Evaluation of an On-board High-Sensitivity, Real-time Electronic Particulate Matter Sensor Using HeavyDuty On-Highway Diesel Engine Platform

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COORSTEK SENSORS

SwRI®

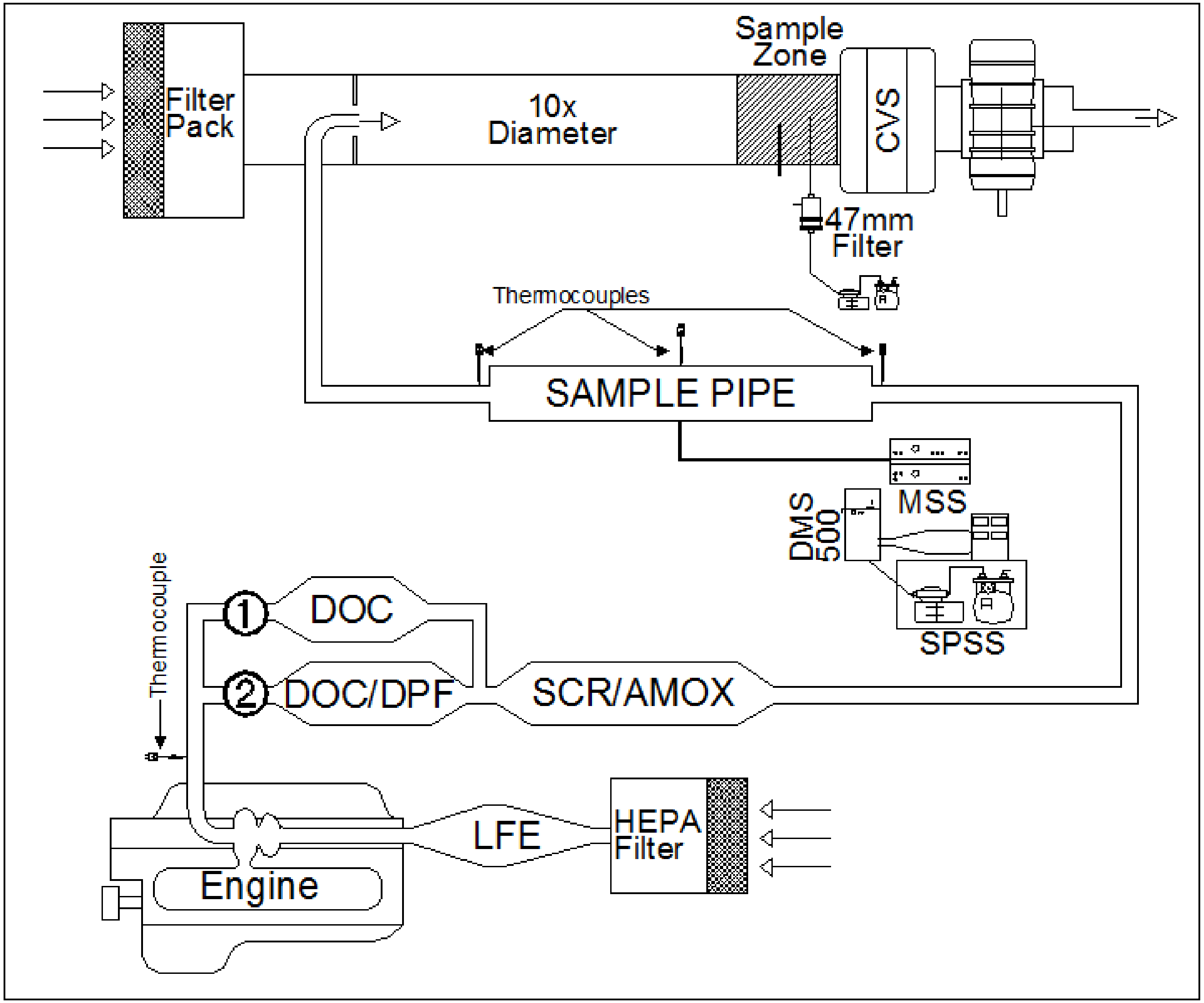
Background

- OBD sensors are very effective means to be used as emission monitors onboard vehicles
- There is a need for more sensitive sensors that can measure PM under typical vehicle operation:
  - In the case of heavy-duty vehicles with exhaust filters, a sensor sensitivity down to 0.001 g/hp-hr or 2 mg/mi is desirable in order to report emissions with working and non-working filters
  - In the case of light-duty vehicles with exhaust filters, a sensor sensitivity down to 0.5 mg/mi is desirable in order to report emissions with working and non-working filters
  - In the case of GDI, a sensor sensitivity down to:
    - 0.5 mg/mi will be a desirable target for 2025 since the emissions will be limited to 1 mg/mi
    - 0.5 to 3 mg/mi will be a desirable for the time between 2018 and 2025, since the emission is limited to 3 mg/mi

