In-Use NTE PM Measurement Methodology using an In-Line, Real-Time Exhaust PM Emissions Sensor

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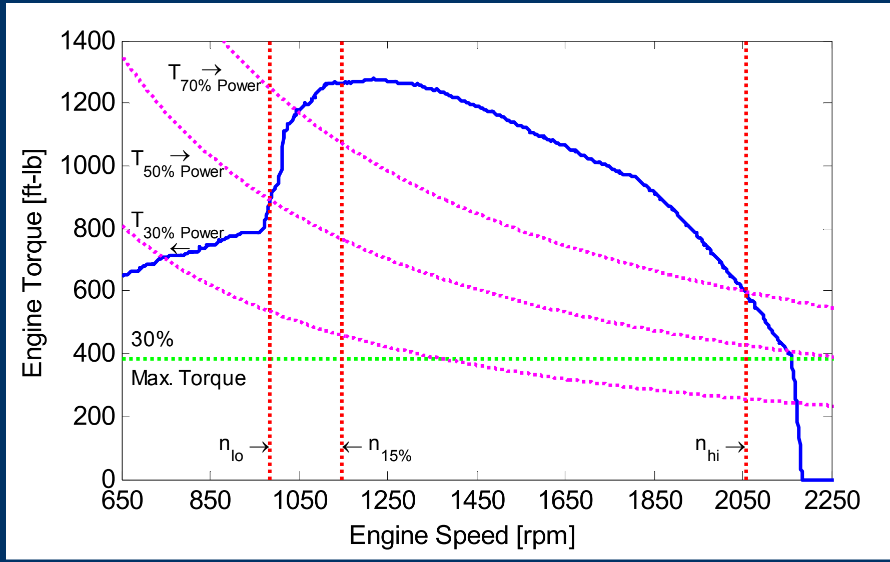
- Particle Sensor Technology
- NTE Measurement Methodology
- Experimental Setup
- Results and Discussion
  - Engine Dynamometer Results
  - Chassis Dynamometer Results
  - (On-Road Testing Results)
- Conclusions

Introduction

- In-use Emissions Compliance Measurements/Testing:
  - Quantification of PM mass emitted during Not-to-Exceed (NTE) events
  - Establishing mass reference for aerosol in real-time

- Other Fields of Application
  - On-board Diagnostics Applications
  - PM Sensor for Development and Implementation of DPF Regeneration Strategies
  - Combustion Research and Engine Base Calibration Applications

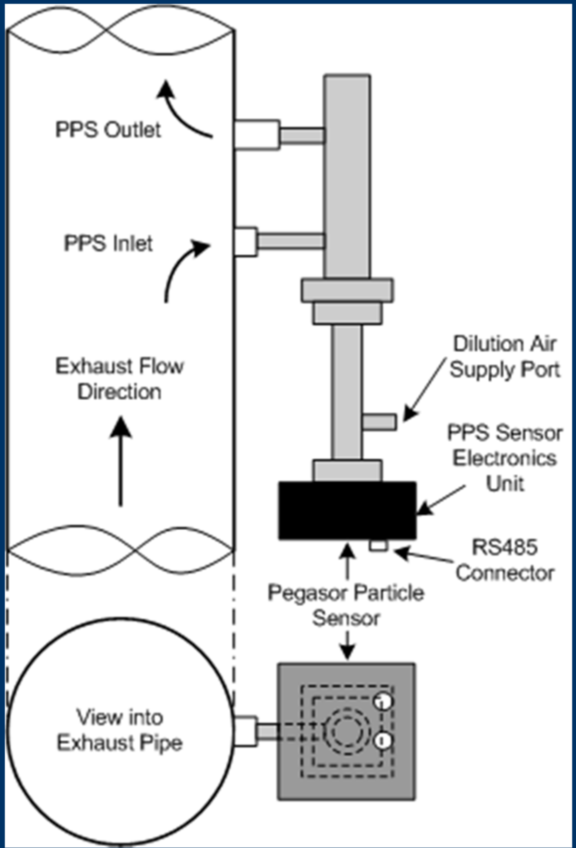


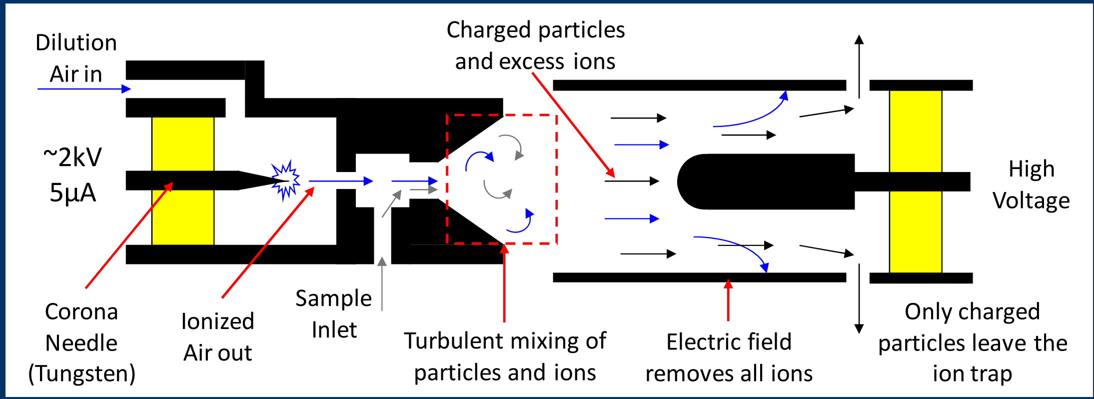
Engine lug-curve form Mack MP7 – 355E (MY 2004)

Sensor - Description of Technology

- Measurement based on escaping current principle

PPS Installation on Exhaust:





