Challenges in Developing and Advancing Mini-PEMS for Gathering Emissions and Activity Data for Nonroad, Light- and Heavy-Duty Vehicle Programs

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Outline

- Purpose
- Goals
- Measurement Setup
- Validation Results
- Lessons Learned
- Future Development
- Conclusions

Purpose

- Faster, more economical method of obtaining emissions data as compared to PEMS.
  - Faster turn-around → more vehicles tested
  - Lower cost
    - Equipment
    - Staff resources
  - Field testing including HD and nonroad

- Application
  - Screening tool for emissions non-compliance
  - Input to modelling software
  - Regulation development

Challenges in Developing and Advancing Mini-PEMS

Goals

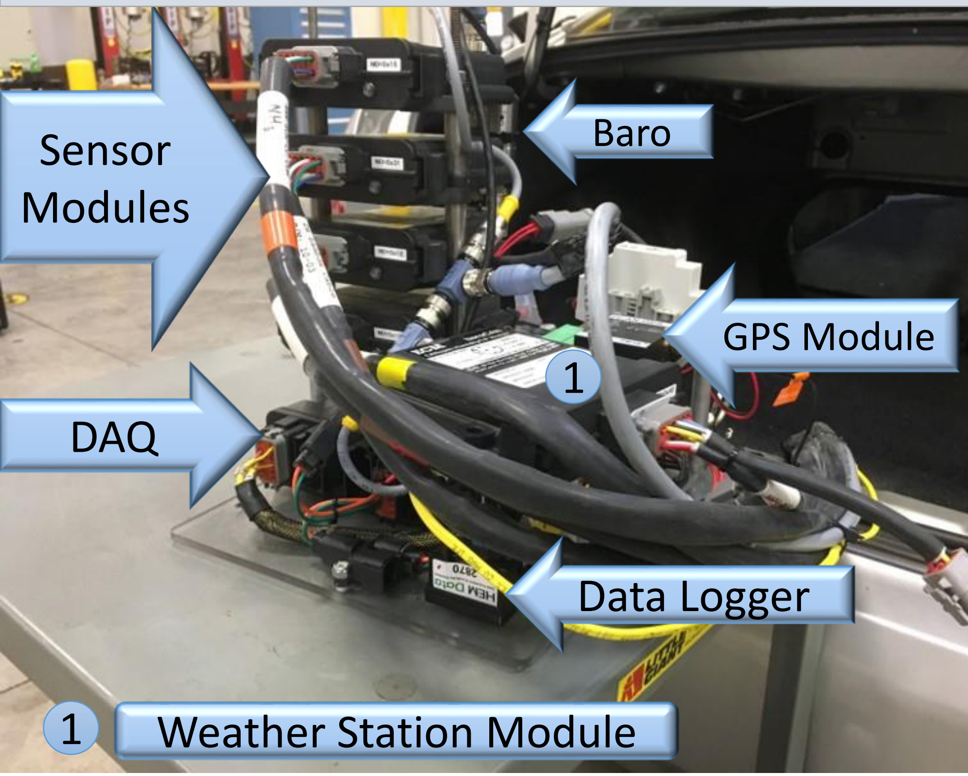
- Robust Mini-PEMS design
- Approx. Unit Cost: $15k
- Setup time: < 1 hr
- Test and Analysis of two vehicles per day per person
- With/without connection to vehicle OBD data
- Modular Design – CAN Capable Components

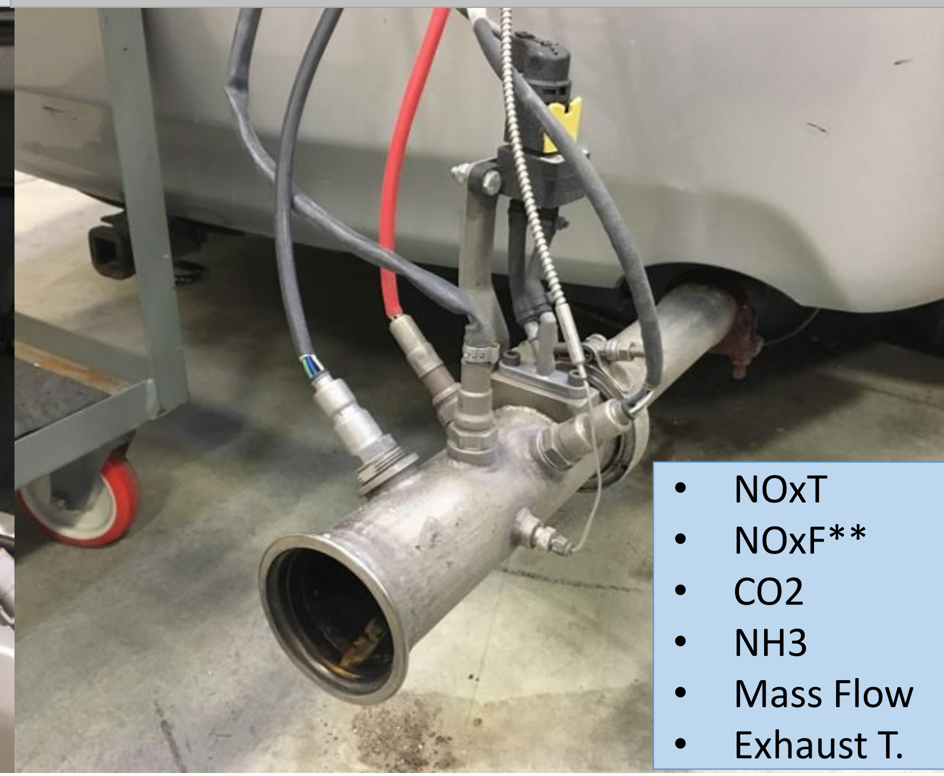
- NOx (gm/mile): ±15% Error
- Fuel Economy: ±5% Error
- Exhaust Mass Flow: ±5% Error

Measurement Setup - System

Measurement Setup – Sensors, Modules and DAQ*

Sensor Modules and DAQ	2.5" LDV Tailpipe Adapter





* Complete list of components provide in Appendix A
** Additional pictures of NOxF sensor in Appendix B