Objectives

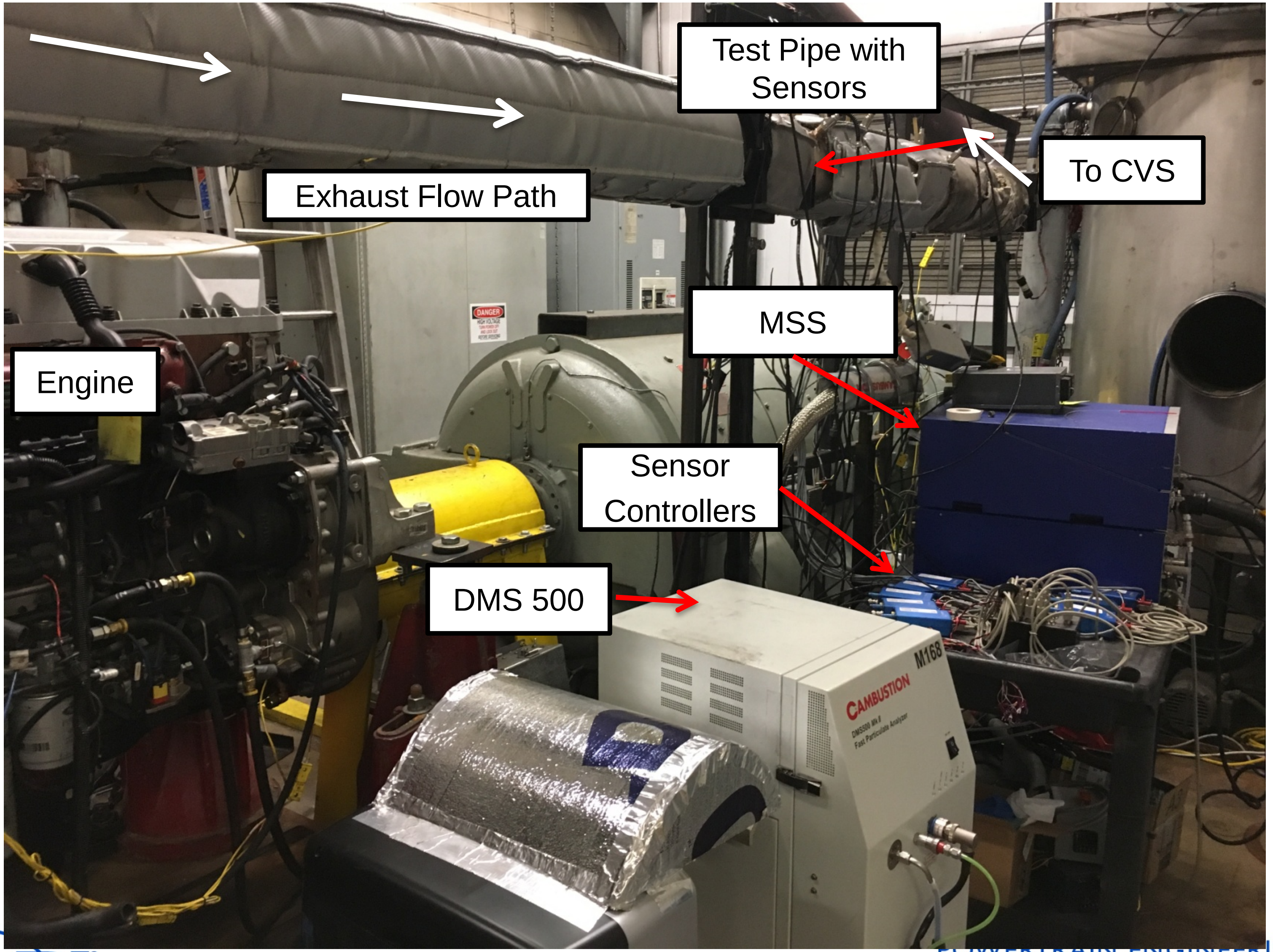
- To evaluate CoorsTek PM sensors on a 2010 Heavy-duty diesel engine platform using state-of-the-art laboratory reference particle instrumentation
- To examine the sensor response at low engine exhaust soot mass concentration, ranging from 0.5 mg/m3 to 4 mg/m3
  - This represents an exhaust filtration efficieny in the range from 90% to 99%

Test Cell Configuration (Similar to SwRI Sensor Consortium Setup)



Control valves for tuning exhaust emissions

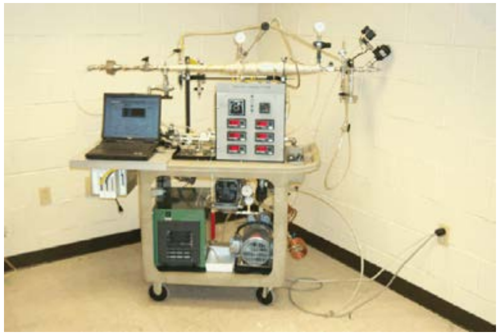
Test Cell Setup



Reference Particle Instruments

AVL MSS (Soot Mass)

TSI EEPS
(Size, Number)



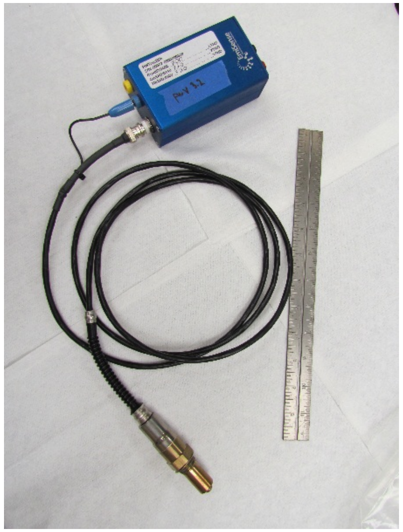
SwRI SPSS, Facilitate Solid Particle Measurement
(Used Upstream of EEPS)