Picture provided by Pegasor Oy

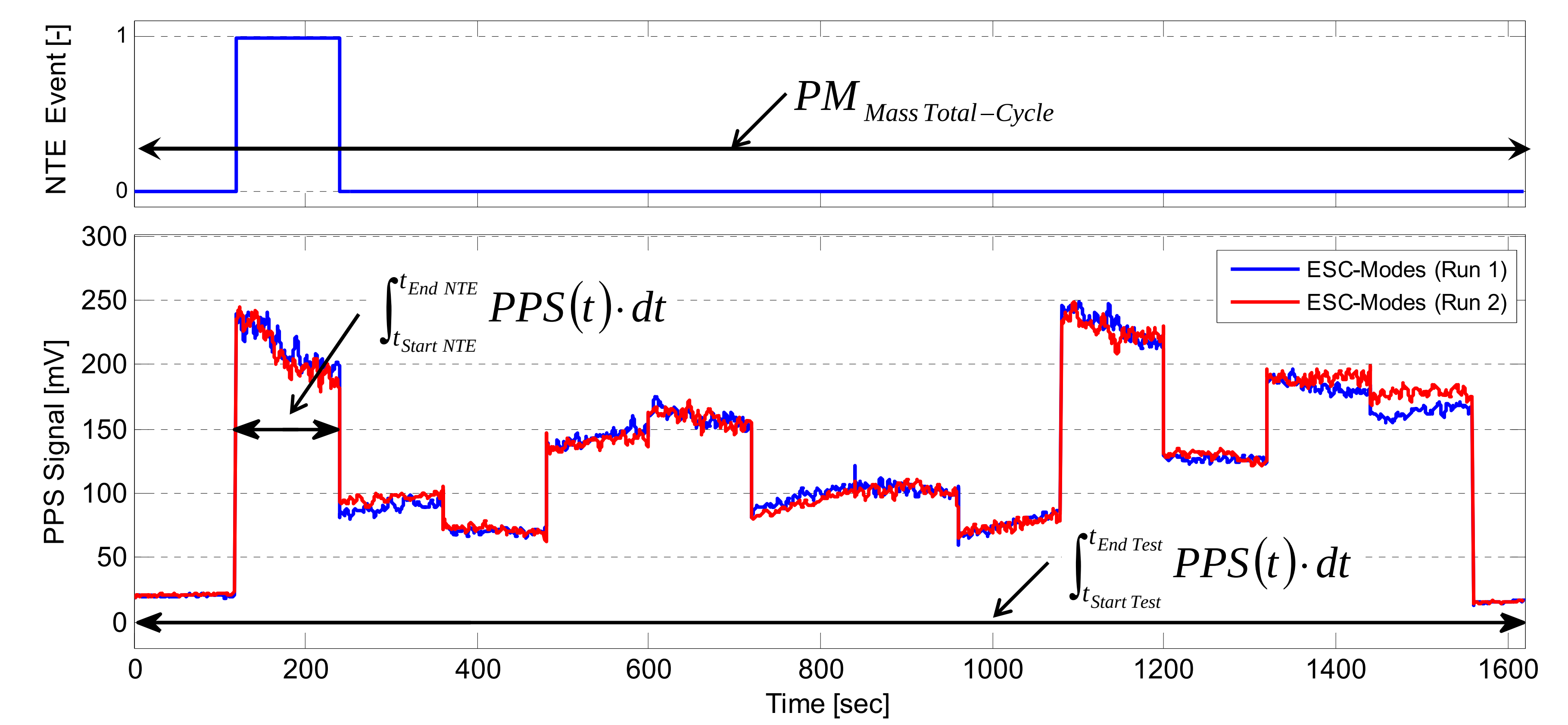
Advantages:

- Real-time
- Continuous operation
- No PM sample collection
- No external dilution of exhaust needed

Operational Parameters:

- Sampling rate up to 100 Hz
- Sensor output can be calibrated to [mg/m^3] or [#/m^3]

NTE In-use Measurement Method



Calculation of PM mass [mg] during NTE event:

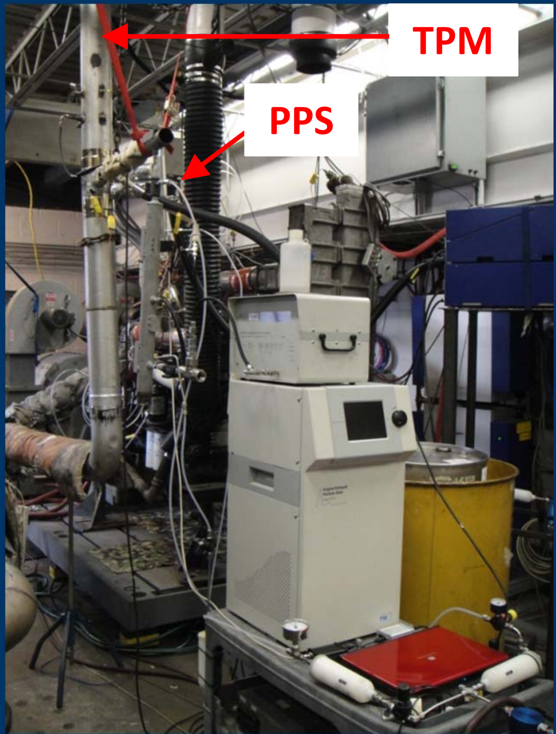
$$PM_{Mass\ NTE} = PM_{Ratio\ PPS} \cdot PM_{Mass\ Total-Cycle}$$

$$PM_{Ratio\ PPS} = \frac{\int_{t_{Start\ NTE}}^{t_{End\ NTE}} PPS(t) \cdot dt}{\int_{t_{Start\ Test}}^{t_{End\ Test}} PPS(t) \cdot dt}$$

$PM_{Mass\ Total\text{-}Cycle}$ = TPM from gravimetric filter sample

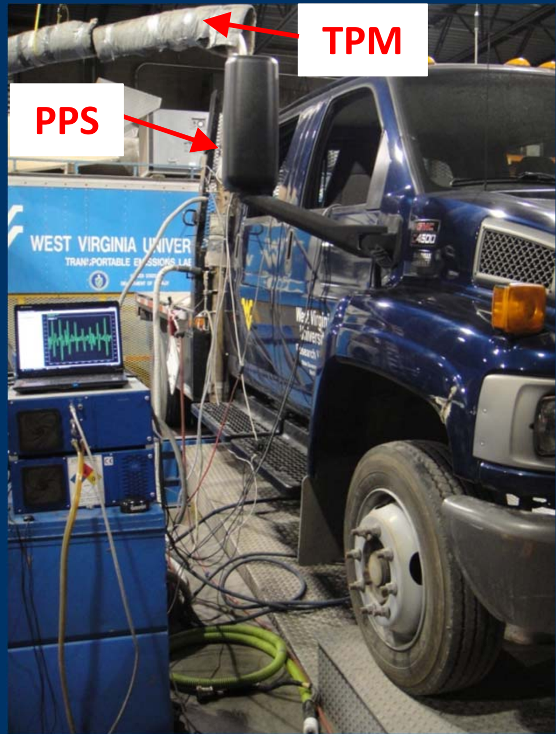
Experimental Setup

Engine Dynamometer:



- Full flow dilution tunnel (CVS-SSV)
- 11L Mack MP7 - 355E (2004)
- No aftertreatment system
- EEPS (TSI, Model 3090)
- CPC (TSI, Model 3025)
- MSS (AVL, Model 483)
- Intake Air Flow Measurement
- Proportional Flow TPM Sampling

Chassis Dynamometer:



- Full flow dilution tunnel (CVS-SSV)
- 6.6L Duramax - GMC4500 (2004)
- GVW ~ 12’000 pounds
- Diesel Oxidation Catalyst (DOC)
- Exhaust Flow Measurement
- Horiba OBS and Sensors SEMTECH
- Proportional Flow TPM Sampling

On-Road Testing:

- 6.6L Duramax - GMC4500 (2004)
- GVW ~ 12’500 pounds
- Diesel Oxidation Catalyst (DOC)
- Exhaust Flow Measurement
- Horiba OBS and Sensors SEMTECH
- Constant Flow TPM Sampling

Setup - Engine Test Cell/Chassis Dynamometer

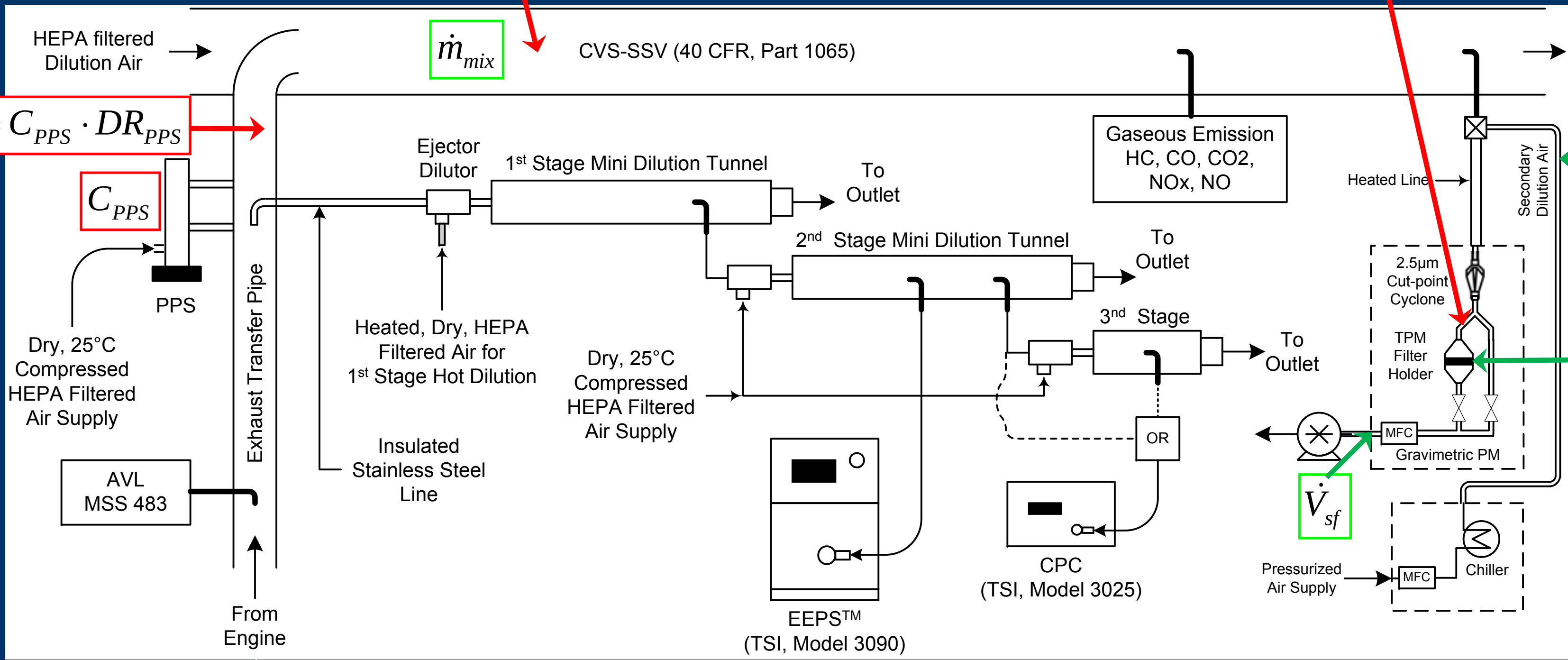
$$C_{CVS} = C_{Exh} \cdot \frac{1}{DR_{CVS}}$$

$$\alpha_{Loss} = f\left(L, D, \dot{V}, \Delta T\right)$$

(Not applied to presented results)

$$C_{Filter} = C_{CVS} \cdot \frac{1}{DR_{Sec\ PM}}$$

$$C_{Exh} = C_{PPS} \cdot DR_{PPS}$$



$\dot{V}_{sec}$

TPM

$\dot{V}_{sf}$

Intake Air (LFE) & Fuel Flow Measurement (Engine Test Cell)

$\dot{V}_{Intake}$ & $\dot{m}_{fuel}$

Exhaust Flow Measurement, Annubar® (Chassis Dynamometer)

$\dot{V}_{Exh}$

$$DR_{PPS} = 0.0053 \cdot [psi] + 1.3082$$

$$DR_{CVS} = \frac{\dot{m}_{mix}}{\dot{m}_{Exh}}$$

$$DR_{Sec\ PM} = \frac{\dot{V}_{sf}}{\dot{V}_{sf} - \dot{V}_{sec}}$$

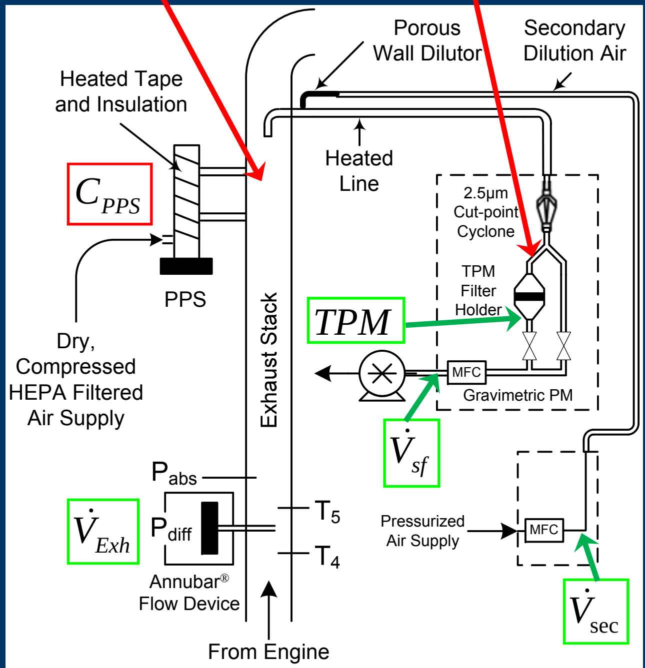
Dilution System for EEPS and CPC:

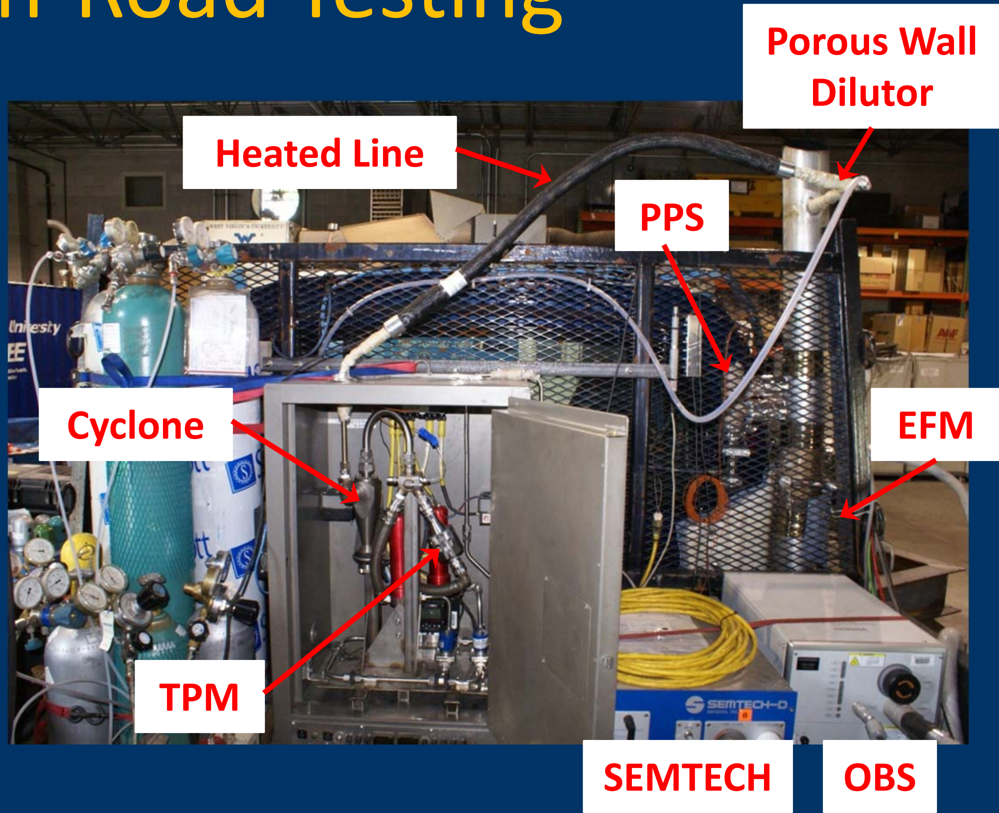
1st Stage	Hot, ~ 130C	DR = 6
2nd Stage	Cold, ~ 25C	DR = 24
3rd Stage **	Cold, ~ 25C	DR = 8
** *Only for CPC*		

Setup - On-Road Testing

$$C_{Exh} = C_{PPS} \cdot DR_{PPS}$$

$$C_{Filter} = C_{CVS} \cdot \frac{1}{DR_{Sec\,PM}}$$

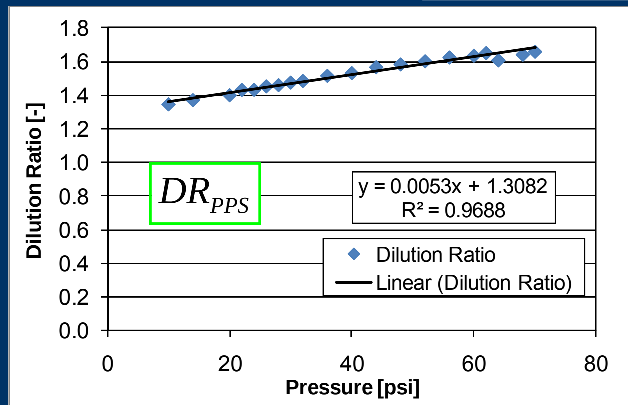




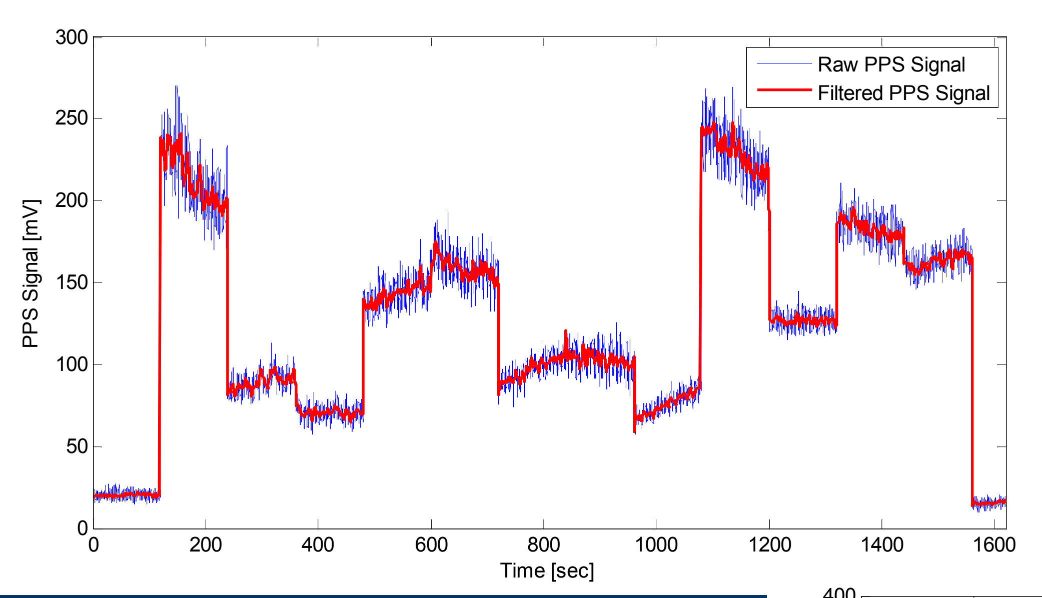
$$\alpha_{Loss} = f\left(L, D, \dot{V}, \Delta T\right)$$ (Not applied to presented results)