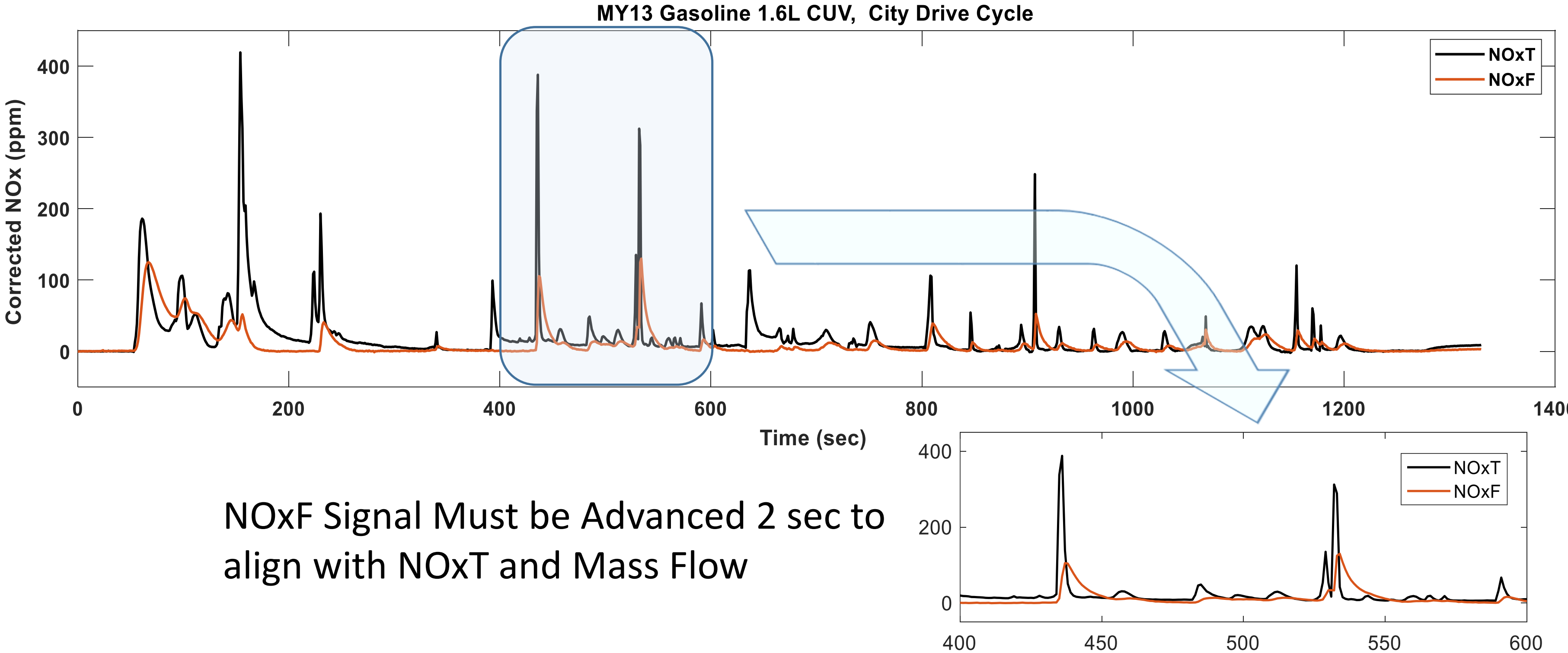
Challenges in Developing and Advancing Mini-PEMS

Measurement Setup: Signals

Measured Signal	Description
NOxT	Tailpipe NOx, Cross-Sensitive to NH3
NOxF	Acid Wash Filter to remove NH3 but with signal delay
CO2	Fuel economy calculation
NH3	Only for lean burn engines
Exhaust Mass Flow	Pitot Tube Mass Flow Sensor
Lambda	Additional Signal from NOx and CO2 sensors
Barometric Pressure Relative Humidity Ambient Temperature	Weather Station Required for NOx humidity correction
Vehicle Speed Longitude, Latitude & Altitude	GPS Signals
4x K-Type Thermocouples	Tailpipe Exhaust Temperature + 3 additional
4x Analog Signals, 0-10V	Dyno Speed + 3 additional

Measurement Setup: NOxT and NOxF – Why Both ?

- Acid wash filter on NOxF sensor will cause a diffusion delay of the signal.
- NOxT signal is used to align the NOxF signal with the exhaust mass flow.



NOxF Signal Must be Advanced 2 sec to align with NOxT and Mass Flow

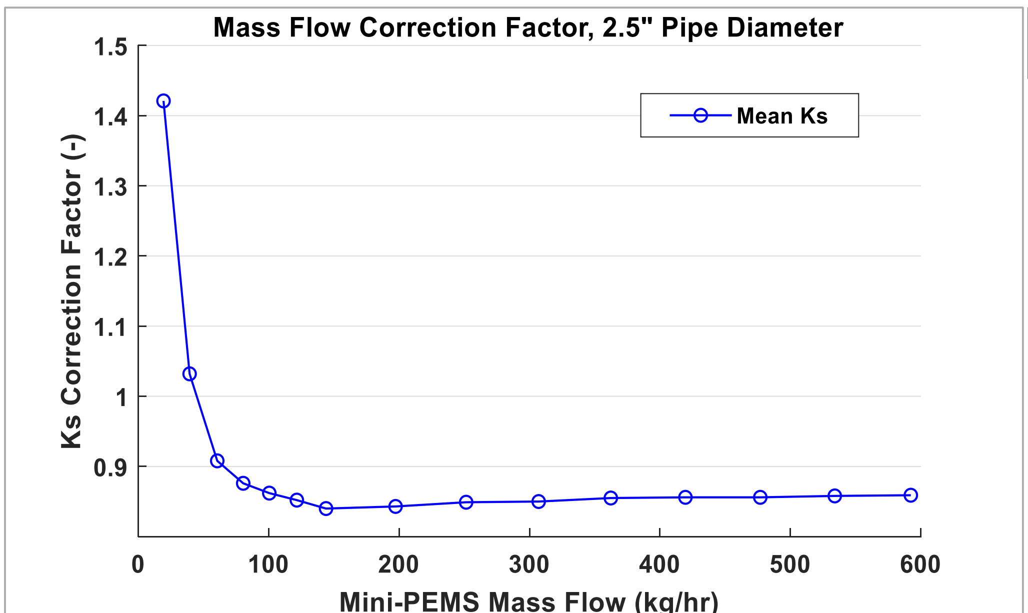
Measurement Setup: Mass Flow Rate Calculation

