Electrostatic PM Sensing

Low-cost On-board ePM for Continuous Compliance Monitoring and Geofencing

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March 18, 2022

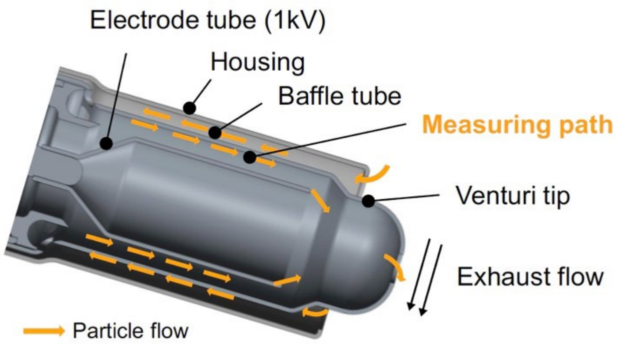
11th Annual PEMS Conference

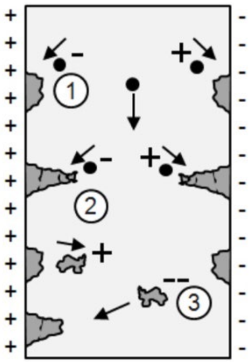
Agenda

1. ePM Review
   - -Performance
   - -Limitations
2. Applications
   - -OBD
   - -OBM

ePM / PMTrac® Measurement Principle Review

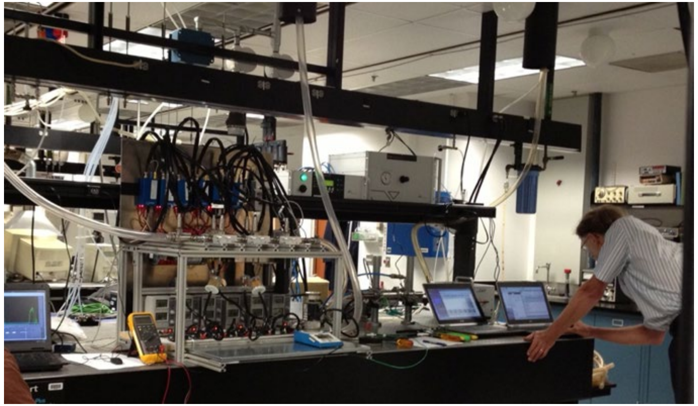
- "Agglomeration and charge loss sensor" essentially a 1kV concentric electrostatic trap.
- Venturi tip draws an extract of the exhaust gas into the electrical field between the electrodes (measuring path). Three events occur:
    1. **Initial capture**: The charged fraction of particles are accelerated to oppositely-charged electrode.
    2. **Agglomeration**: Field-directed assembly of dendrites/filaments, with high charge density at filament tips.
    3. **Charge loss**: Soot agglomerates break off, carrying a high charge. After a certain time, particle deposition and dendrite break off is in balance (sensor startup time).
- Measured current is proportional to PM/PN
- Advantages: Sensitivity, Fast Response, Durable
- Limitations: Startup time, Calibration, Transients
- Strong patent portfolio ($30M, blocking rights through 2034+)

