Advanced Aftertreatment Sensor Characterization Methods and Learnings

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OSAR 2024 Conference

Outline

Introduction

- Sensor Fundamentals Team Overview
- NOx Sensor Operation and Performance

Methods

- Sensor Characterization Methods
- Sensor Test Matrix

Results

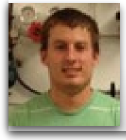
- Test Matrix Results
- NOx Sensor Broadcasting Zero
- NH_3 Sensor

Implications and Conclusions

Sensor Fundamentals: Team Overview

We have assembled a substantial, dedicated, ***sensor team & laboratory*** at Cummins to:

- Mitigate risk with introduction of new, unusual, & difficult AT sensor technologies
- Drive supplier improvements.
- Reduce warranty and/or expand capabilities of mature technologies

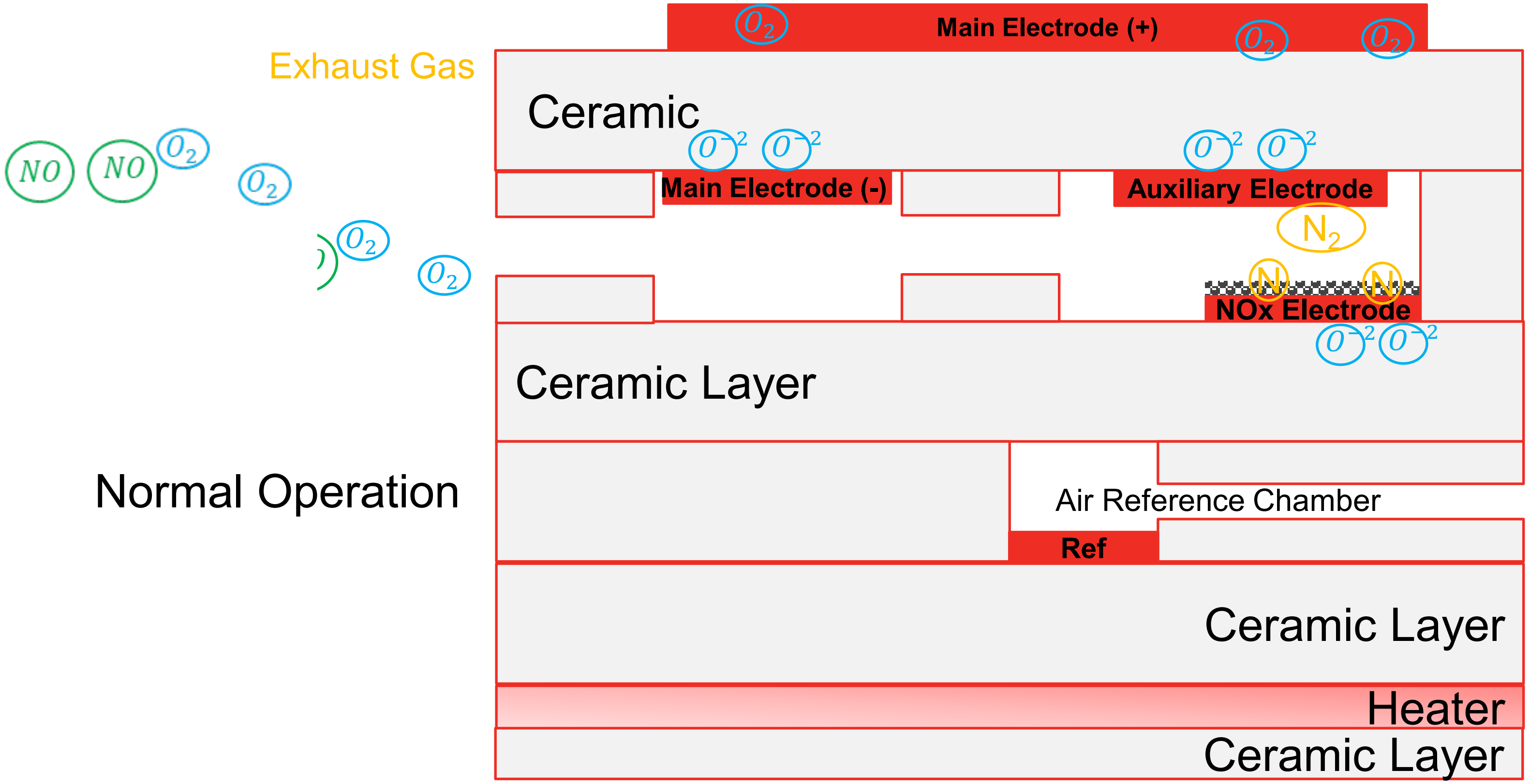

Tyler Rash → Group Lead: Planning, technical consulting, personnel development


Yang Li → NO_x Sensor Performance Characterization & Aging

NO_x Sensor Operation:

Factors

- Temperature
- Pressure
- Flow
- Gas Composition



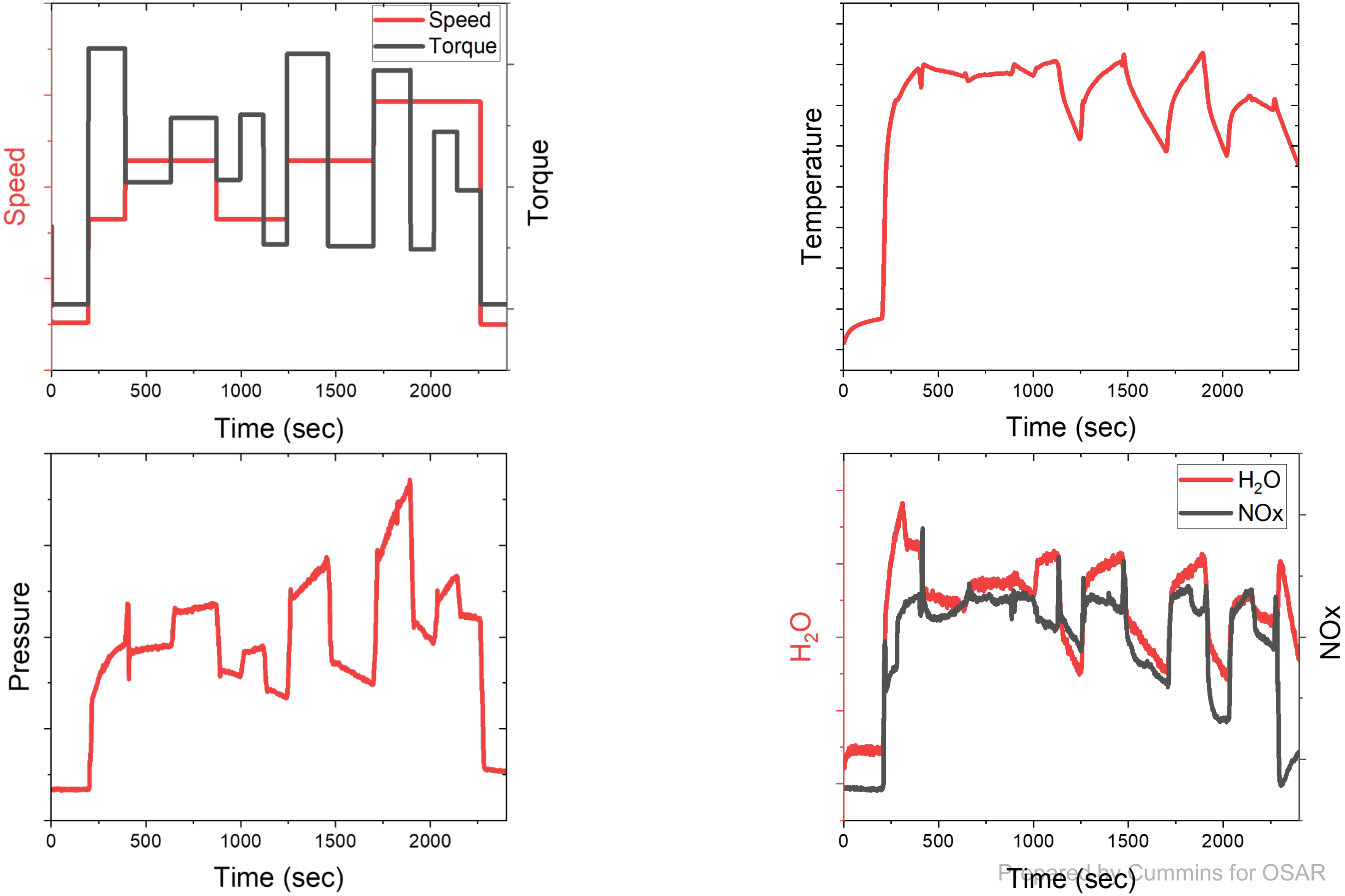
Normal Operation

NO is diffused into N and O, then Oxygen pumped out through the ceramic