Mass Flow Rate: ISO 5167-1:2003(E)

$$q_m = \underbrace{K_s \varepsilon}_{\text{Calibrated}} A_q \underbrace{\sqrt{2 \cdot dp \cdot \rho}}_{\text{Measured}}$$

$$K_s = \frac{\dot{m}_{LFE}}{\dot{m}_{sensor}} \text{, Using Flow Bench}$$

q_m = mass flow
K_s = flow coefficient
ε = expansibility factor
Assume ε=1 (at present)
A_q = area of pipe x-section
dp = differential pressure
ρ = density of fluid




Flow Bench

Measurement Setup: PEMS Validation

- Sensors Inc. DS and LDV systems
  - NOx, NO, NO2: NDUV Analyzer (not cross-sensitive to NH3)
  - CO, CO2: NDIR Analyzer
  - THC: FID
  - Mass Flow: Pitot Tube

Mini-PEMS Validation with Sensor Inc. LDV System

Validation – Vehicles Tested

Vehicle	Fuel	Disp. (L)	Method
MY13 CUV	Gas	1.6	Sensors Inc. PEMS DS
MY13 Sedan	Diesel	2.0	Sensors Inc. PEMS DS
MY17 Full Size Truck	Gas	5.3	Chassis Dyno, Horiba Analyzers
MY09 SUV	Gas	3.6	Sensors Inc. PEMS DS
MY09 Sedan	Gas	2.4	Sensors Inc. PEMS LDV

Appendix C → MY17 Full Size Truck

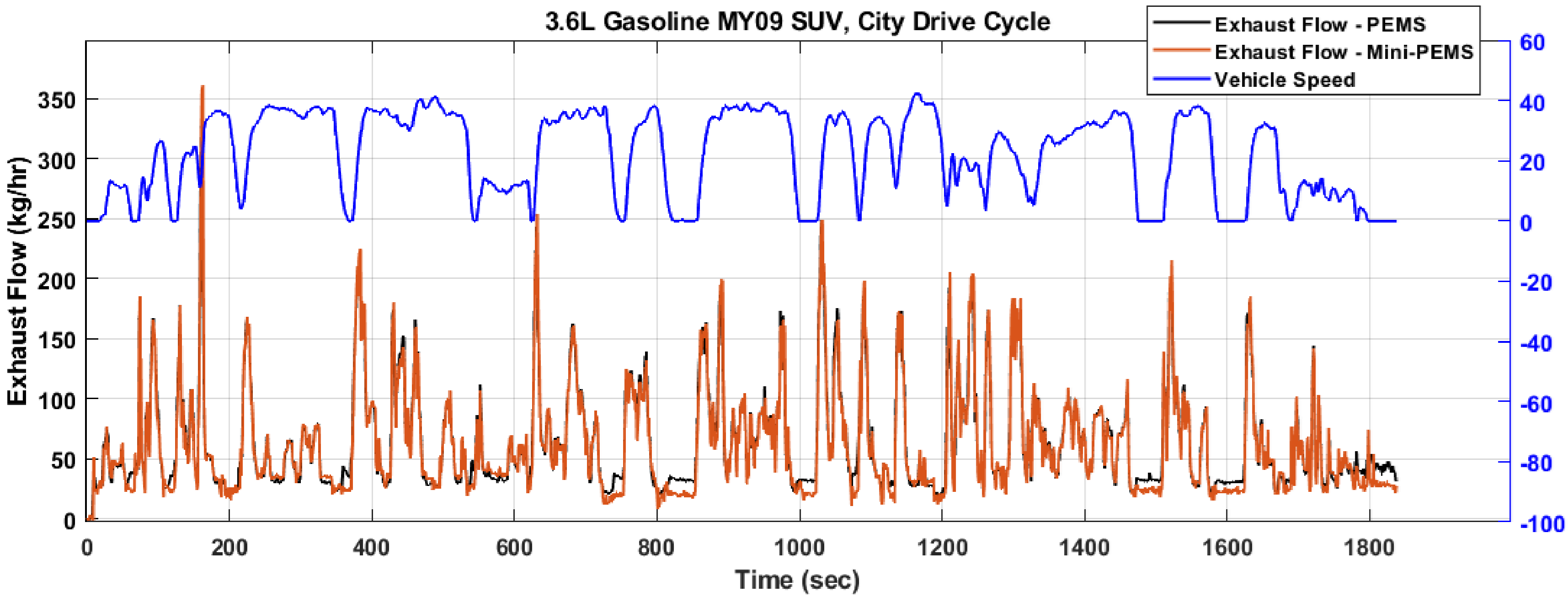
Case 1 → MY09 SUV

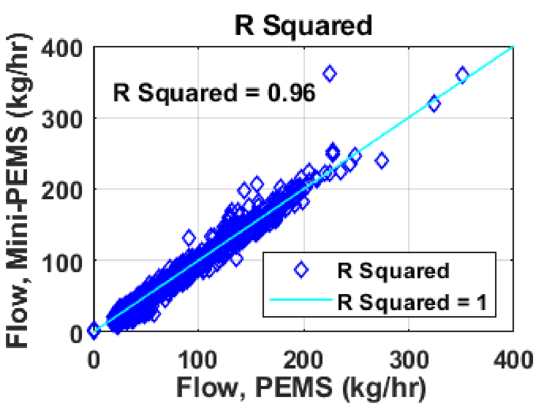
- **PEMS Testing** as conducted on the road with city and highway driving
- **Chassis Dyno Testing** consisted of FTP75 and US06 cycles

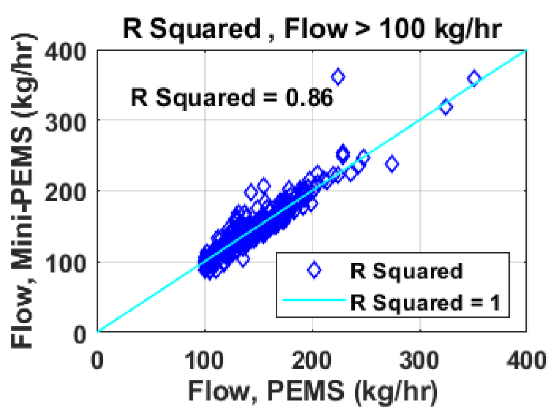
Validation – Case 1 – Validation with PEMS