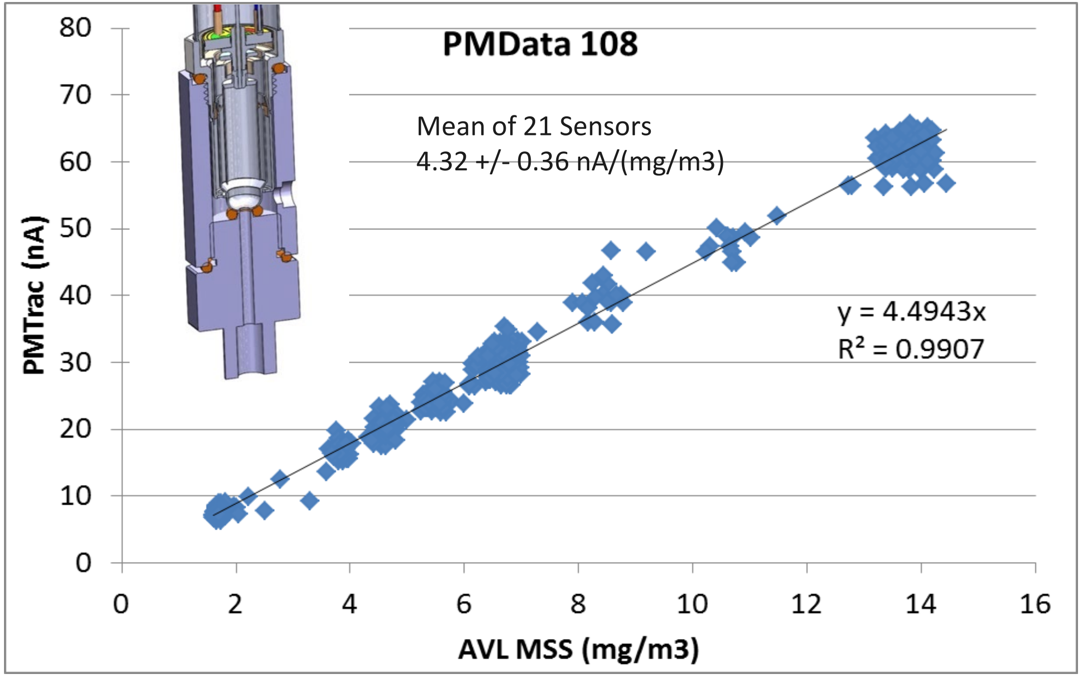




Test Results 2012: Constant EGV/EGT R^2 =.99

- Ford Multi-sensor test rig for characterizing sensors (Matti Maricq)
- Jing Mini-CAST soot generator with Dekati FPS-4000 diluter
- AVL MSS
- TSI Dusttrak
- Constant EGT = 24 ºC
- 0.5, 1, 2 LPM sample flow rates
- EGV ~ 14, 30, 70 m/s