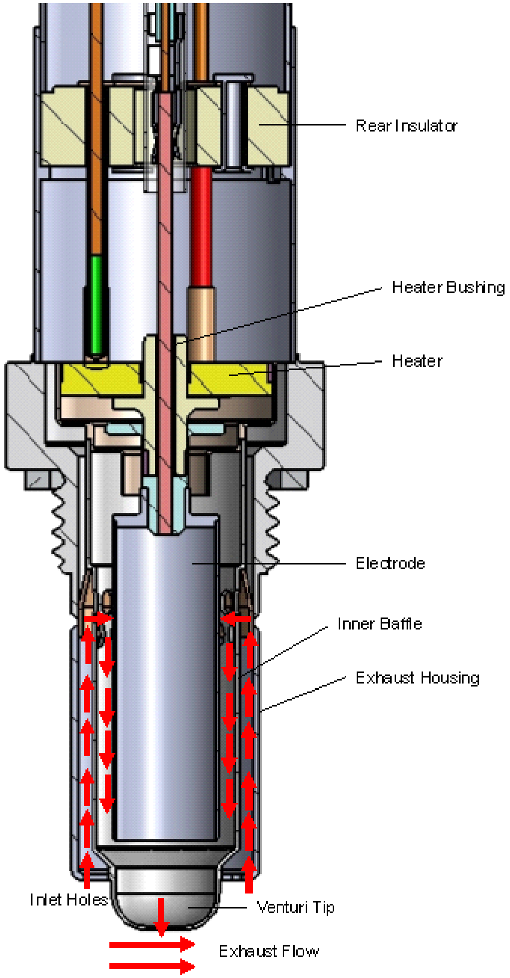
Full Flow CVS and Part 1065 Filter measurement were also included for transient testing

Test Matrix

PM Emissions g/hp-hr	FTP	WHTC	NRTC	RMC
	No. of Repeats			
0.020	5	5	5	5

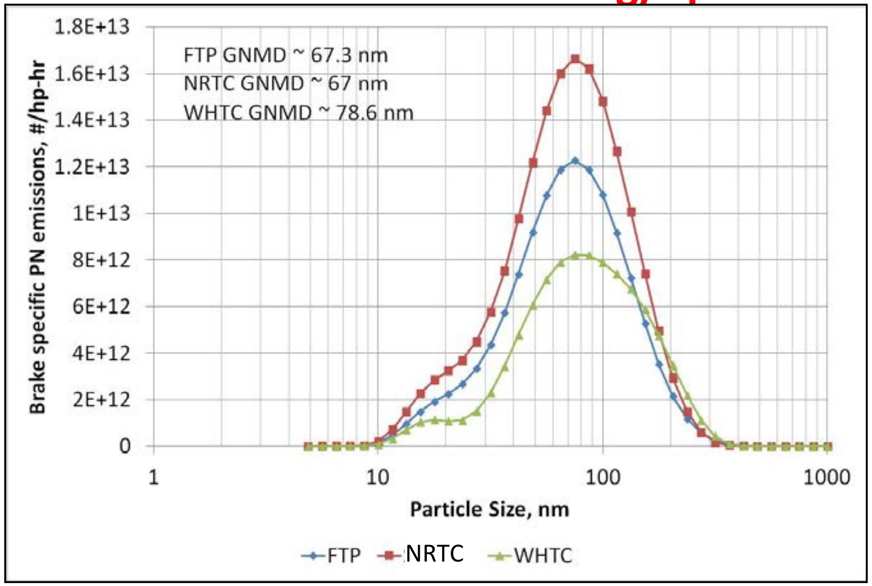
- 8 sample sensors were used in parallel
- Data logged at 10hz