- Case 1: Mini-PEMS Validation with PEMS
    - 3.6L Gasoline MY09 SUV
    - City Drive Cycle
    - PEMS: Sensors Inc. DS

Validation – Exhaust Mass Flow – 3.6L Gasoline SUV

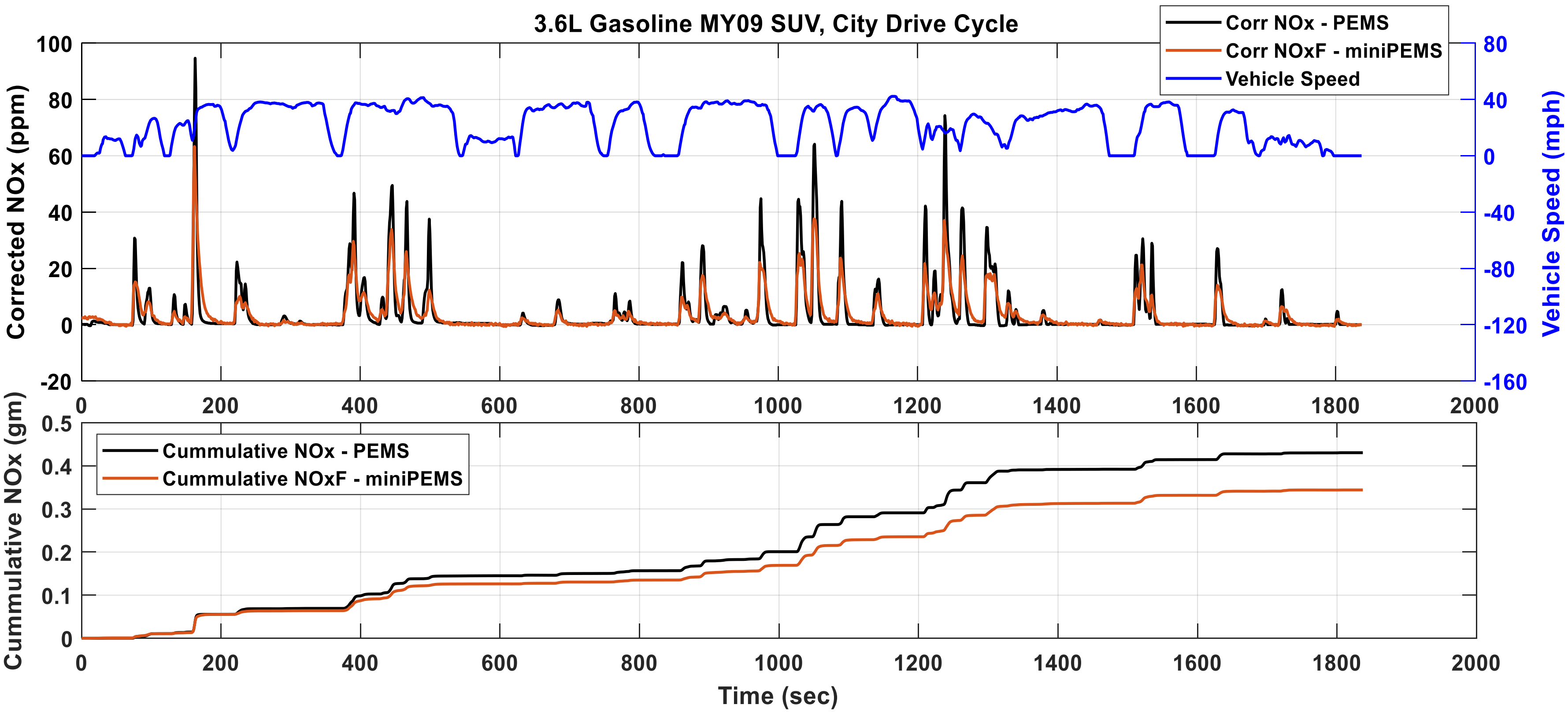






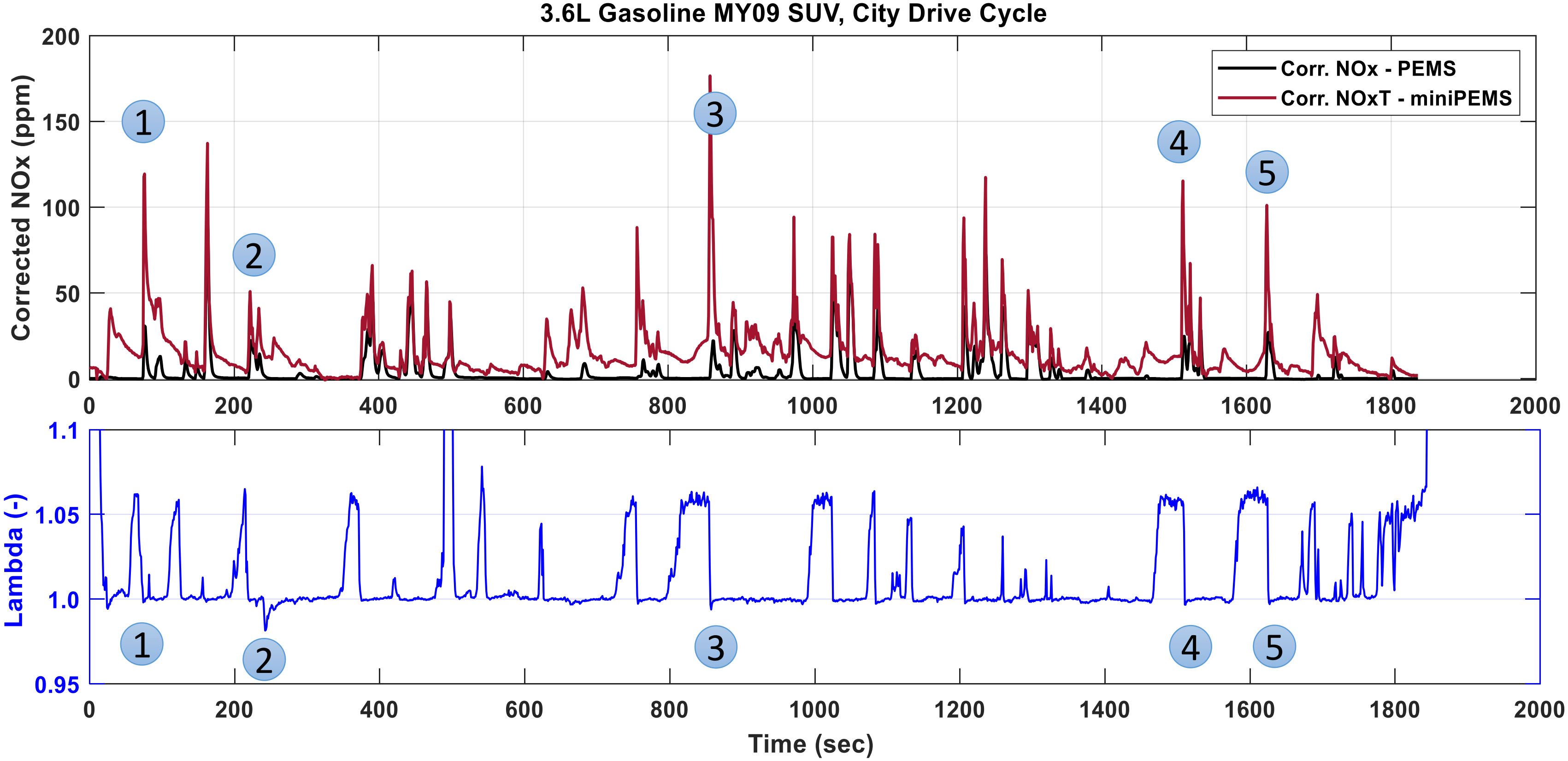
Total Exhaust Mass	(kg)
PEMS	33.0
Mini-PEMS	32.0
% Error - Mini-PEMS	-3.0 %