$$DR_{PPS} = 0.0053 \cdot [psi] + 1.3082$$

$$DR_{Sec\,PM} = \frac{\dot{V}_{sf}}{\dot{V}_{sf} - \dot{V}_{sec}}$$

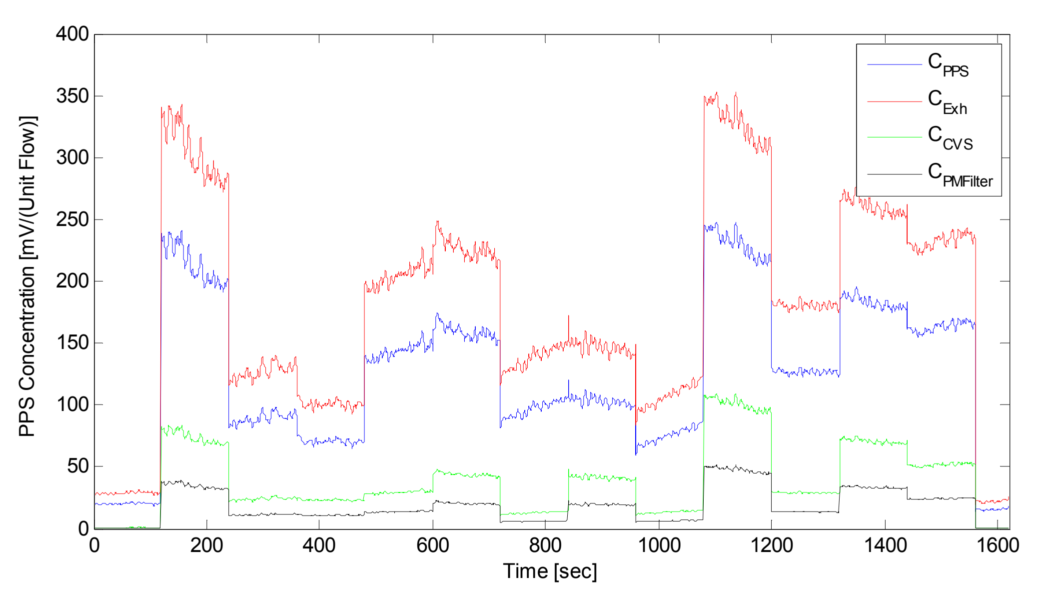


Results - Engine Test Cell

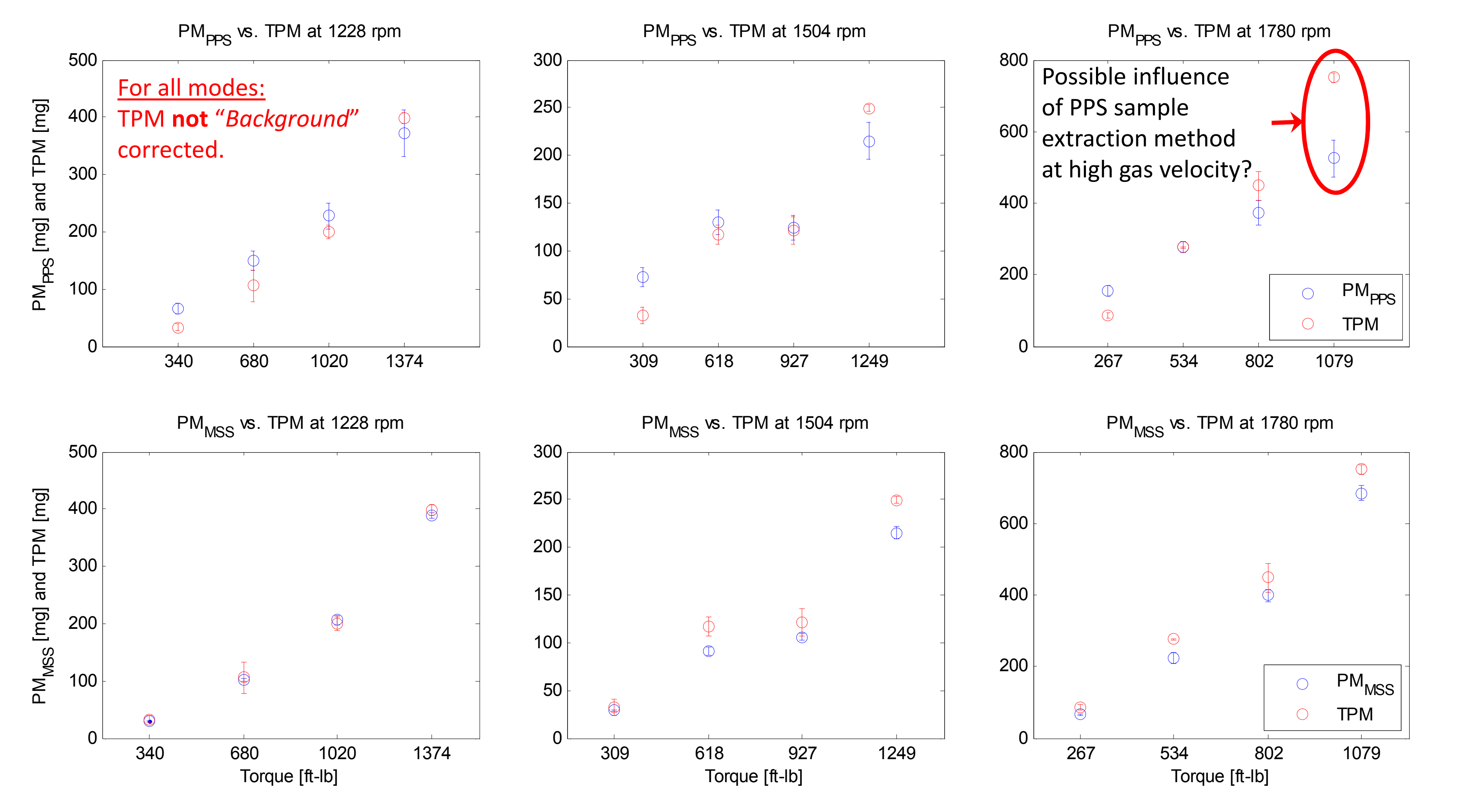


- **PPS Signal Filtering/Smoothing:**
  - Savitzky-Golay (Least-Squares Smoothing Filters)
  - *For Steady-State:*
    - Frame Size - 8.1 sec
    - Filter Order - 3
  - *For Transient Cycle:*
    - Frame Size - 2.1 sec
    - Filter Order - 5
- **Instrument Grounding at On-Road**

PPS Concentration as calculated at different locations in the measurement stream between PPS sample cell (blue line) and gravimetric filter face