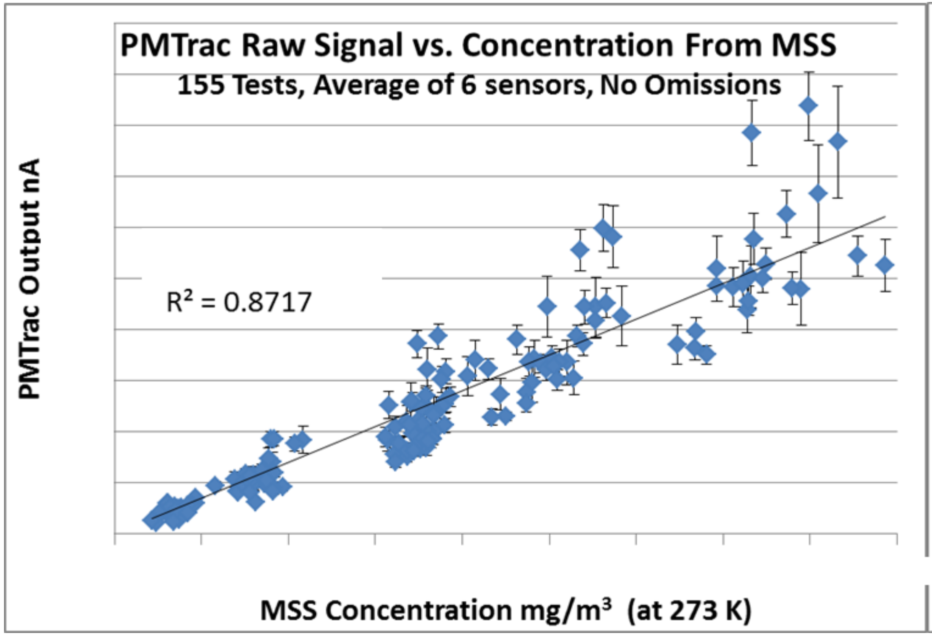


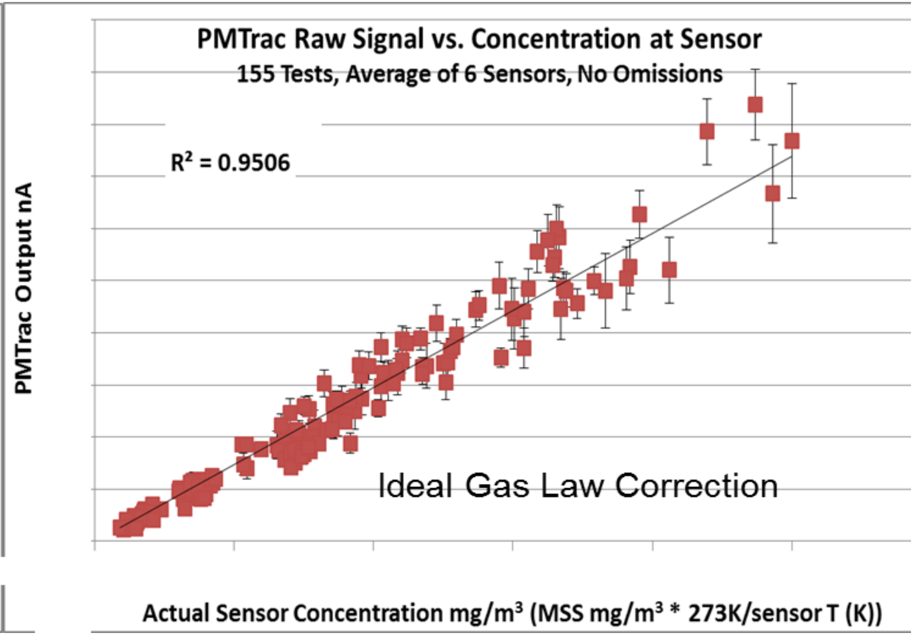


(Presented at PEMS Conference 2014)

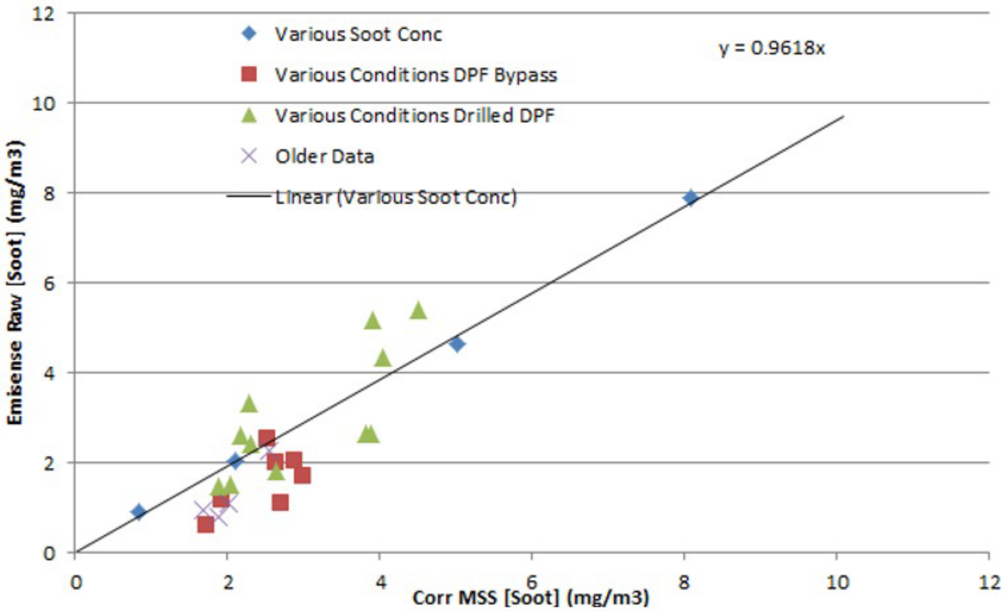
2013 Steady State Testing SwRI PSPD-I

- EGT=200~500C; EGV=10~70m/sec; PM=0~15mg/m³
- Uncorrected R^2=0.87; Gas law correction R^2=0.95
- Similar results at multiple OEMs