Validation – NOxF – 3.6L Gasoline SUV



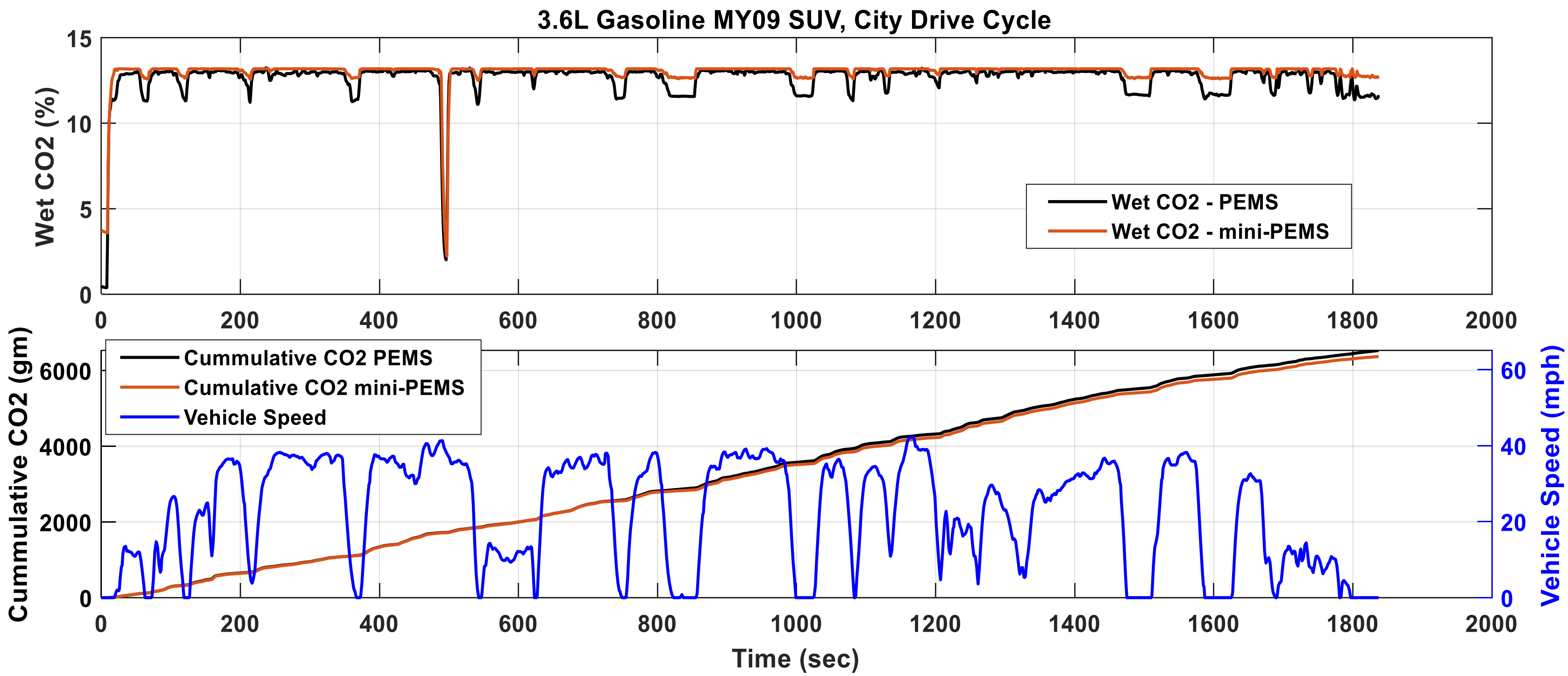
Measurement	NOx Mass (gms/mile)
PEMS	0.038
Mini-PEMS	0.031
Percent Error	-18.4 %

Validation – Effect of NH3 on NOxT – 3.6L Gasoline SUV



- Differences between NOx-PEMS and NOxT-Mini-PEMS can be significant.
- NH3 is highly suspected to be the cause of these differences. Verification Required.
- NH3 is generated across the catalyst during rich conditions (examples are numbered above).
- Even slightly rich conditions appear capable of generating NH3.