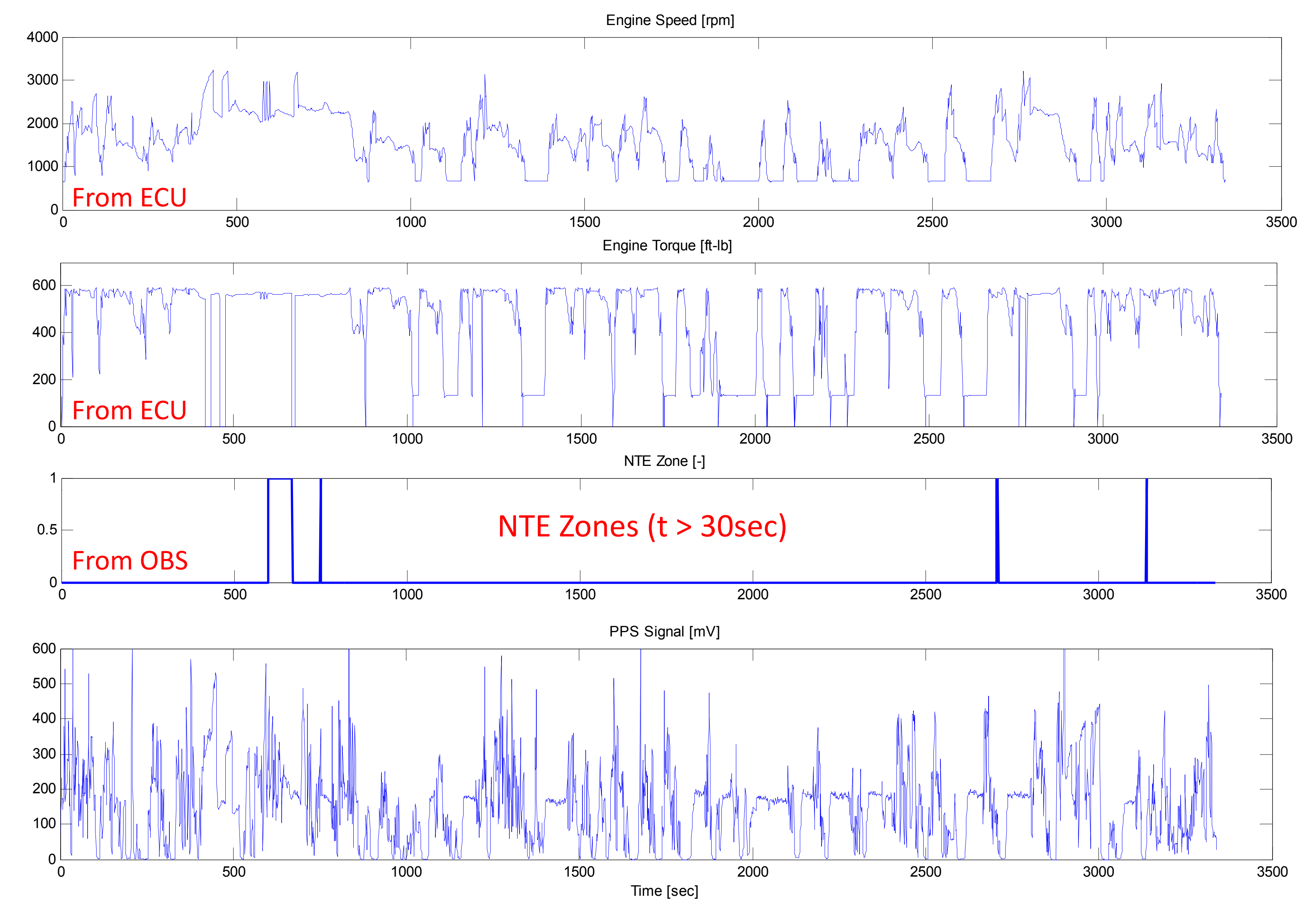


Results - Engine Test Cell (ESC)



- AVL MSS => Corrected for temperature influence and thermophoretic losses
- TPM includes absorbed SOF => PPS and AVL do not measure this fraction => Possible correction based on HC