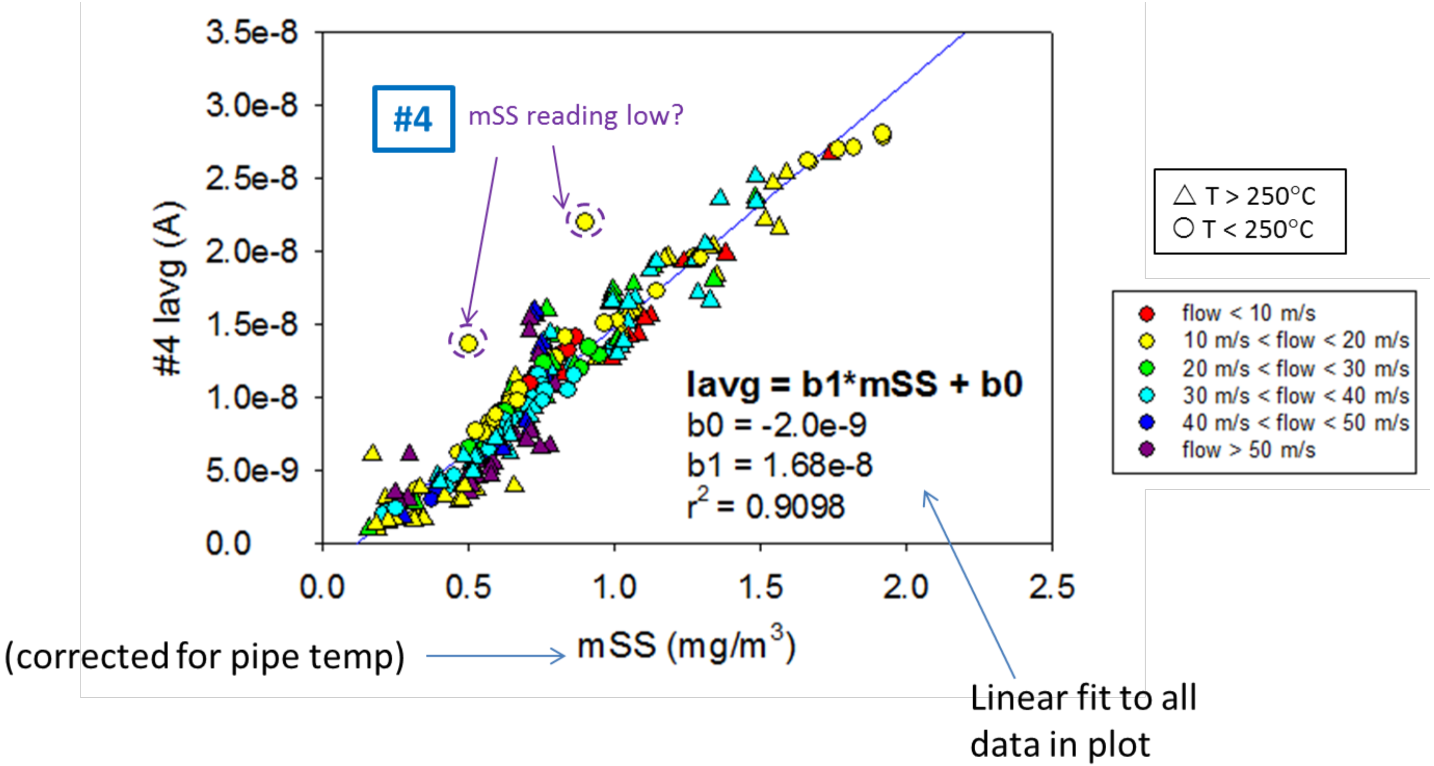
Electrostatic Sensor Accuracy



In 2013, GM tested the EmiSense electrostatic sensor and found that it had good correlation with matching the soot concentration reported by the MSS at a wide range of different supplied soot rates.

2013 Steady State Engine Dyno (Ford RIC 9) $R^2 = 0.91$

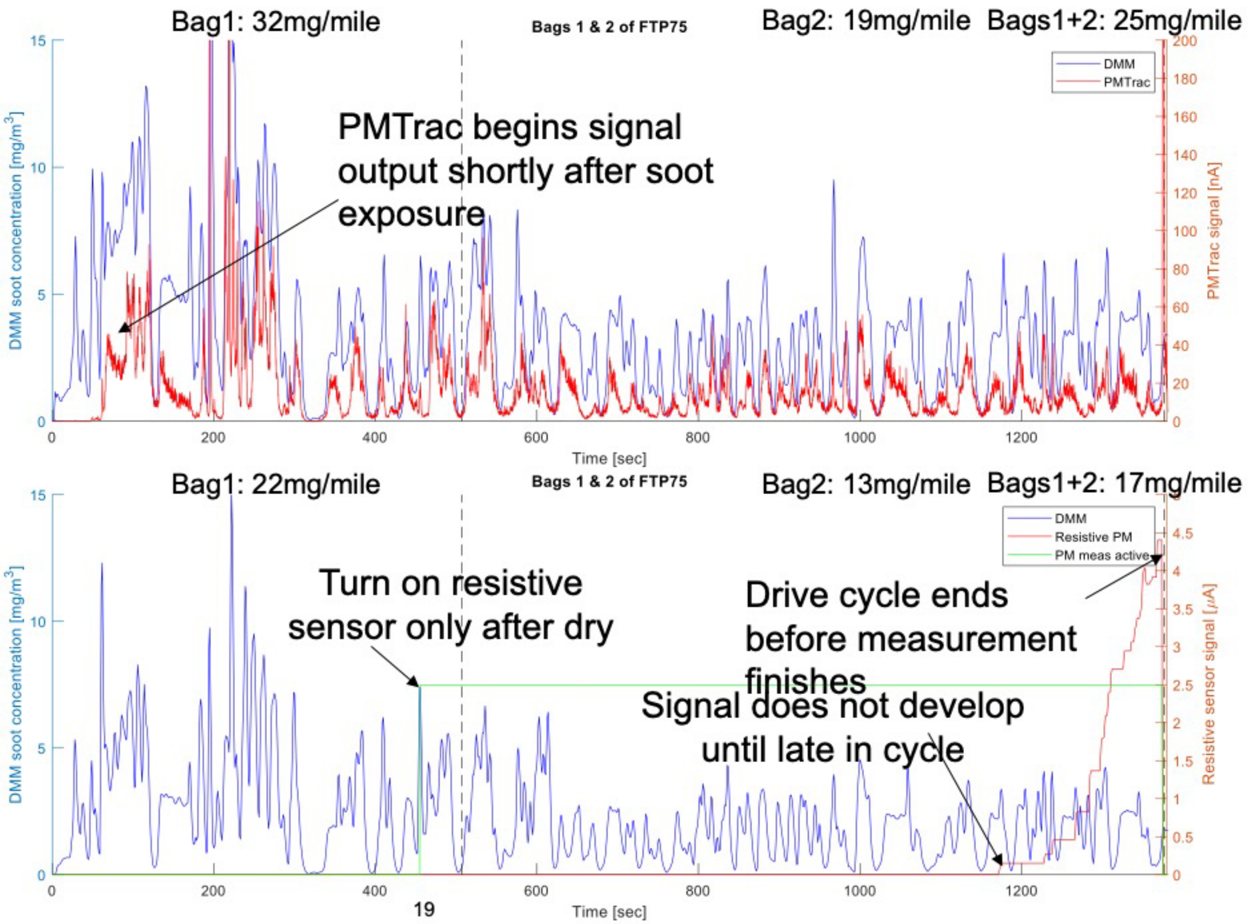
- 275 runs, all steady-state for PM within run
- Avg. sensor current for entire steady-state run vs. avg. MSS reading.
- Sensors can measure <0.5 mg/m^3



