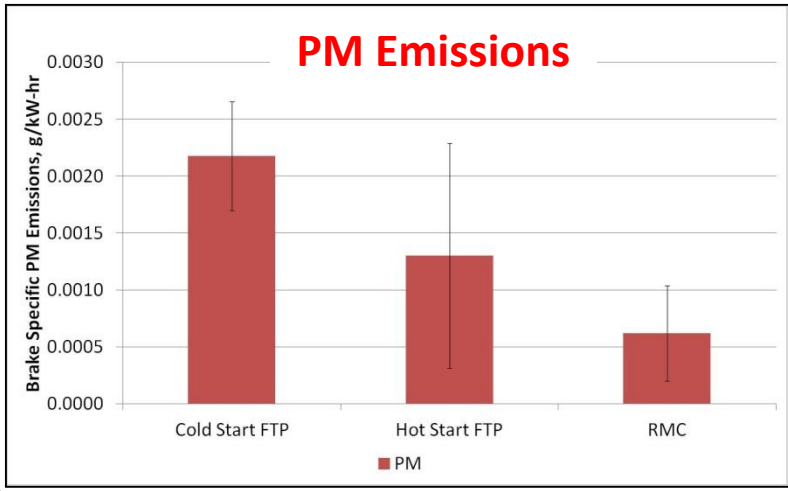




Ash profile seems to follow the PN profile, suggesting that residual ash are carried by the soot particles

Results – Solid PN Emissions (Diesel Engine/SCRF)