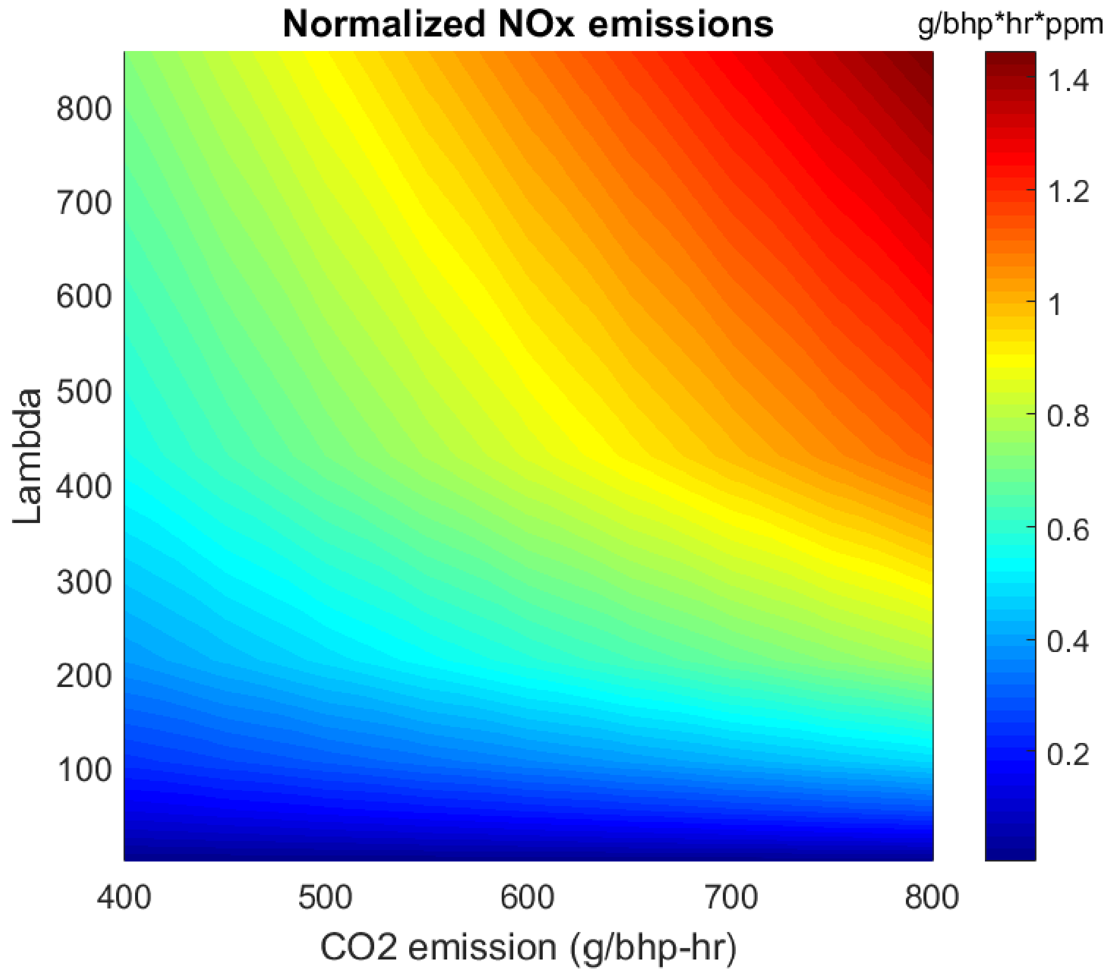
This slide was based on a slide produced by Alok Joshi circa 2013

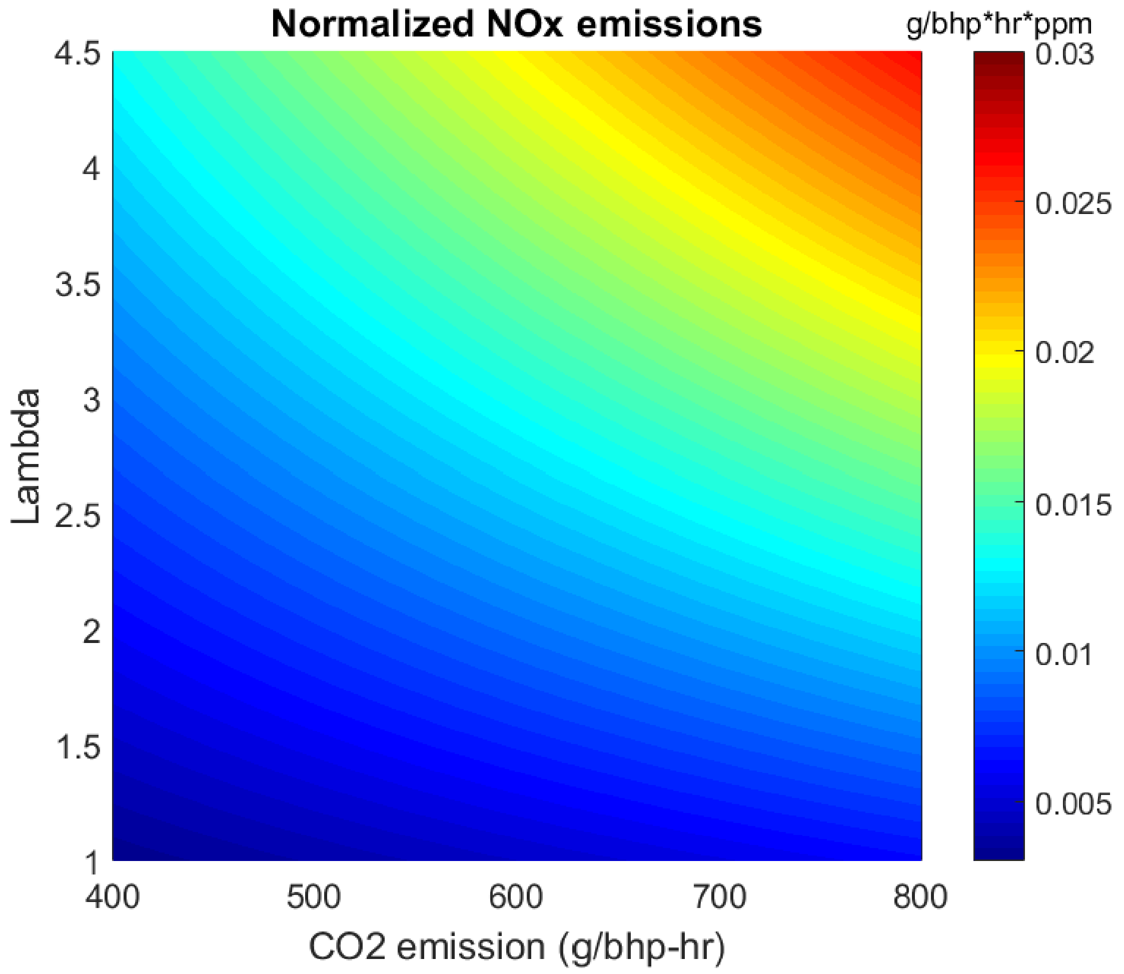
Environment That We Study

What to expect during the RMC-SET?