HV PM sensor comparison to resistive PM sensor

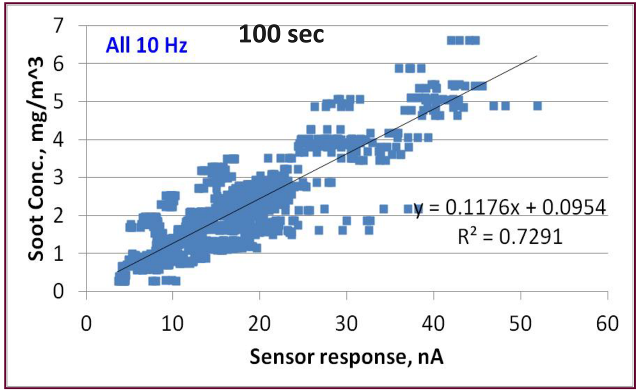
Research and Advanced Engineering

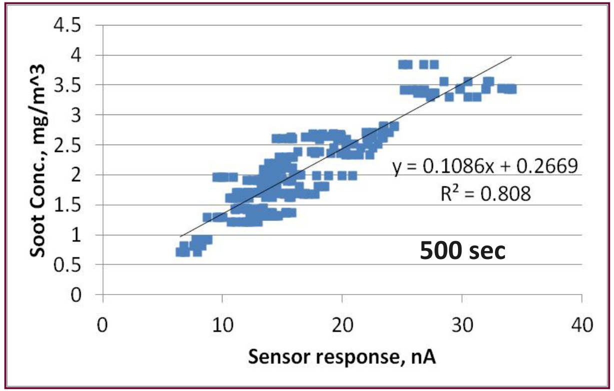
This comparison is not quite fair because the PMTrac was run with a higher leak rate, but it illustrates the stark contrast in the time it takes signal to develop, as well as the amount of information contained in the signal with each technology.

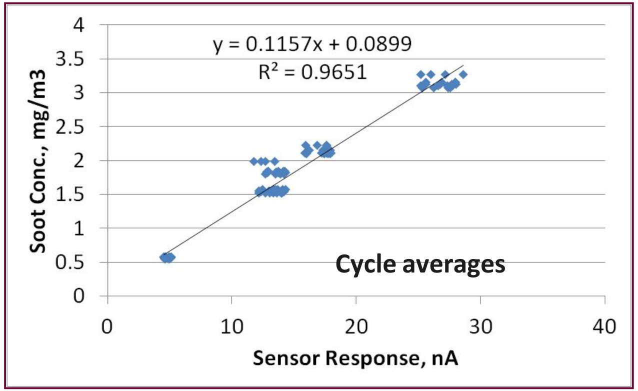


2018 Transient Drive Cycle Testing

- Flow transients / pressure pulses disrupt the dendritic equilibrium, creating over-report spike followed by under-reporting recovery
- While more complex transfer functions might be able to correct for transient noise, Dr. Imad Khalek from SwRI explored a simple windowing approach (2018 PEMS)
- Longer windows provide higher correlation, but lower IUMPR/response time
- No transfer function, various windows, combined drive cycles (FTP, NRTC & WHTC):