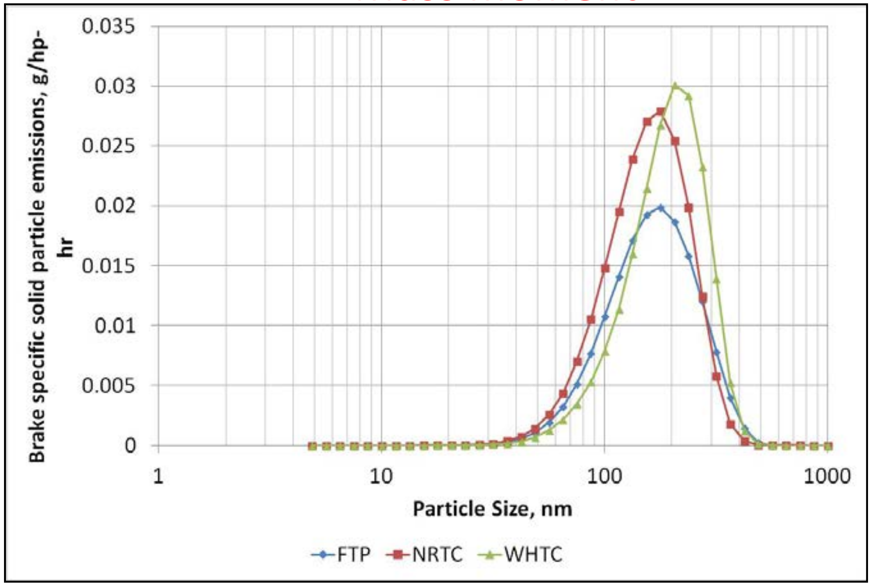


Cycle Based Analysis – Typical Size Distributions

Emission level at ~ 0.02 g/hp-hr

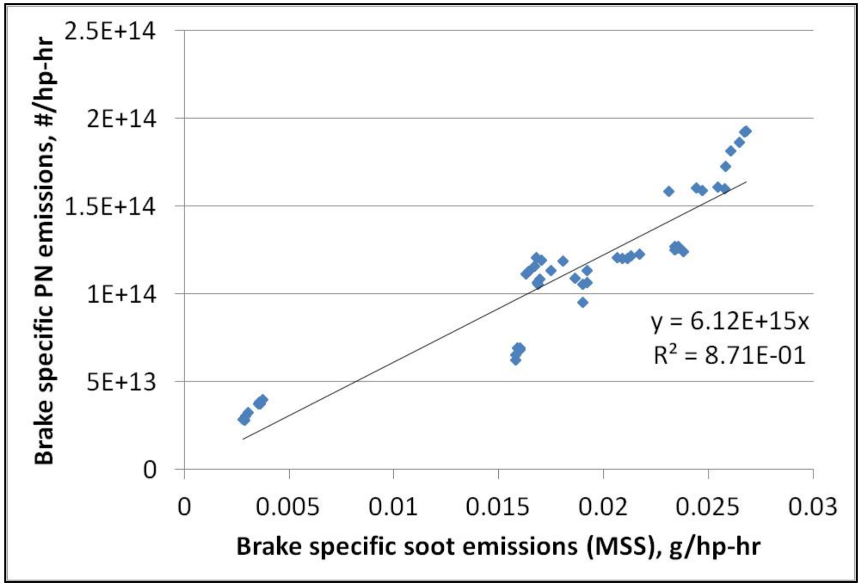


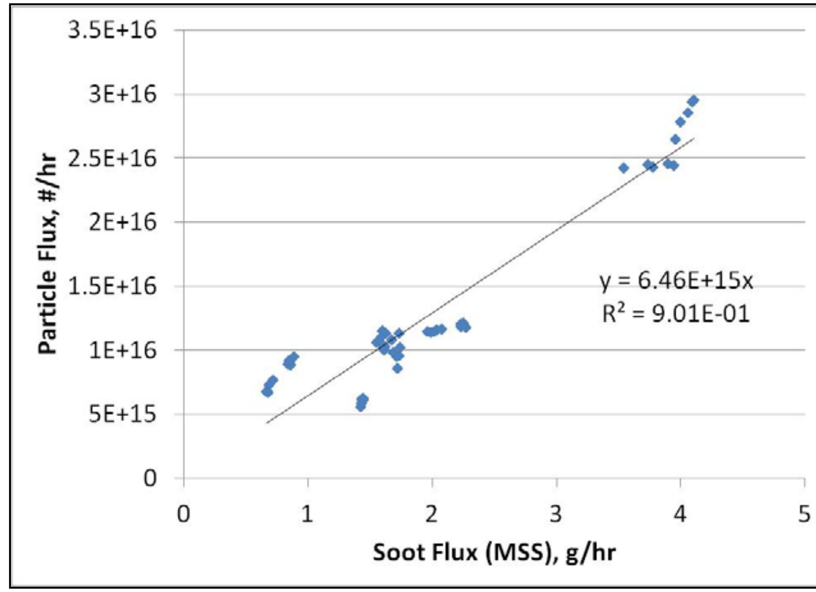
Mass moment

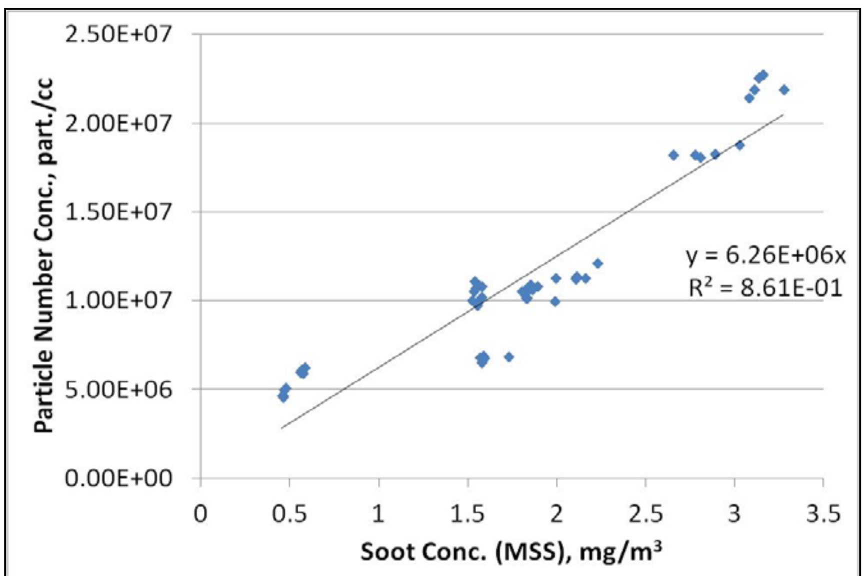


- Solid particle size distribution determined using DMS 500 coupled with a catalytic stripper
- Typical Geometric Number Mean Diameter for FTP ~ 67 nm, NRTC ~ 66 nm and WHTC ~ 74 nm