Results - Chassis Dynamometer

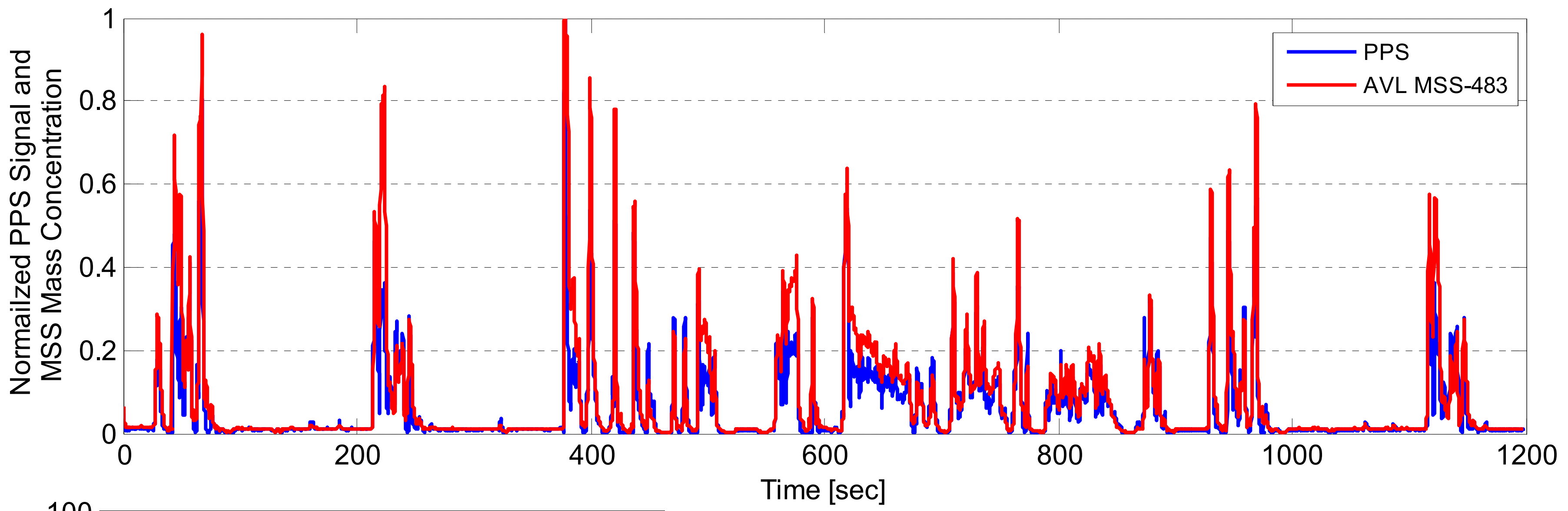


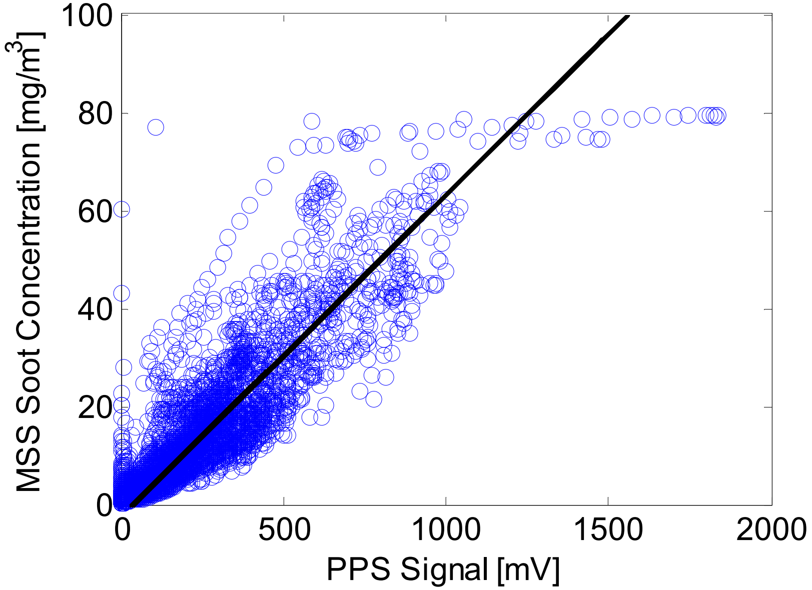
Conclusion and Outlook

- Response of PPS to PM emissions during the transient test cycle (FTP) was similar to that of EEPS (R^2 Value: 0.8969) and AVL MSS (R^2 Value: 0.8479).
- Development of NTE In-use Measurement Method using the PPS Signal to calculate PM during NTE events.
- Demonstration of this method based on engine dynamometer experiments => PPS-Method captures general trends.
  - Possible influence of high exhaust flow rates on sample extraction efficiency
  - Accounting for particle losses within transfer pipes
  - Influence of SOF on gravimetric filter weight
- Chassis Dynamometer and On-Road analysis is ongoing.

Thank You for Your Attention

Results - PPS vs. AVL MSS, Engine-out





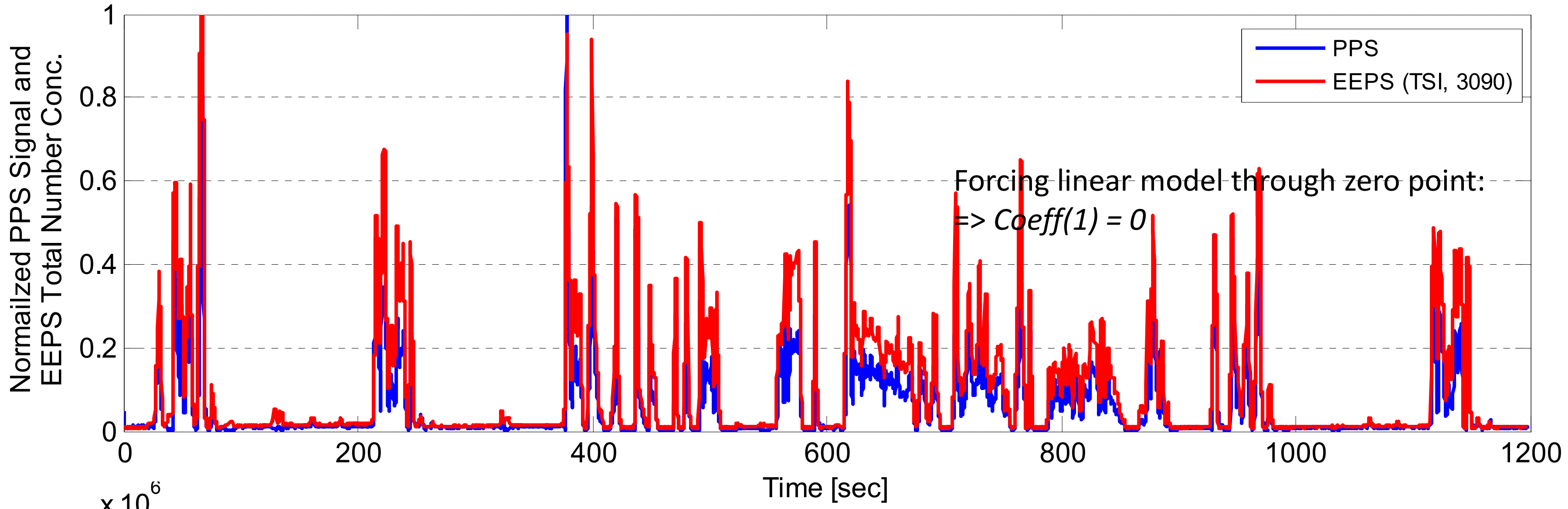
- Engine: Mack MP-7 (MY 2004)
- No aftertreatment, engine-out measurement
- FTP-Cycle, Dynamometer

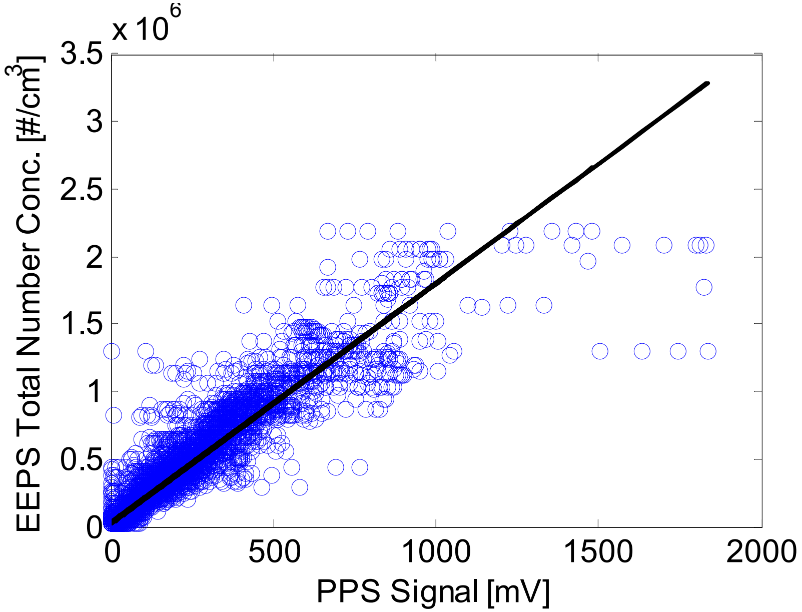
Linear Regression Coefficients:
(Least Squares Method)

PPS [mg/m3] = 0.1787+ 0.0581*PPS [mV]

R-Square Value: 0.8479

Results - PPS vs. EEPS, Engine-out





- Engine: Mack MP-7 (MY 2004)
- No aftertreatment, engine-out measurement
- FTP-Cycle, Engine Dynamometer

Linear Regression Coefficients:
(Least Squares Method)