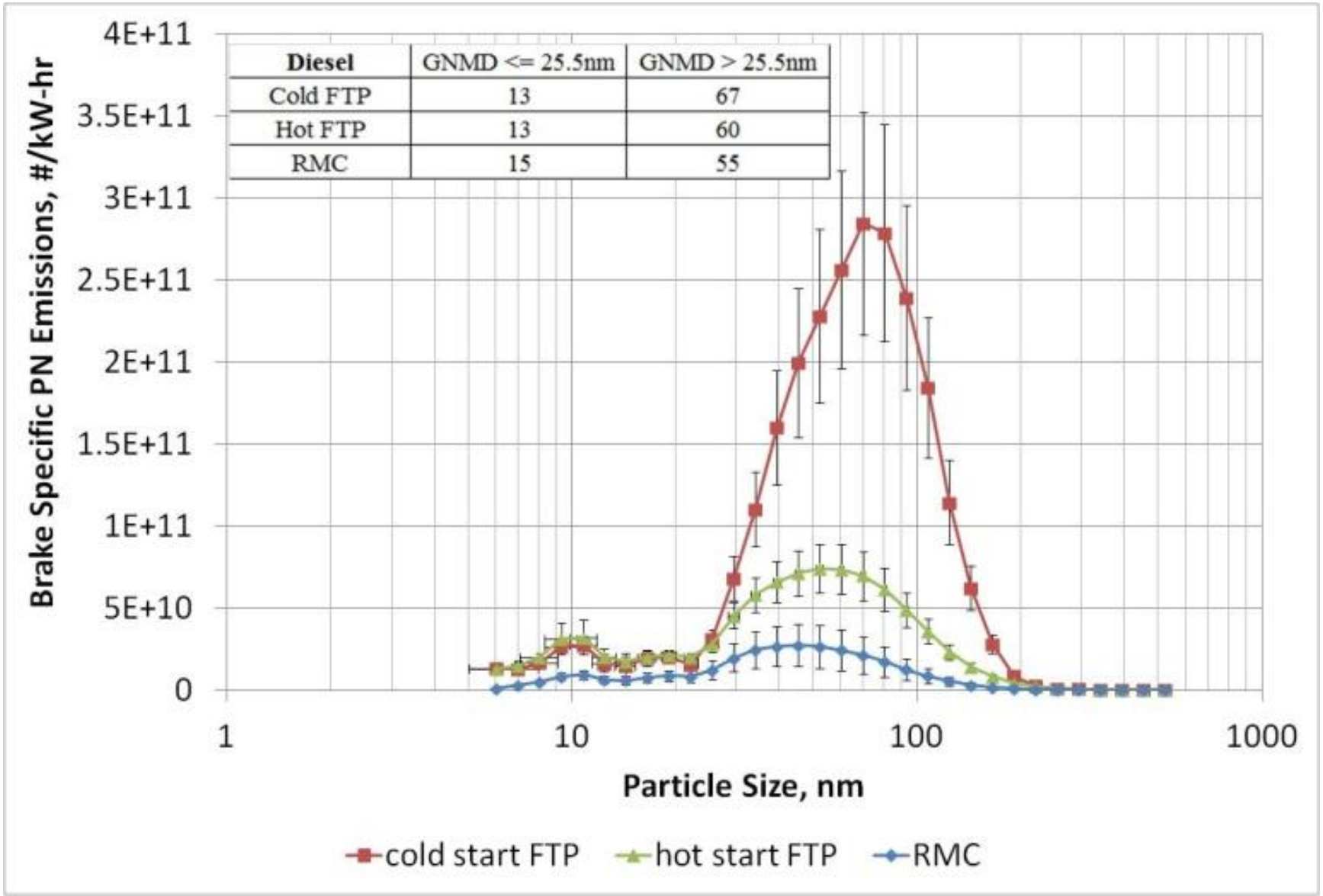


Eu PN Limit $6x10^{11}$ #/kW-hr (particles > 23nm)

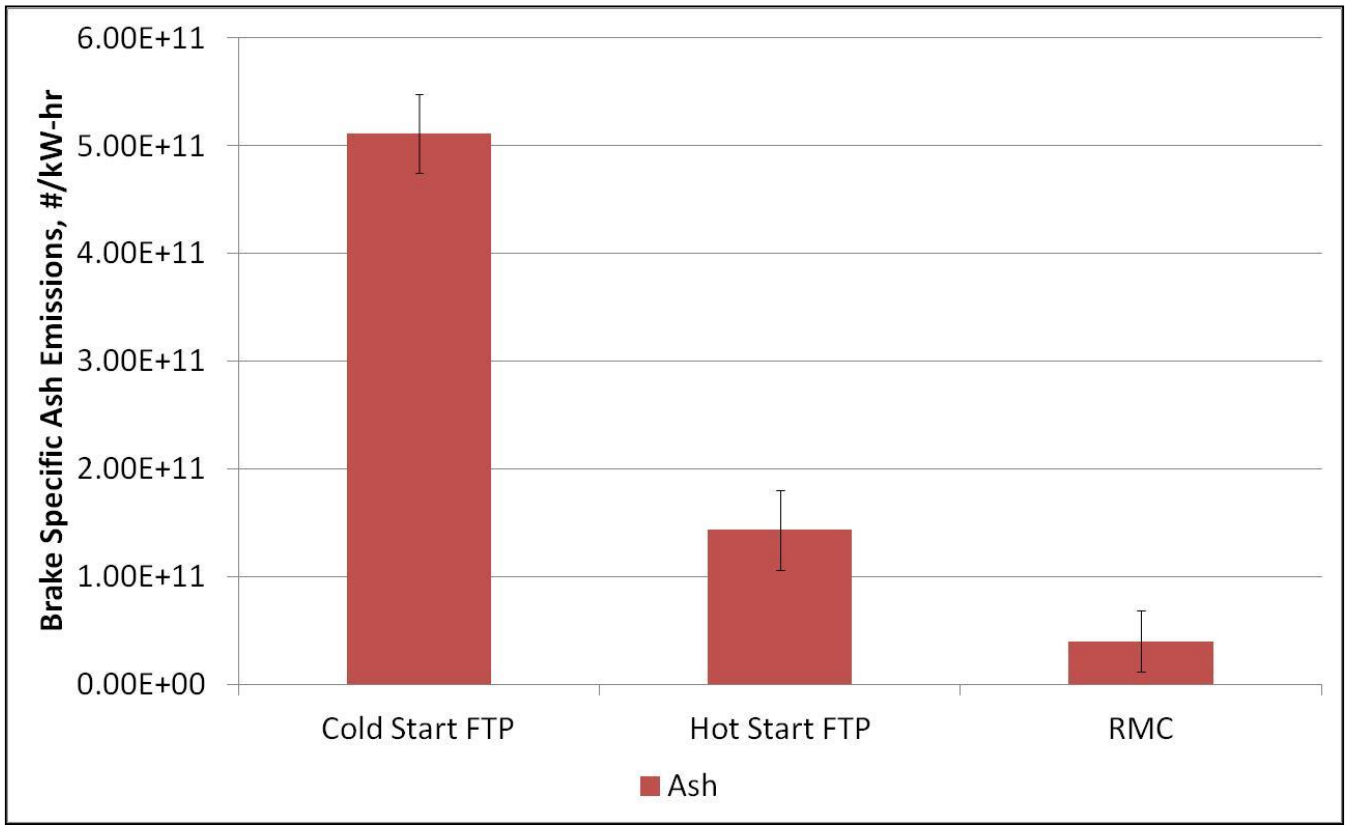
- Cold Start FTP indicated highest emissions of particles >25 nm
- Sub 25 nm particle emissions were comparable between cold and hot start FTPs
- Sub 25 nm particles constitute ~ 10% of total number emissions for cold-start FTP and ~ 30% for hot-start FTPs