Validation – Fuel Economy – 3.6L Gasoline SUV



Measurement	CO2 Mass (gms/mile)
PEMS	577.8
Mini-PEMS	563.8
Percent Error	-2.4 %

Measurement	Fuel Economy (MPG)
PEMS	15.36
Mini-PEMS	15.80
Percent Error	2.9 %

Lessons Learned

- Signal Alignment with Mass Flow
  - Alignment of NOxT to NOxF
  - Even small alignments are important
- Sensor Drift
  - NOx and Mass Flow sensors will drift
  - Methods to minimize NOx drift:
    - Warm-up of NOx Sensors before each test (20 minutes)
    - NOx sensor conditioning minimum of 8 hrs after approx. 20 hrs of use
  - Method to minimize mass flow drift
    - Zero the sensor before each drive cycle
  - Drift correction - Numerical
    - NOx – Linear interpolation of offset
    - Mass Flow – backwards/forwards calculation

Future Development – Robust Packaging

Development Design

Prototype Design

Design Includes: Control Modules, DAQ, Data Logger, Battery (8 hours) and Barometric Pressure
Dimensions: W21”xH8.5”xD16”
Weight: approx. 25 lbs

Next generation prototype expected to be smaller

Future Development

- Develop mini-PEMS design for HD and non-road (large and small) applications.
- Flow Bench Development
  - Better approximation of vehicle on flow bench
  - Develop $\boldsymbol{K_s}$ for additional pipe diameter sizes (2”- 5”)
  - Calibration of ε (expansibility factor) at higher flow rates
- Improved signal time alignment (PEMS / Mini-PEMS)
  - Acquire data at 5 Hz (versus 1 Hz)
- Take advantage of any New/Improved sensor technology
- Validation of NH3 generation

Conclusions

- An alternative Mini-PEMS design has been proposed
  - Capable of measuring exhaust mass flow,
  - Without NH3 cross-sensitivity,
  - Having a known margin of error.
- Sensor conditioning is important
  - NOx sensor heat-up prior to testing and after 20 hrs
  - Zeroing of the mass flow sensor before each cycle
- The NH3 cross-sensitivity of the production type NOxT sensor may cause significant inaccuracies due to NH3 generation.
- With the same mass flow sensor calibration, the percent error of the mass flow was typically less than ± 5% across a variety of vehicles having the same LDV (2.5” diameter) adapter size.

Contact Information and Acknowledgements

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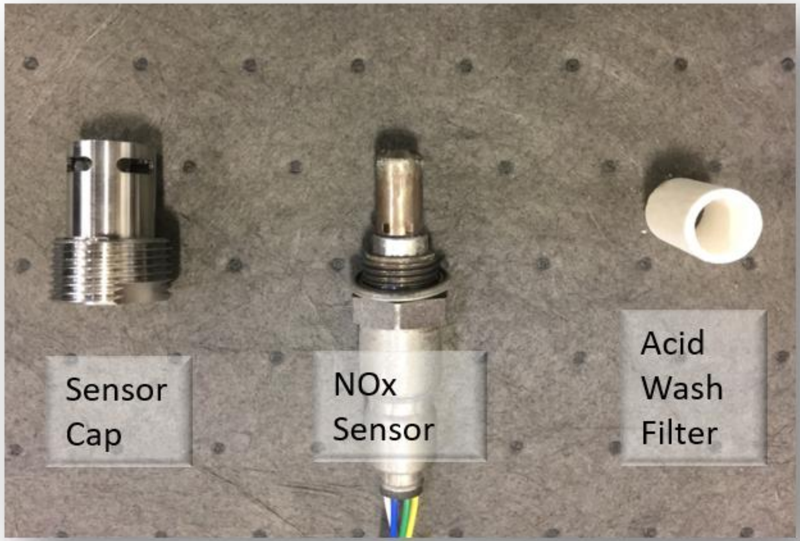
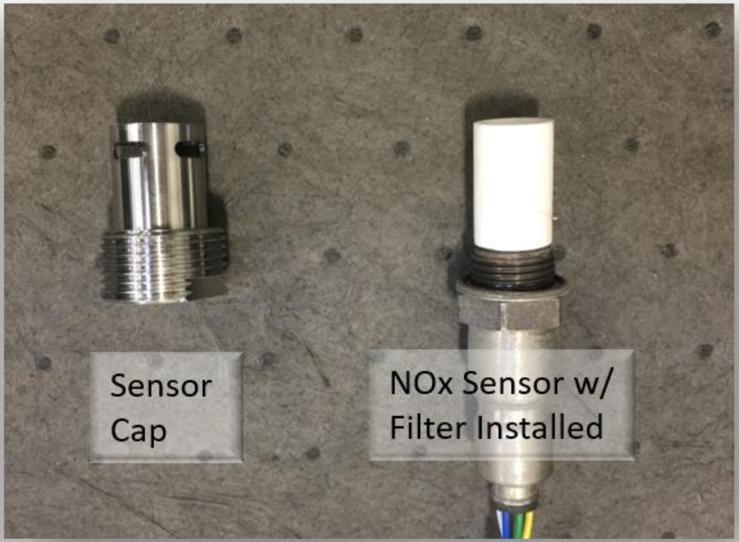
Appendix A – List of Mini-PEMS Major Components

Component	Manufacturer	Product Name
Mass Flow Sensor	SysTec Controls	Truckflow TFI4-2P Sensor
NOxT Sensor & Module	Engine Control and Monitoring (ECM)	NOxCANt
NOxF Sensor & Module	Engine Control and Monitoring (ECM)	NOxCANf
NH3 Sensor & Module	Engine Control and Monitoring (ECM)	NH3CAN
Weather Station (RH, baro, Tamb)	Engine Control and Monitoring (ECM)	baroCAN
CO2 Sensor & Module	Engine Control and Monitoring (ECM)	CO/CO2CAN
Data Logger	HEM Data	OBD Mini Logger
Data Acquisition (DAQ)	HEM Data	Mini ADAQ 1400
GPS (vehicle speed, altitude, long, lat)	Peak	PCAN-GPS