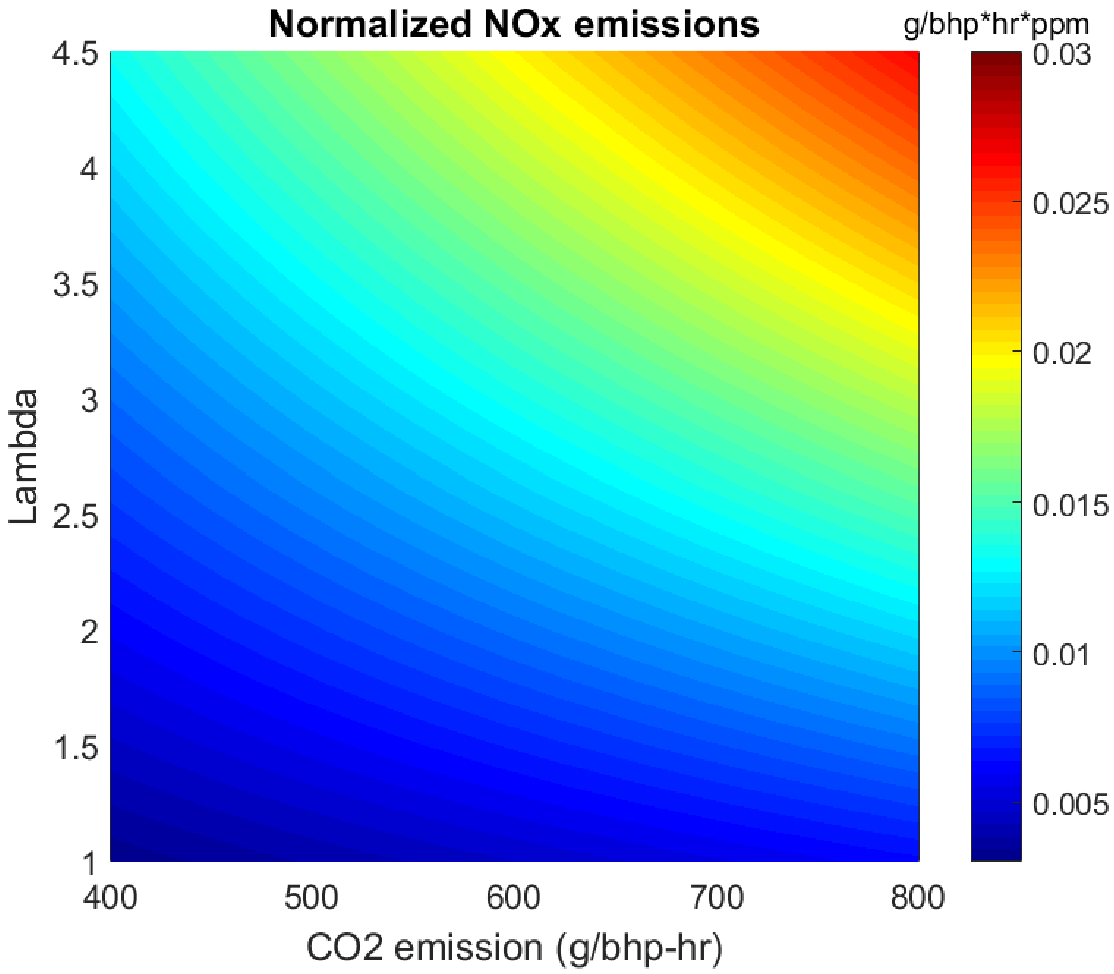
Estimated NOx Emission with Diesel

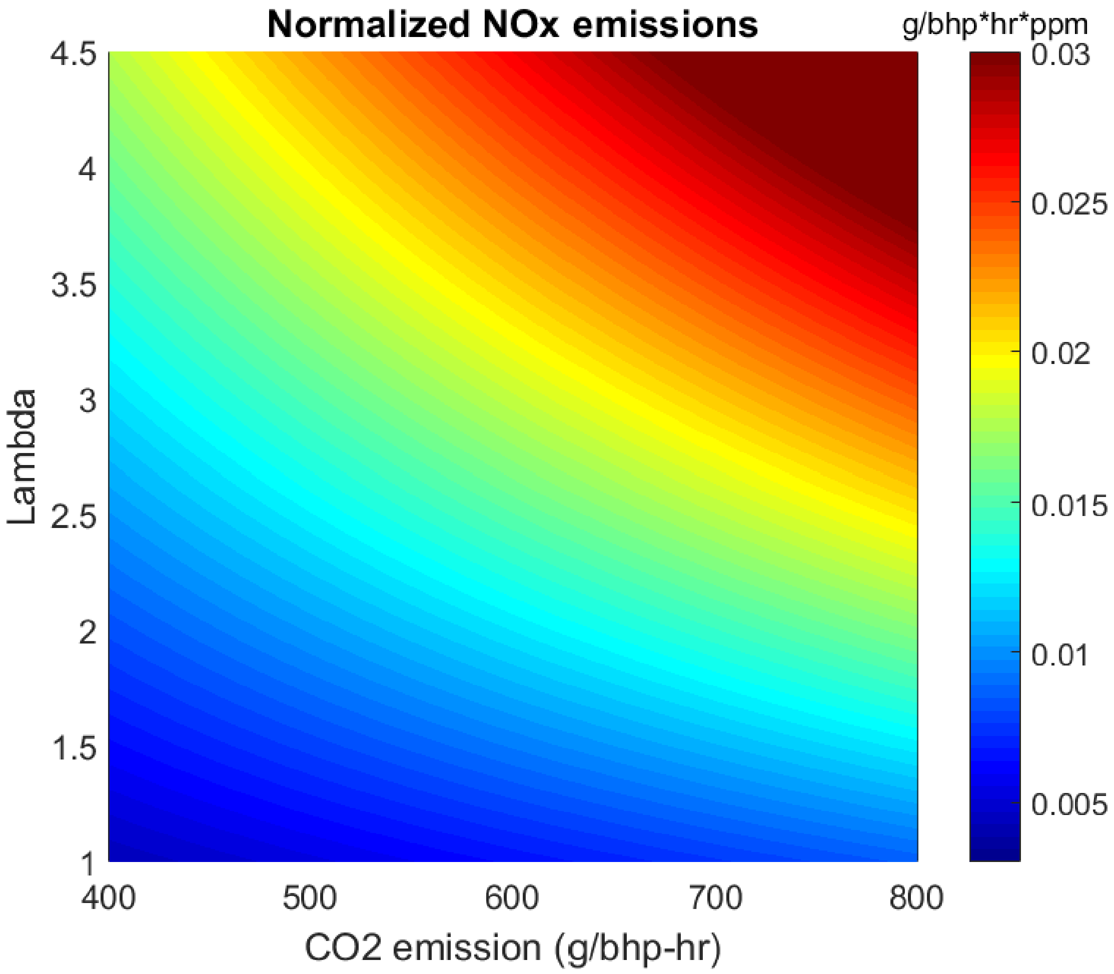




Estimated NOx Emission

Diesel (*left*) vs Natural Gas (*right*)





Sensor Characterization Methods: Sensor Exerciser and Test Instrument (SETI)

Gas Flow Bench Capabilities

- Test 9 sensors at a time
- Customizable sensor comm. interface.
- Temperature Range: 20-550 ^{o}C.
- Isobaric flow sweep capability (<40 psi)
- Flow Range: 20 – 250 LPM
- ≈0.2 sec response time measurements
- Independently controlled H_2, CH_4, C_3H_8, CO, CO_2, N_2, O_2, H_2O, NO, NO_2, & NH_3 concentrations.

Features

FTIR

O_2 Analyzer

HCLD (NOx)