Results - Size Distribution (Diesel Engine/SCRF)

Diesel	GNMD <= 25.5nm	GNMD > 25.5nm
Cold FTP	13	67
Hot FTP	13	60
RMC	15	55

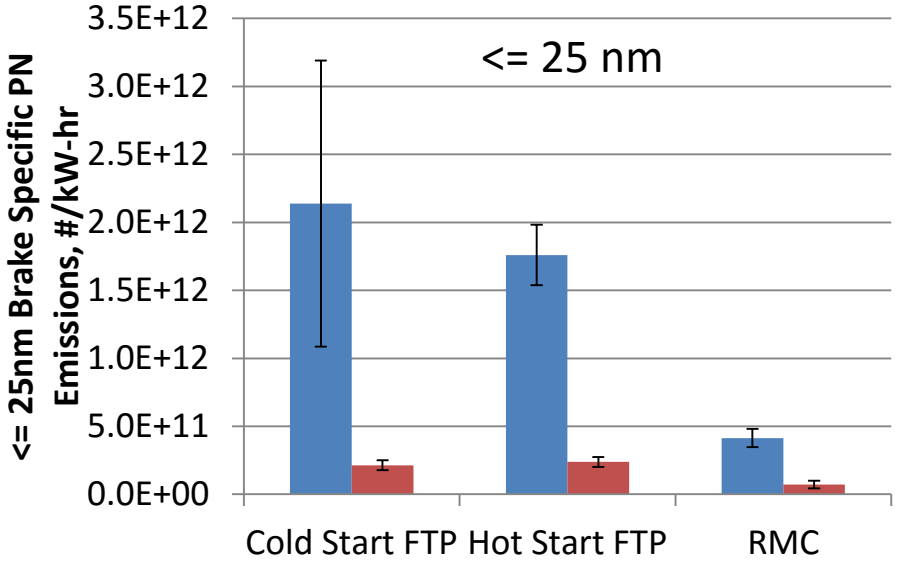


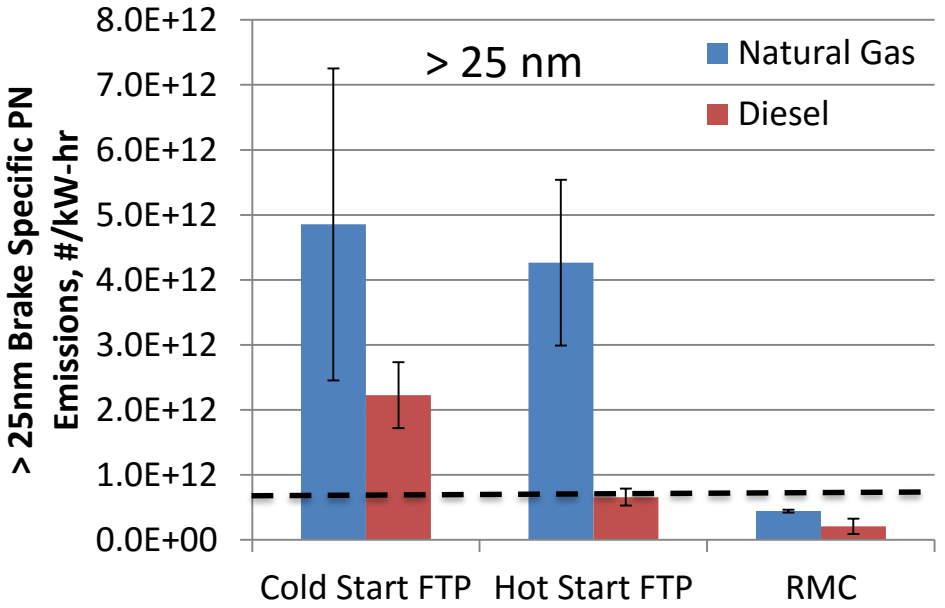
Results - Ash Emissions (Diesel Engine/SCRF)

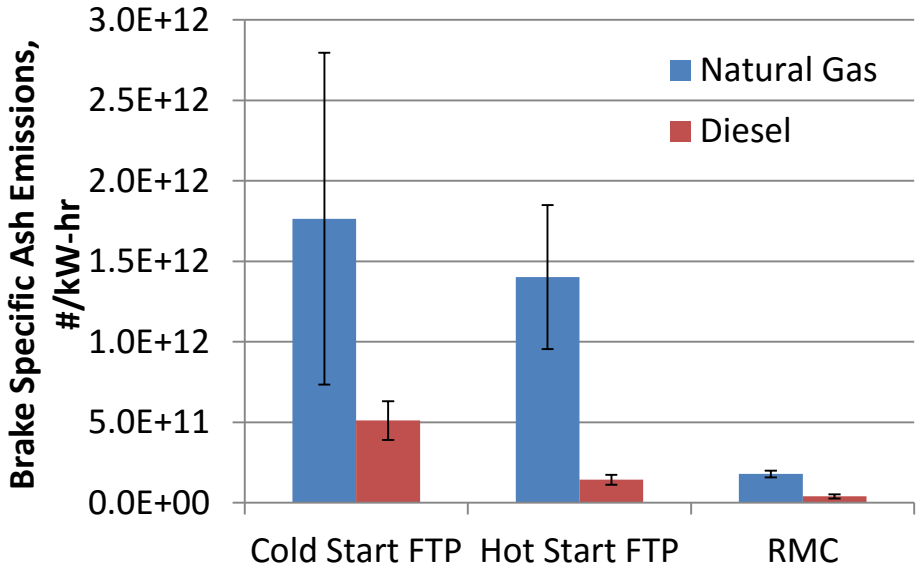


- Ash emissions was ~ 15 to 20% of total number emissions
- Cold-start cycles resulted in more ash emissions compared to hot-start cycles

Comparison – Natural Gas vs. Diesel w/DPF







Main Observations/Conclusions

- **Solid PN > 25 nm**
  - Natural gas engine produced a factor of 2 (cold-start FTP & RMC) to a factor of 8 (hot-start FTP) higher PN, compared to diesel with SCRF/SCR
- **Solid PN< 25 nm**
  - Natural gas engine produced a factor of 5 (RMC) to 10 (cold-start FTP) higher PN, compared to diesel with SCRF/SCR
- **Ash PN**
  - Natural gas engine produced a factor of ~5 (FTP cold-start & RMC) to a factor of 10 (hot-start FTP) higher ash, compared to Diesel with SCRF/SCR
- This work shows that the CNG engine (without filter) emit more solid particles and ash than a diesel with DPF/SCR

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For questions or any other matters please contact:

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