Cycle Based Analysis – Number and Mass Comparison

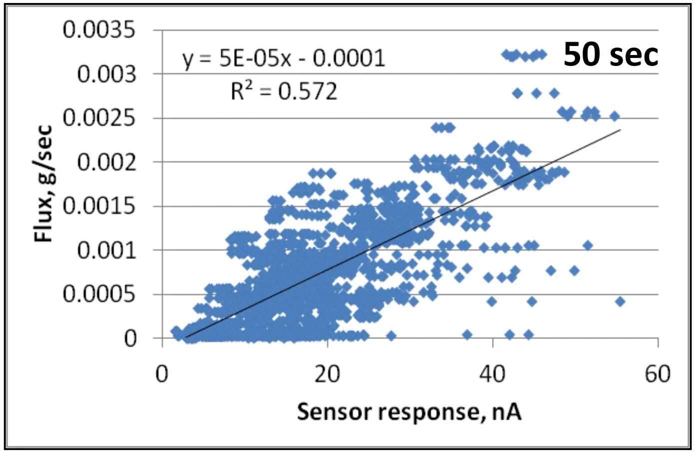


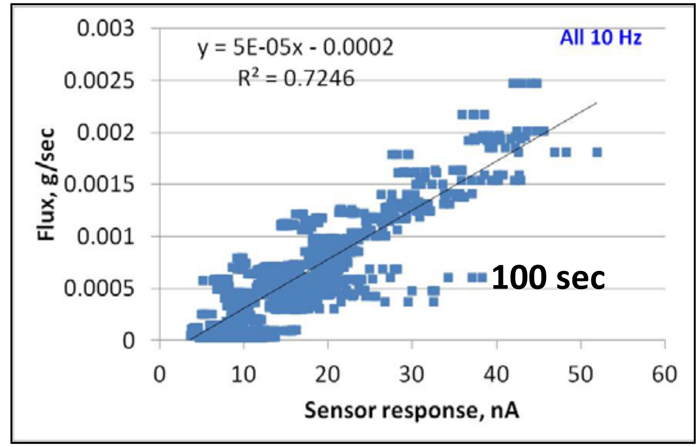


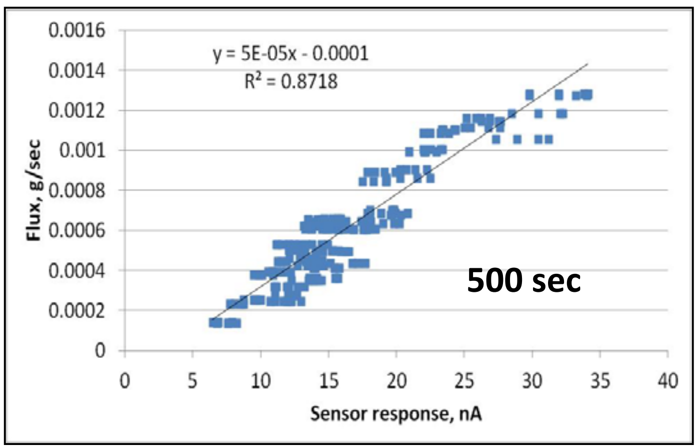


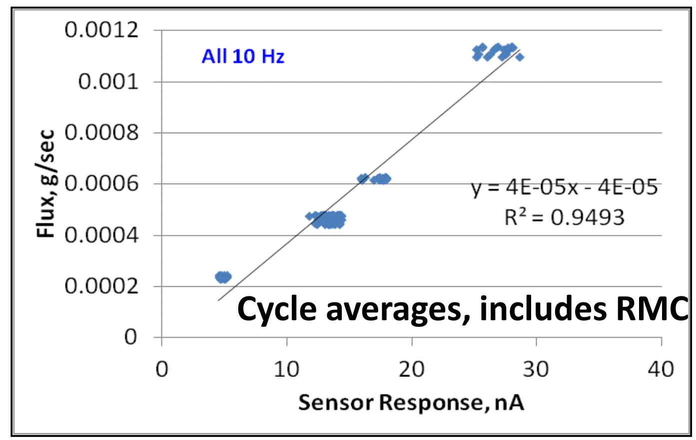
- Data includes all cycles
- Good correlation between soot mass and number was observed
  - **Sensors be used to study sensor response to Solid PN and Soot Mass**

Effect of Windowing Lengths (used for averaging) – Flux Basis, 10 Hz (FTP, NRTC and WHTC)