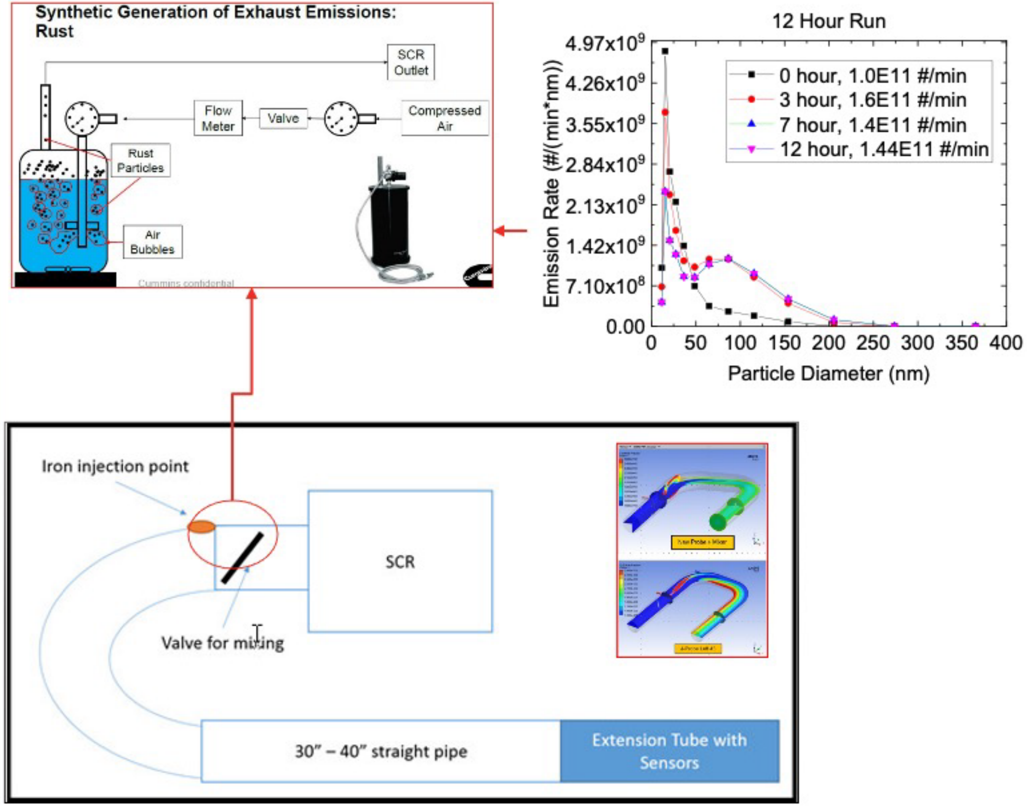
Conclusions from 2020 SAE Paper

- ePM sensitive to detecting very low PM emissions down to 0.5 mg/m^3
- Sensor to sensor variability was not significant
- 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 12% relative to the mean value
- Key Papers
  - https://doi.org/10.1016/j.jaerosci.2016.03.003
  - https://doi.org/10.1016/j.jaerosci.2018.07.002
  - https://saemobilus.sae.org/content/2020-01-0385/

Standard Error of Estimate (SEE)	
Window Length	**Sensor response (na) with MSS Conc. (mg/m^3)**
100 sec	28.91%
200 sec	22.51%
300 sec	13.75%
400 sec	12.78%
500 sec	12.74%
600 sec	12.11%
Entire cycle	8.15%

Accelerated Life Test (ALT) 3.0 Overview . . .