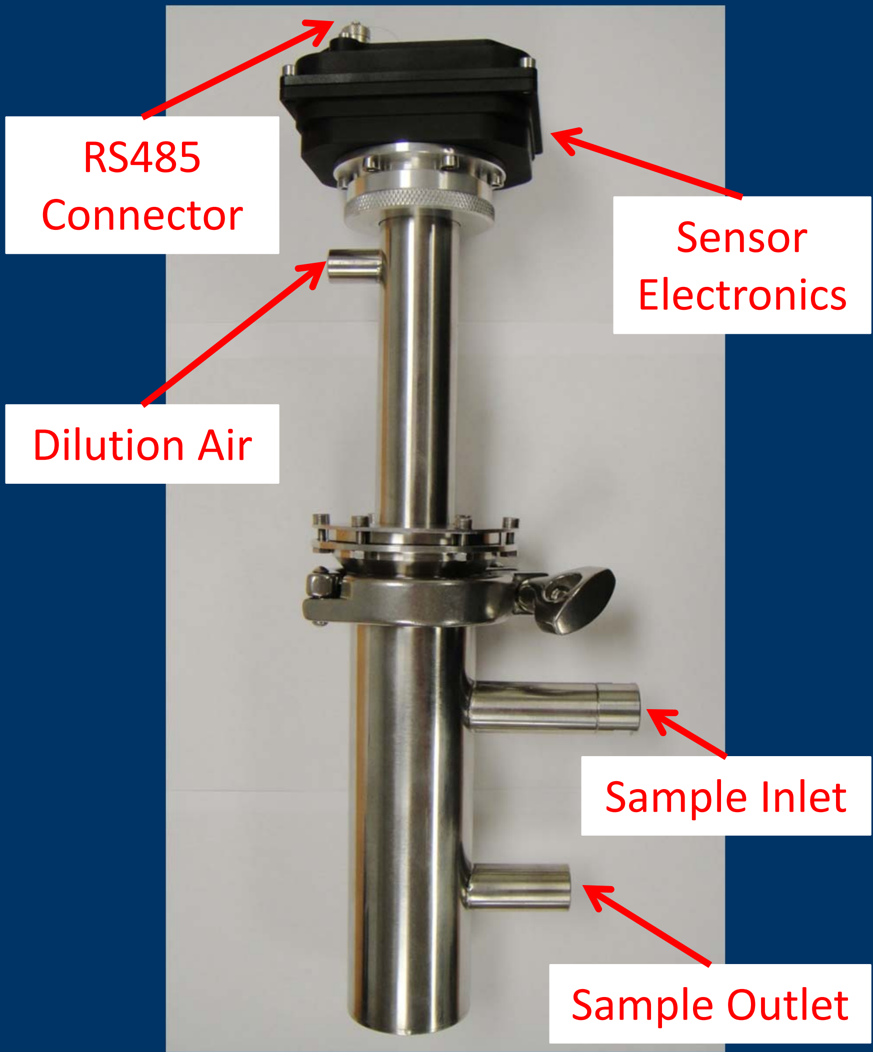
PPS [#/m3] = 2.244E4+ 1.777E3*PPS [mV]

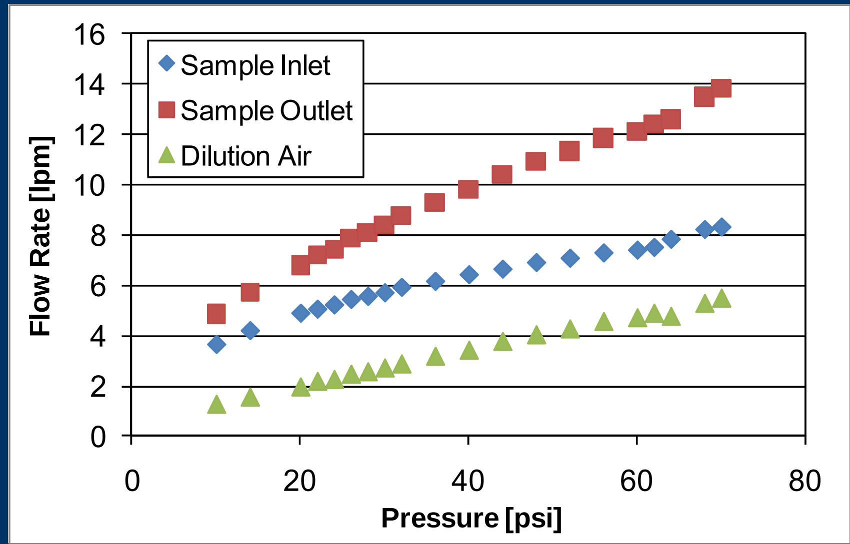
R-Square Value: 0.8969

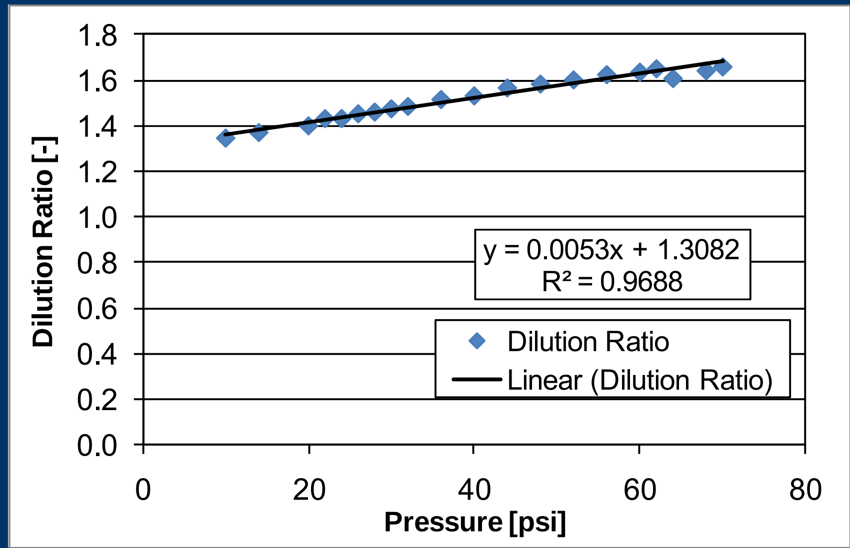
Sensor – Operational Parameters, cont'

- Low temperature version max 250 °C
- High temperature version max. 850 °C
- High concentration version 10 µg/m^3-250 mg/m^3
- High sensitivity version ~1µg/m^3
- Sensor dimensions 20-40 mm diameter, 100-200 mm long – to be decided together with customers
- Electronics; 80x40x20 mm^3
- Sensor output calibrated to mg/m^3 or #-particles/cm^3
- Sensor is installed outside the tailpipe with only inlet and outlet in the tailpipe
- Environmental conditions up to 85 degrees C, IP 45

Sensor - Description of Technology Cont'd







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