Thermal MFCs

Coriolis MFCs

Humidity Sensors

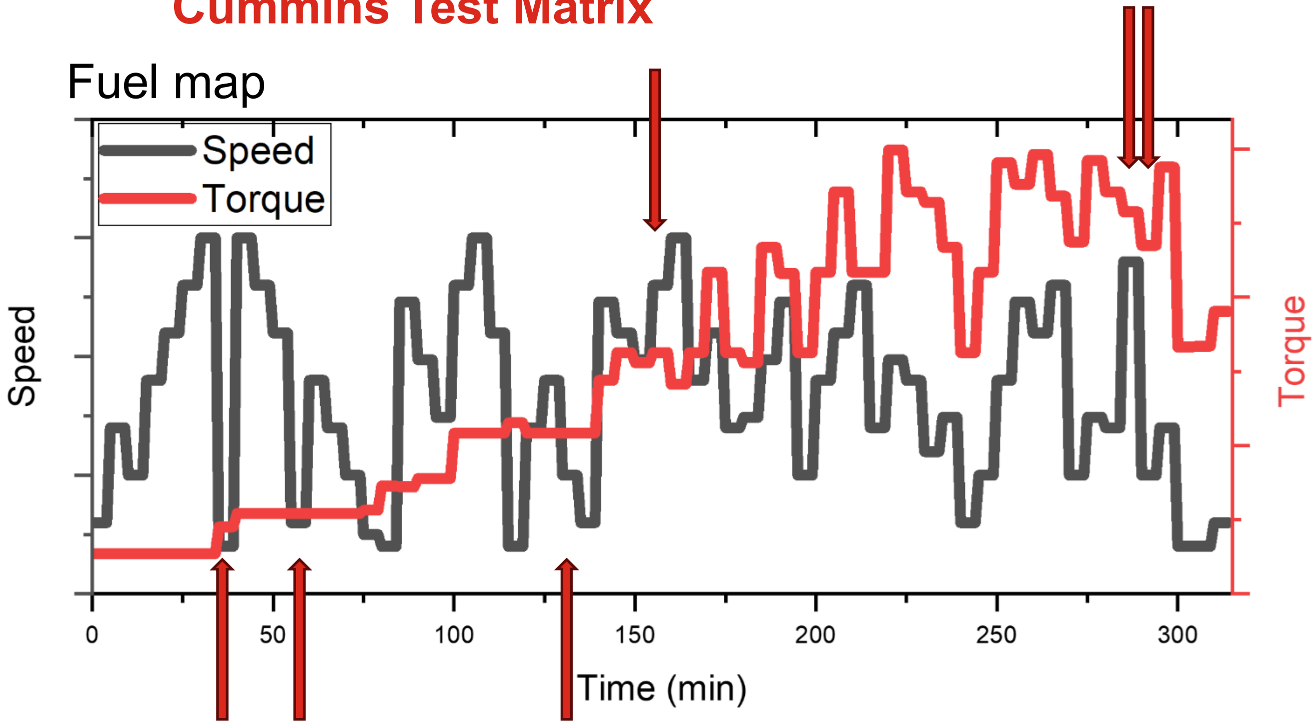
Pressure Sensors

Test Matrix

OSAR Test Matrix

Flag	NO	NO2	H2O	O2	Temp	Flow
None	ppm	ppm	%	%	C	LPM
1	10	0	6	10.5	200	20
2	10	0	6	10.5	200	20
3	25	0	6	10.5	200	20
4	50	0	6	10.5	200	20
5	75	0	6	10.5	200	20
6	100	0	6	10.5	200	20
7	0	0	6	10.5	200	20
8	0	10	6	10.5	200	20
9	0	25	6	10.5	200	20
10	0	50	6	10.5	200	20
11	0	0	6	10.5	200	20
12	10	25	6	10.5	200	20
13	25	10	6	10.5	200	20
14	10	10	6	10.5	200	20
15	25	25	6	10.5	200	20
16	0	0	6	10.5	200	20
17	10	0	6	10.5	200	20
18	100	0	6	10.5	200	20
19	0	0	6	10.5	200	20
20	100	0	6	10.5	200	20
21	10	0	6	10.5	200	20
22	0	0	6	10.5	200	20
23	0	10	6	10.5	200	20
24	0	50	6	10.5	200	20
25	0	0	6	10.5	200	20
26	0	50	6	10.5	200	20
27	0	10	6	10.5	200	20
28	0	0	6	10.5	200	20