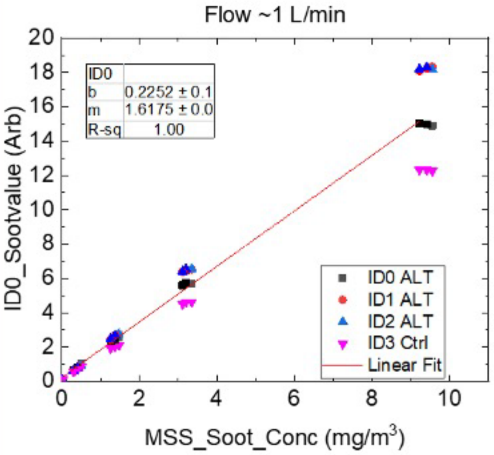
Electronics

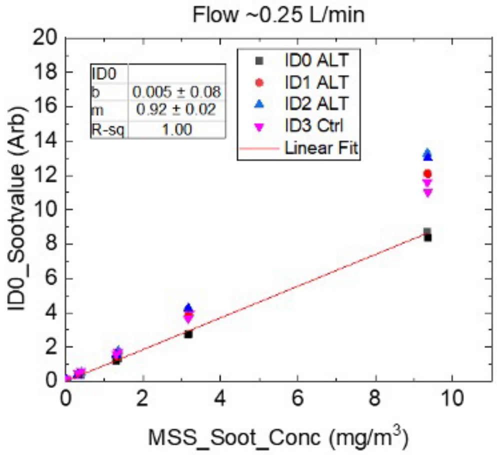


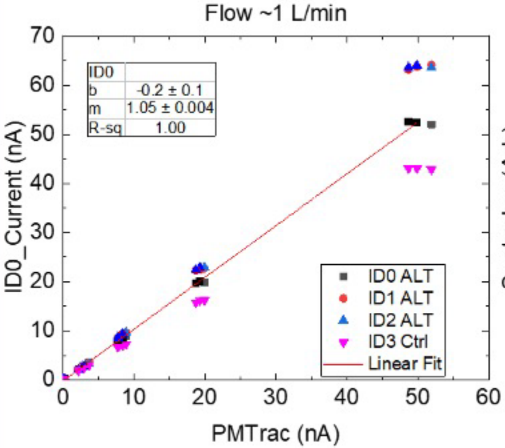
- In ~2017 Cummins completed an accelerated life test for the Emisense PM sensor against one of our primary failure modes (rust exposure).
- The sensors were exposed to 100's of grams of aerosolized fine particulate rust.
- Post test, the sensor performance was characterized on a laboratory bench.
  - The bench test utilized a soot generator, a Micro-Soot Sensor, TSI DustTrack, Emisense PMTrac, a new Continental ePM, and three ALT 3.0 subjected Continental ePM sensors.
- Results of the laboratory test were all positive (see next slide)

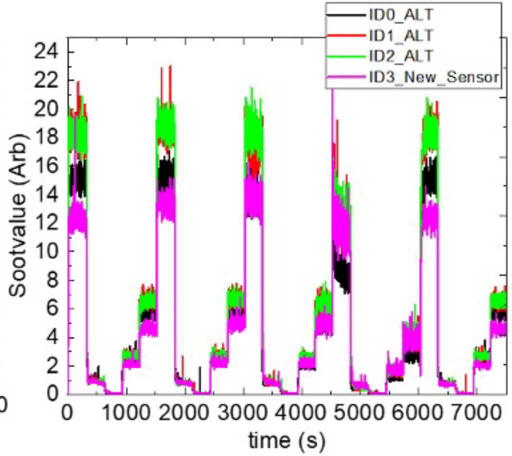
ALT Results Electrostatic, Emisense.

Electronics









- Data in top left shows two things:
  1. Pre and post ALT the sensors are linearized very well with respect to both soot concentration and soot flux which correlates with brake specific emissions.
  2. There is some sensor to sensor variability and ***perhaps*** (more data needed to know for sure) a small increase in sensitivity of the sensor (good?) induced by ALT as evidenced by the higher gain than the new control sensor.
- Data in top right shows that all sensors have a flow dependent behavior that would need to be accounted for on the application.
- Data in the bottom left shows that these sensors are ***very*** similar to a new PMTrac (i.e. correlated with a slope of ~1).
- Data in the bottom right shows that…:
  1. These sensors have a good response time (i.e. << 1 min).

Performance & Limitations

- So what do we have here?
- +/-30%, fast, durable, in-situ soot sensor
- Limitations:
  1. **Startup time.** At low concentrations (<1mg/m^3), startup time can be up to 600+ seconds.
  2. **Calibration.** Sensitivity (nA/mg/m^3) is a function of PSD and PCD.
  3. **Transients.** Pressure pulses cause false spike followed by under-reporting.