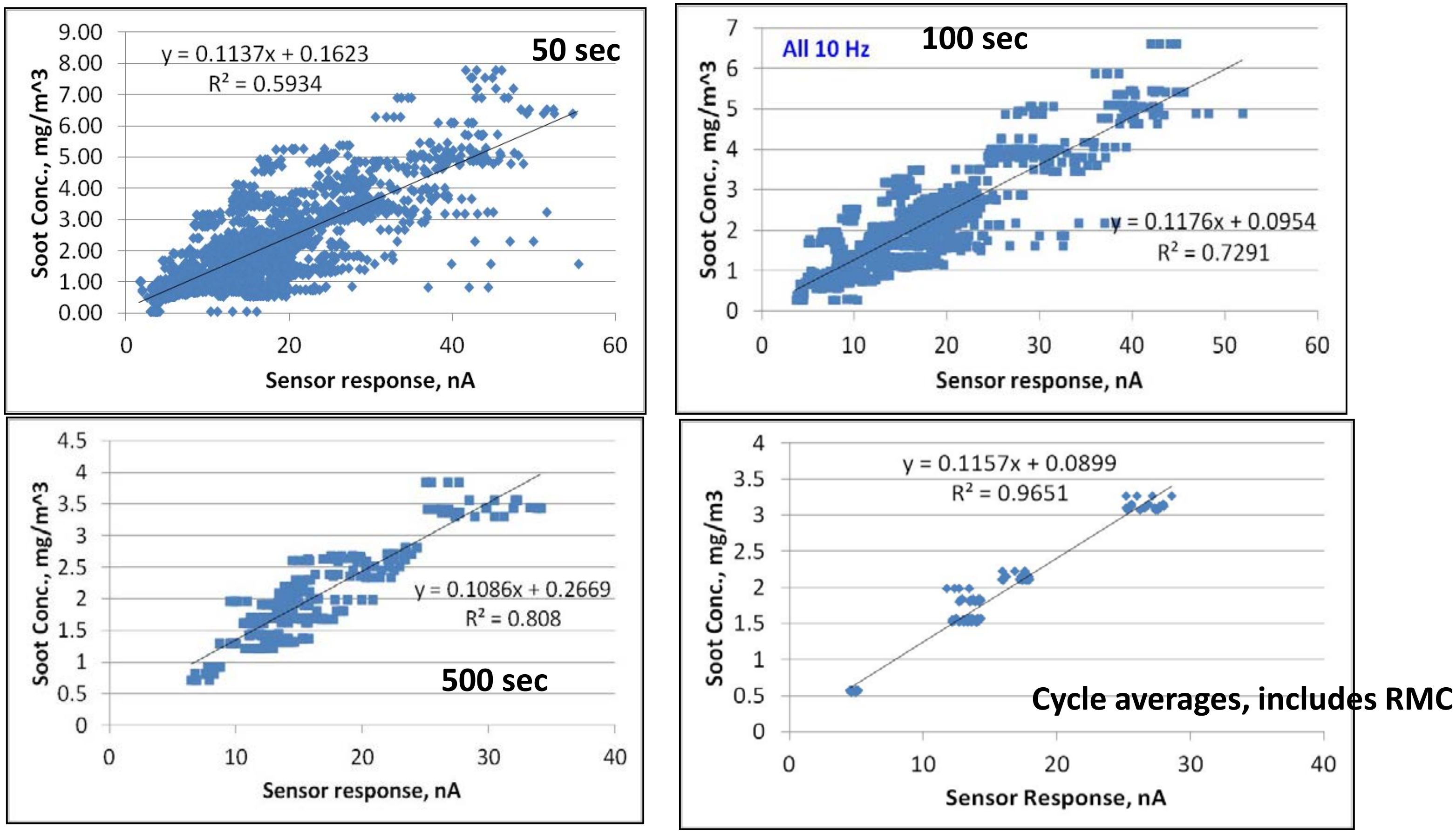






- Reference instrument response time not as fast as sensors', hence the need for windowing
- Increasing window lengths showed better correlation

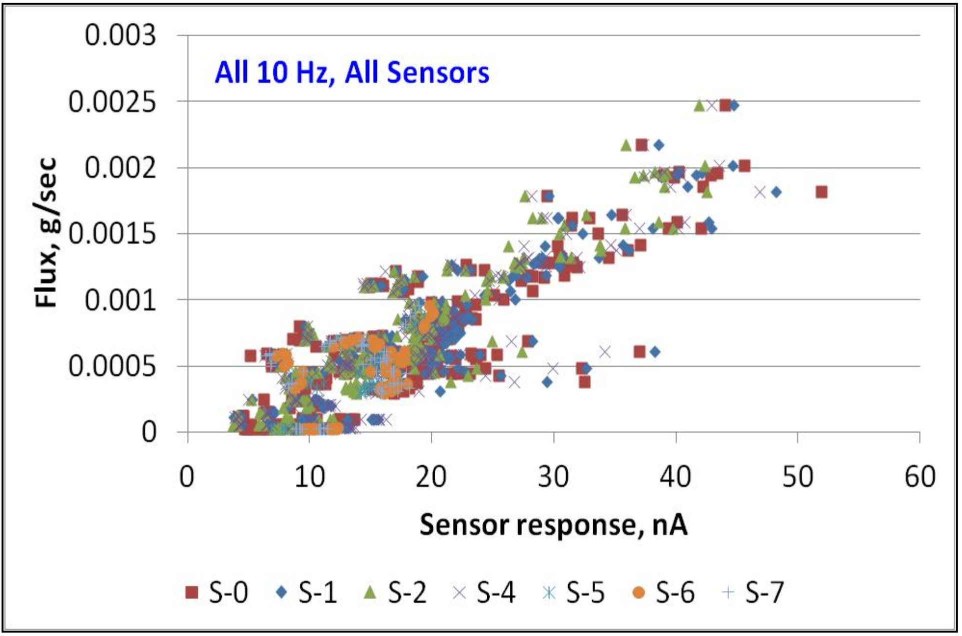
Effect of Windowing Lengths (used for averaging) – Conc. Basis, 10 Hz (FTP, NRTC & WHTC)