Cummins Test Matrix

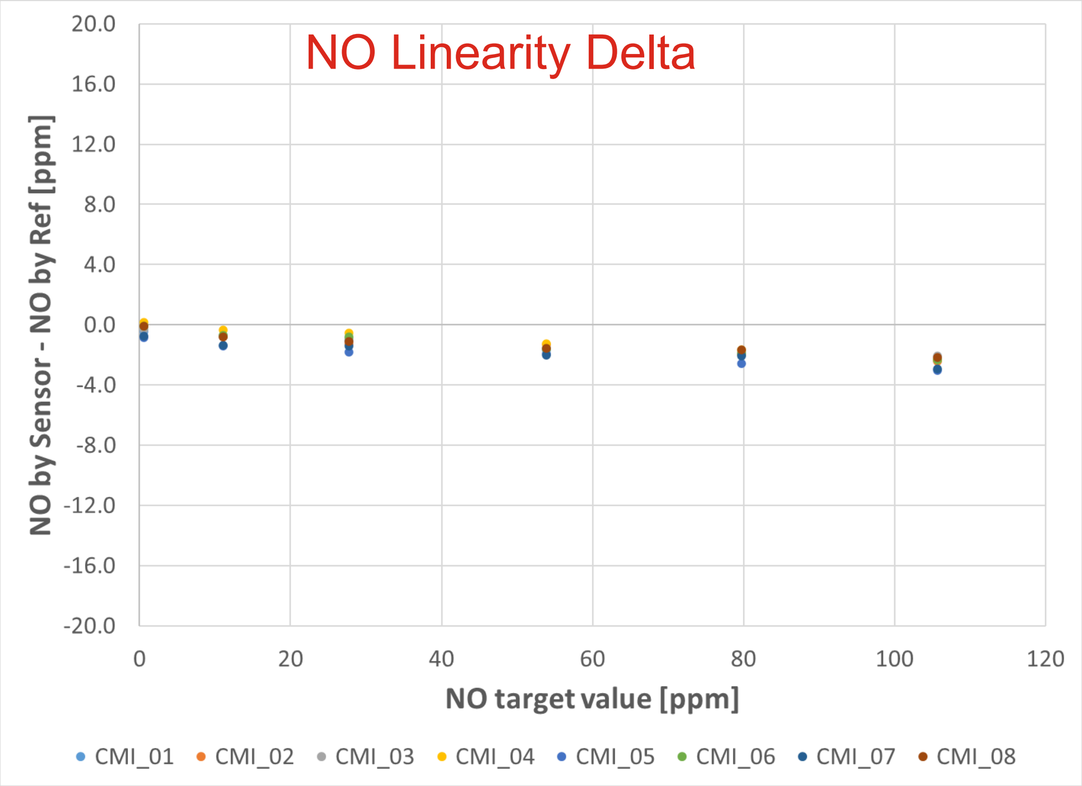


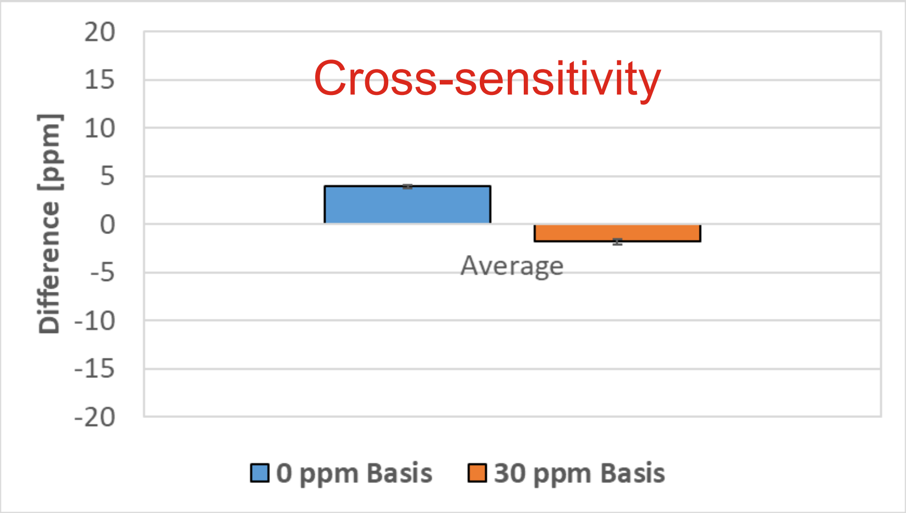
Factors replicated for fuel map simulation:

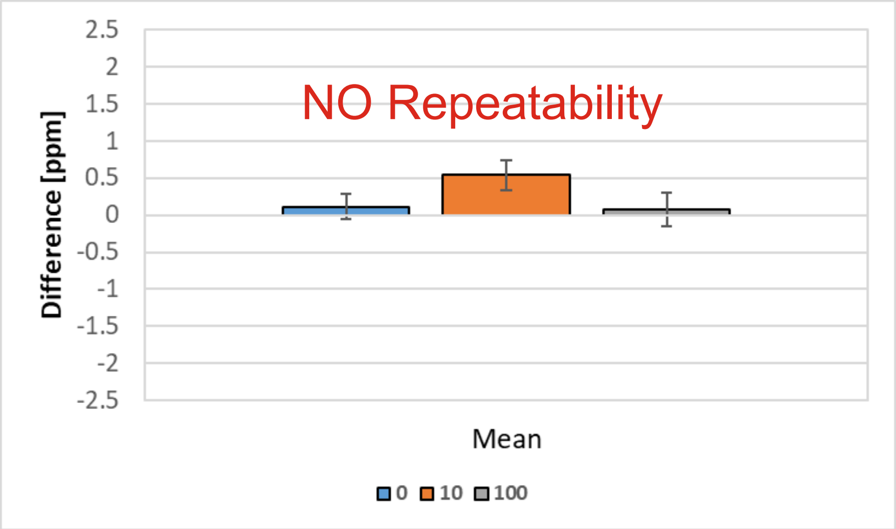
1. Temperature
2. Flow rate