Appendix B – NOxF Sensor

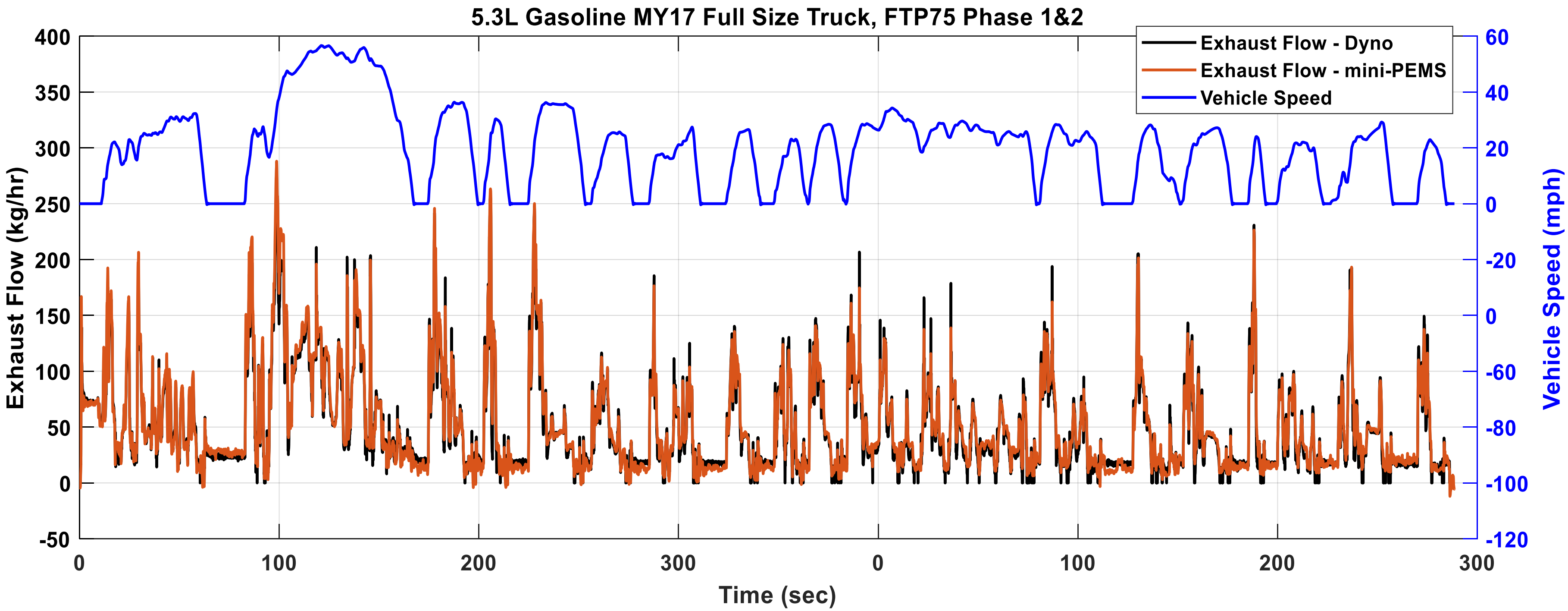


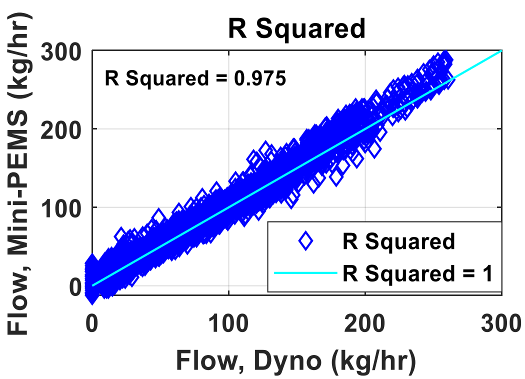


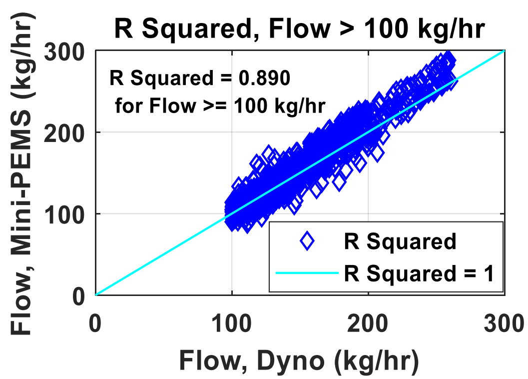
Appendix C – Validation Case 2

- Case 2: Mini-PEMS Validation with Chassis Dyno
  - 5.3L Gasoline Full Sized Truck
  - FTP75 Phase 1 and 2
  - Certification Dyno with Horiba emissions analyzers
    - Raw Emissions
    - Exhaust Mass Flow = (CVS Flow – Dilution Air)