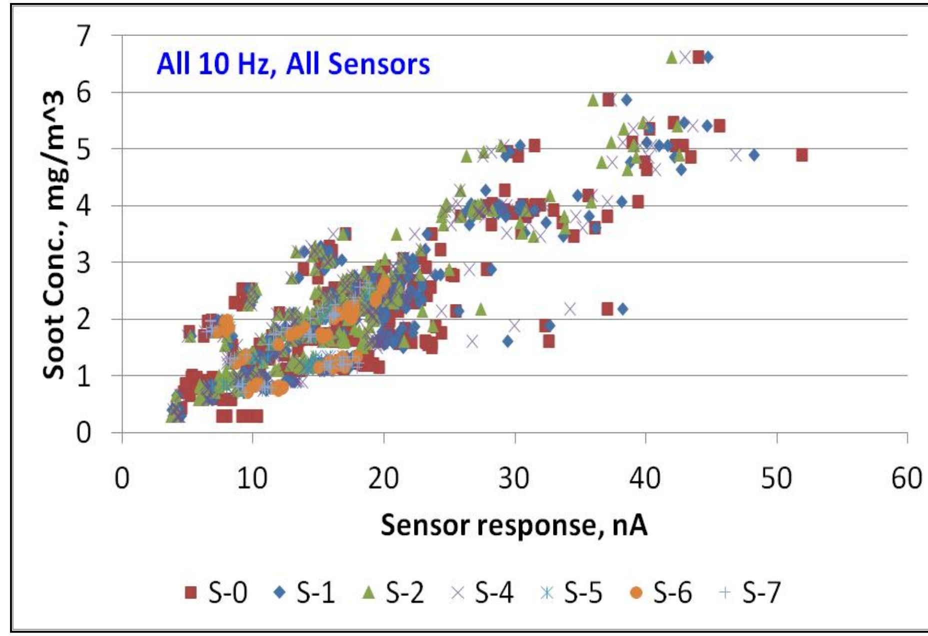
- Increasing window length showed better correlation
- 100 second windows were used for analysis in the results section