3. NO/NO2/H_2O/CO_2/O_2 concentration

OSAR Matrix Result

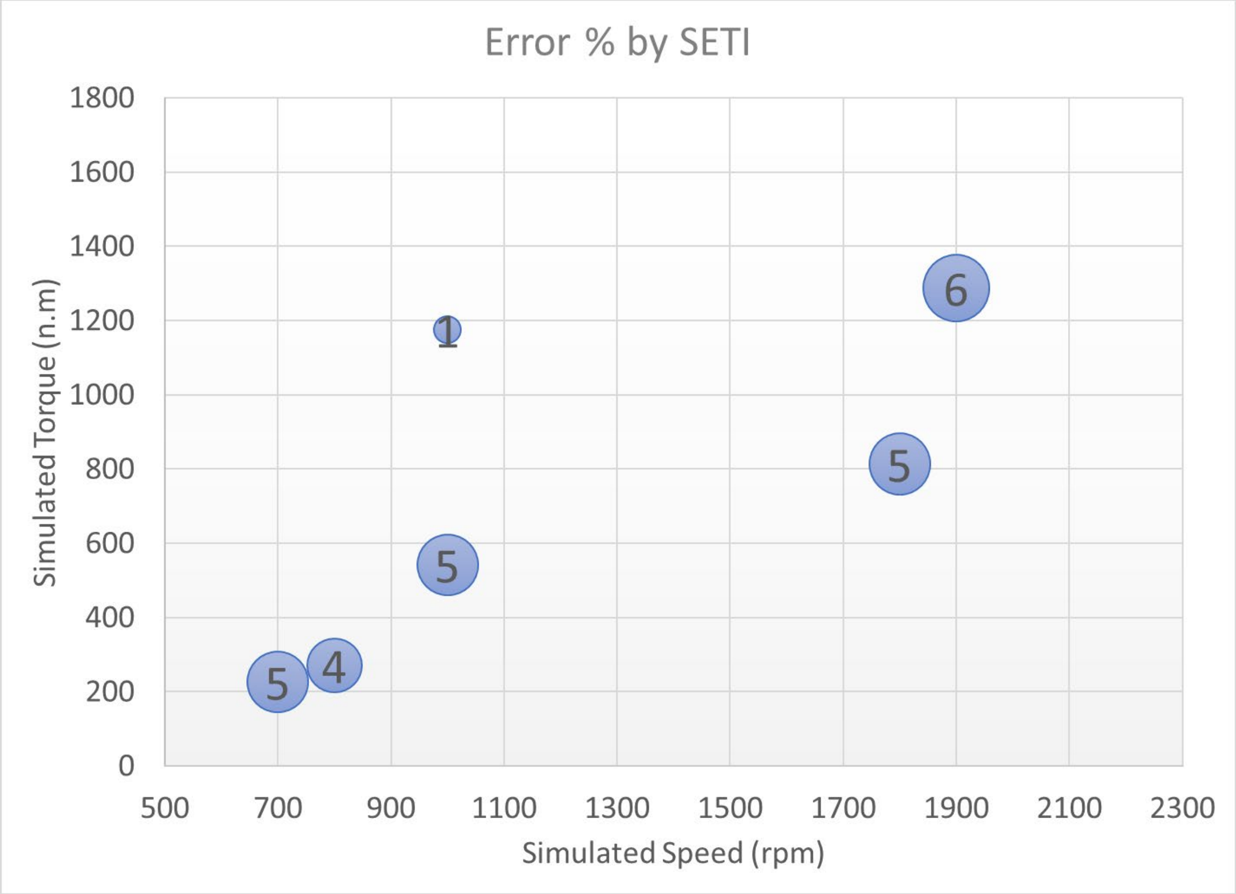
Flag	NO	NO2	H2O	O2	Temp	Flow
None	ppm	ppm	%	%	C	LPM
12	10	25	6	10.5	200	20
13	25	10	6	10.5	200	20
14	10	10	6	10.5	200	20
15	25	25	6	10.5	200	20