Appendix C – Exh. Mass Flow – 5.3L MY17 Gasoline Truck

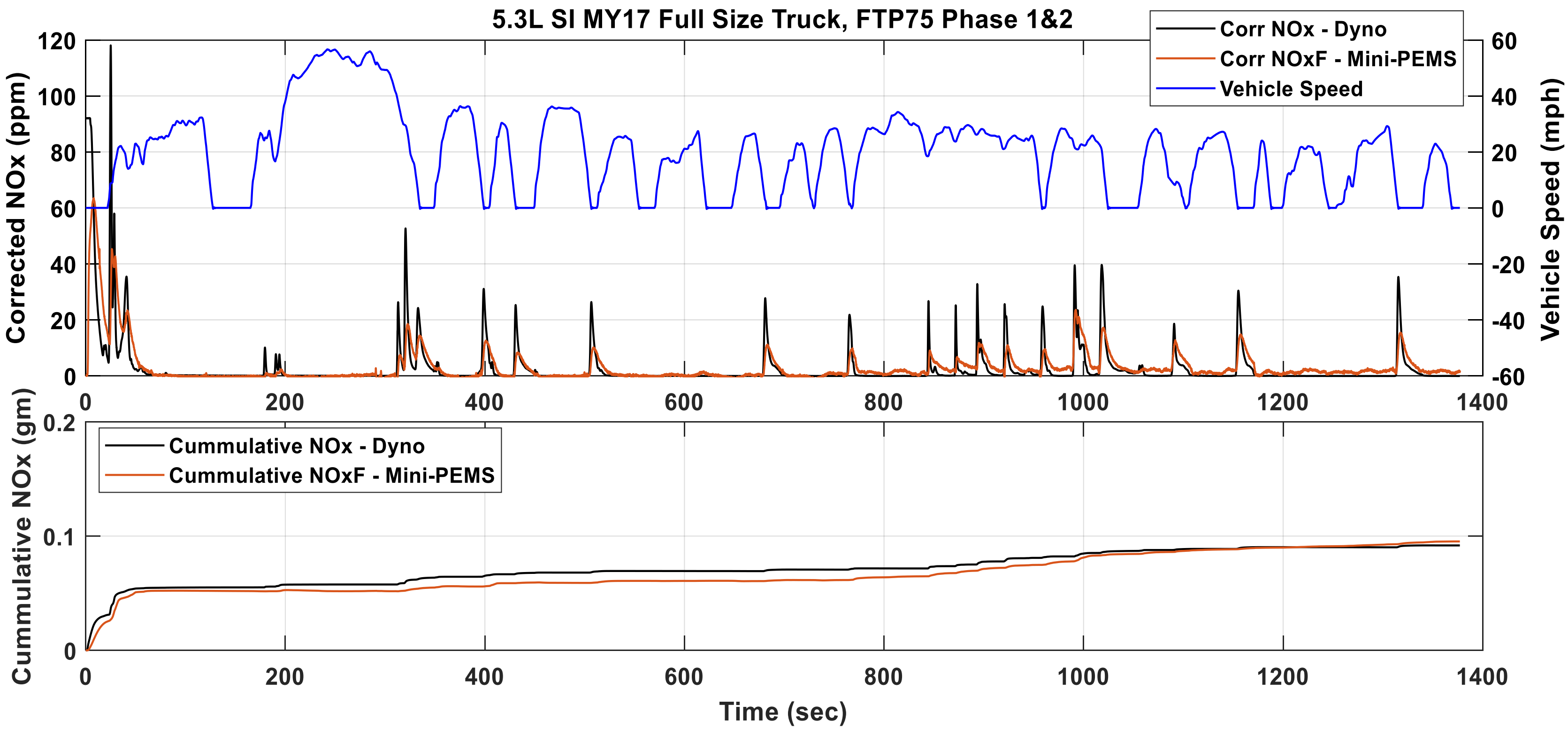






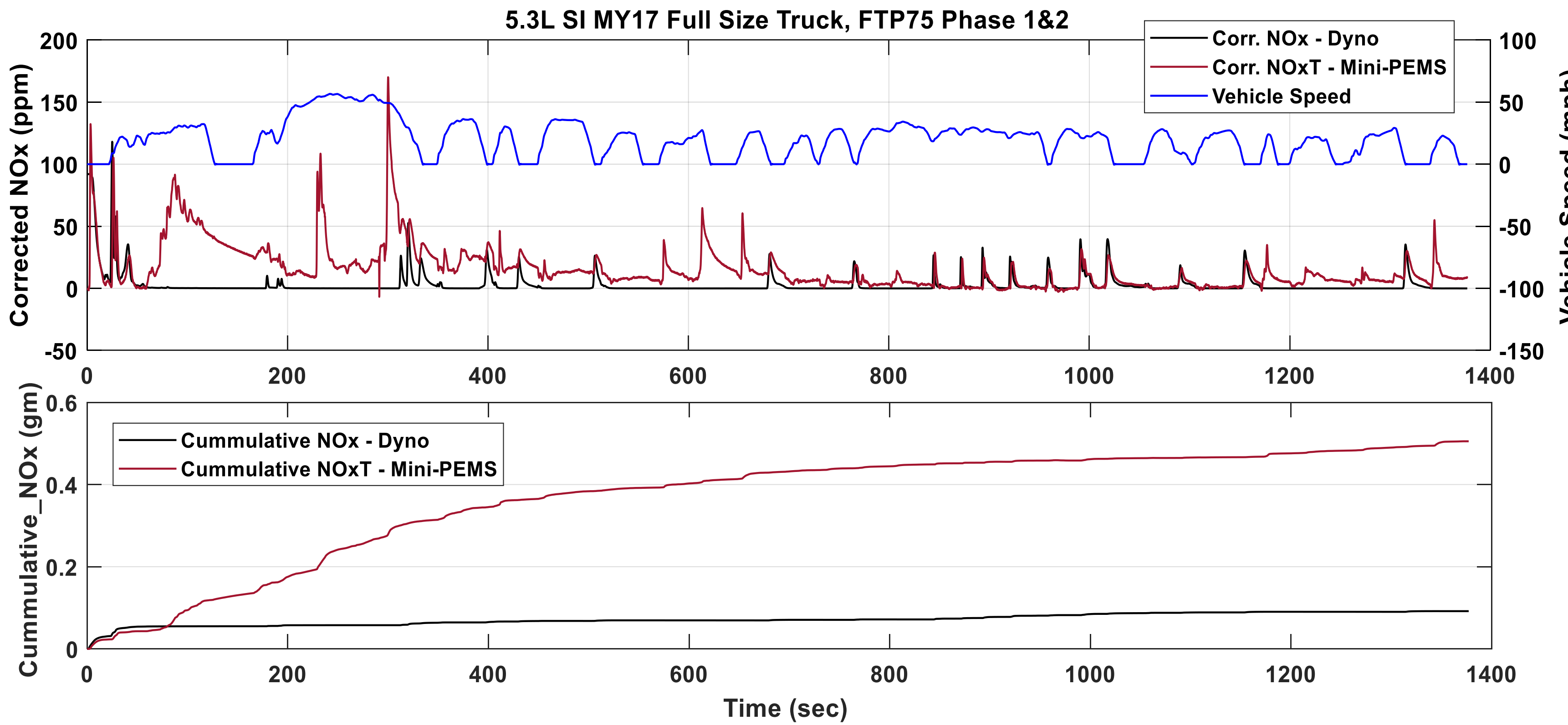
Total Exhaust Mass	(kg)
Chassis Dyno	19.0
Mini-PEMS	19.5
% Error - Mini-PEMS	2.6 %

Appendix C – NOx – 5.3L MY17 Gasoline Truck



Measurement	NOx Mass (gms/mile)
Chassis Dyno	0.0124
Mini-PEMS NOxF	0.0128
Percent Error	3.2 %

Appendix C – NOx – 5.3L MY17 Gasoline Truck



Measurement	NOx Mass (gms/mile)
Chassis Dyno	0.0124
Mini-PEMS NOxT	0.0681
Percent Error	450 %