Results-2b, Global Plot Sensor by Sensor – 10 Hz data

Flux Basis

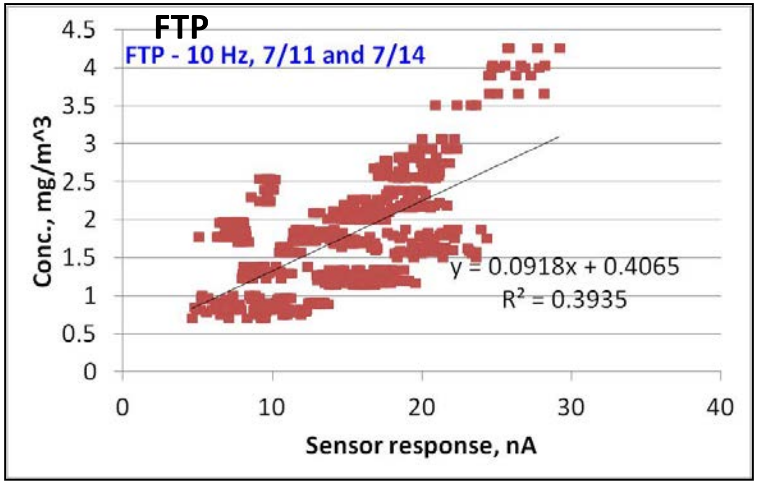


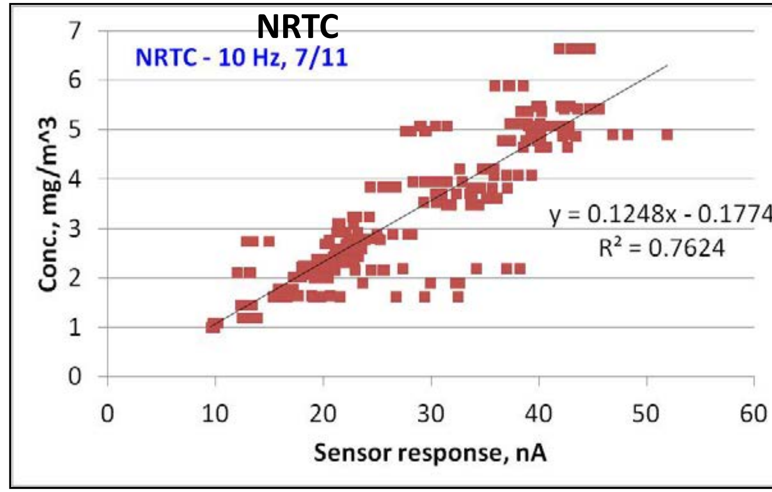
Concentration Basis

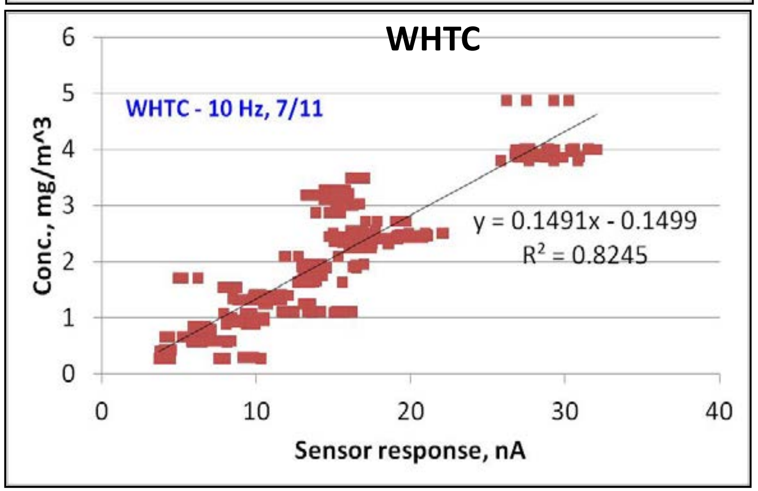


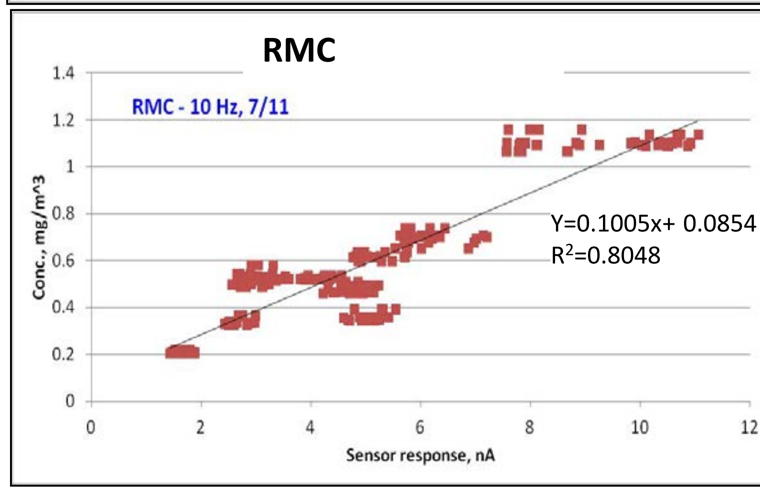
- Above plots includes data from FTPs, NRTCs and WHTCs
- No statistically significant sensor to sensor variability was observed

Results-3d, Cycle by Cycle Basis, Concentration Basis, 10 Hz









- Sensor response observed to be cycle dependent
- WHTC showed the best correlation followed by RMC, NRTC and FTP
- Correlations are stronger for 10 Hz data compared to 1 Hz data
- RMC data was processed mode wise (not 100 sec windows)

Summary Statistics

Slope and R^2 for 10 Hz Data

Window length	with Conc. (mg/m^3)			with Flux (g/sec)			with Brake Specific Soot (g/hp-hr)			Sensor predicted vs MSS brake specific emissions (g/hp-hr)		
	Slope	Offset	R^2	Slope	Offset	R^2	Slope	Offset	R^2	Slope	Offset	R^2
100 sec	0.118	0.095	0.73	0.00005	-0.00016	0.73	0.00079	0.00980	0.28	0.02	0.02	0.004
200 sec	0.116	0.125	0.77	0.00005	-0.00017	0.80	0.00076	0.01112	0.25	0.72	0.01	0.66
300 sec	0.120	0.066	0.83	0.00005	-0.00021	0.84	0.00076	0.01106	0.27	0.66	0.01	0.67
400 sec	0.106	0.309	0.81	0.00005	-0.00013	0.83	0.00056	0.01374	0.16	0.79	0.00	0.73
500 sec	0.109	0.267	0.81	0.00005	-0.00014	0.87	0.00066	0.01218	0.20	0.77	0.00	0.76
600 sec	0.104	0.350	0.83	0.00005	-0.00013	0.90	0.00031	0.01852	0.05	0.88	0.00	0.87
Entire cycle	0.109	0.227	0.94	0.00005	-0.00018	0.98	0.00063	0.01020	0.82	0.89	0.00	0.88

SEE for 10 Hz Data

Window length	Relative to mean			Relative to OBD threshold (0.03 g/hp-hr)	Sensor predicted g/hp-hr with reference g/hp-hr	Sensor predicted brake specific emissions relative to OBD threshold
	Sensor response (na) with Conc. (mg/m^3)	Sensor response (na) with Flux (g/sec)	Sensor response (na) with Brake Specific Soot (g/hp-hr)			
100 sec	28.91%	38.74%	45.21%	34.59%	53.32%	40.80%
200 sec	22.51%	27.70%	40.63%	32.16%	27.34%	21.64%
300 sec	13.75%	23.17%	34.68%	27.47%	23.45%	18.58%
400 sec	12.78%	20.47%	34.90%	26.84%	19.90%	15.31%
500 sec	12.74%	16.74%	34.24%	26.50%	18.58%	14.38%
600 sec	12.11%	12.91%	32.18%	25.44%	11.98%	9.47%
Entire cycle*	8.15%	6.32%	7.67%	5.33%	6.12%	4.26%

- **Note: Only FTPs, NRTCs and WHTCs are included for the above**
- **Correlation between sensor response and reference flux was used to determine sensor predicted brake specific emissions**

Conclusions

- This work showed that the sensors are sensitive to detecting very low PM emissions down to 0.5 mg/m3
- Sensor to sensor variability was not significant
- Sensor response was cycle dependent. The FTP showed a correlation coefficient of 0.4, while the NRTC, WHTC and RMC showed correlation coefficients of 0.72, 0.82 and 0.8, respectively.
- Sensor integrated data over a larger time interval showed a much better correlation than over a short interval.
  - Choosing an integration using 600 seconds time interval, for example, resulted in a correlation coefficient of 0.87 and a standard error of estimate of 10% relative to the mean value
- The current sensor technology will be evaluated this year on a light-duty engine platform and a GDI engine platform, under the ongoing SwRI Particle Sensor Perfromance & Durability Consortium (PSPD-II), along with other sensors provided by Bosch, Denso, NGK-NTK and Stoneridge.

Acknowledgements

- This work was funded by CoorsTek.
- Engine Setup and Configuration was funded by the PSPD consortium, where CoorsTek is a member. The engine platform can be used by members to conduct one-on-one programs outside the consortium as time permits.

- For questions or comments, please contact Dr. Imad Khalek at Ikhalek@swri.org