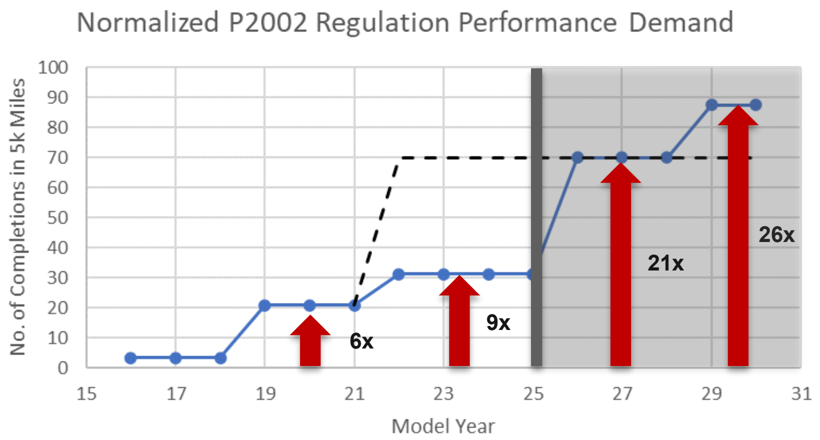
Application: OBD

- MY26 CARB MD Diesel IUMPR is exceeding the capabilities of existing (resistive) sensors.
- ePM can meet IUMPR for DPF monitoring
- Startup time, calibration, and transient noise limitations all acceptable in this application
- ~633K Diesel MD work trucks sold each years in US
- ePM functional on GDI, NG, hybrids (verifying near-zero PM/PN with or without xPF)

CARB DPF Monitor Proposed Revision (2/3)

	Proposed Threshold and IUMPR				
		Option 1		Option 2[a]	
Vehicle/Eng. Category	PM standard (g/mi)	OBD Threshold (mg/mi)	IUMPR	OBD Threshold (mg/mi)	IUMPR
LD Chassis	0.003 (2017-2024MY)	17.5	0.150 (2022-2025MY)	17.5	0.150 (2022-2025MY)
	0.001-0.003 (2025-2027 MY)	17.5	0.336 (2026-2028MY)	10	0.150 (2026-2028MY)
	0.001 (2028+MY)	10	0.200 (2029MY+)	10	0.200 (2029MY+)
MD Chassis	0.008-0.010 (2021MY+)	17.5	0.150 (2022-2025MY)	N/A	N/A
		17.5	0.336 (2026-2028MY)	N/A	N/A
		14.0-17.5	0.336 (2029MY+)	N/A	N/A
	g/bhp-h				
MD Engine	OMNIBUS Proposal	0.03 g/bhp-h	0.300 (2019-2025MY)	0.03 g/bhp-h	0.300 (2019-2025MY)
	0.005 (2024MY+)	0.03 g/bhp-h	0.336 (2026-2028MY)	0.02 g/bhp-h	0.150 (2026-2028MY)
	0.005 (2024MY+)	0.02 g/bhp-h	0.200 (2029MY+)	0.02 g/bhp-h	0.200(2029MY+)

CARB 11/9/2020



Application: OBM

- Continuous Monitoring, RDE, RWEL, I/M, Geofencing, etc.
  - Utility for identifying operating conditions under which PM/PN emissions are above expectations (degradation, tampering, behavior, unexpected)
- Recommendations
  - Calibration
    - Option A: Do basic calibration by engine family with PEMs
    - Option B: Big data, derive sensitivity from large data set and track outliers
  - Transients
    - Log raw signal at 10Hz PLUS calculated average for 100+-sec. window. Provides both "fast" and "accurate" information
  - Start up
    - Unclear if ePM is ever suitable for cold starts
- OBD sensors eventually make good OBM sensors
  - ELD/Fleet Services like Geotab and Momentum, low monthly subscription, easy installation and replacement

Conclusions

- The world needs a durable, low-cost, and responsive tailpipe PM sensor.
  - This is true despite increasing electrification, but also *because* of it, since regulators and consumers expect hybrids, clean diesels, e-fuel vehicles, etc. to be as close as possible to the zero tailpipe emissions of electric vehicles.
- ePM has a real shot at commercialization to solve the urgent MY26 DPF OBD IUMPR problem. Commercialization will lead to further improvements in durability and cost expectations. ($30M to date, ~$7.5M to go)
- OBM/RWEL/Geofencing are also promising application, require development/calibration/integration/big-data work.
- ePM is a whole new class of sensor, and this creates opportunity for discovering new ways to use it.
- S23 ePM / PMTrac® (new generation of sensor seal) evaluation kits are available.

Emisense

ultrafine particle sensors

Thank You!

NOx/O2 Module | PM Module | Data Logger (CAN, GPS, LTE) | GPS & LTE Antennas

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