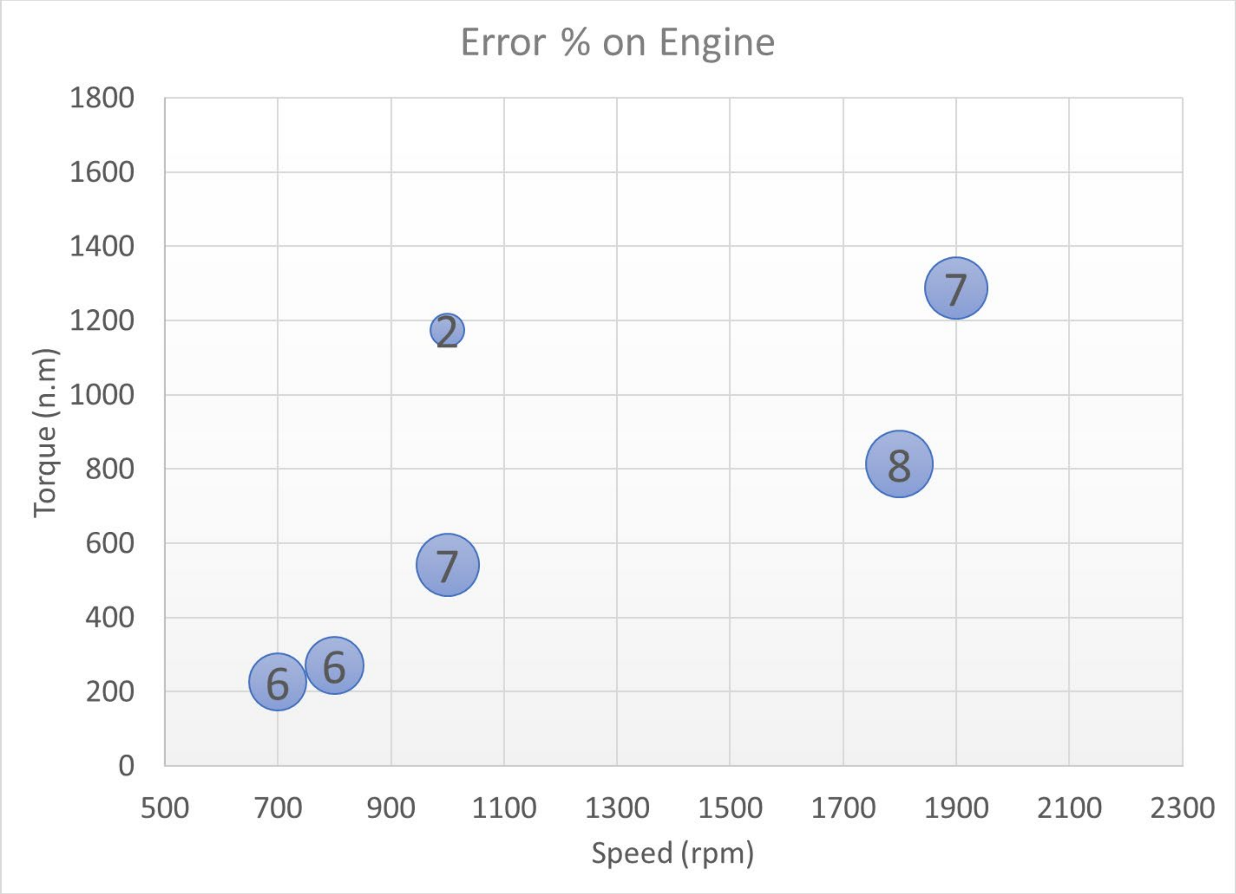




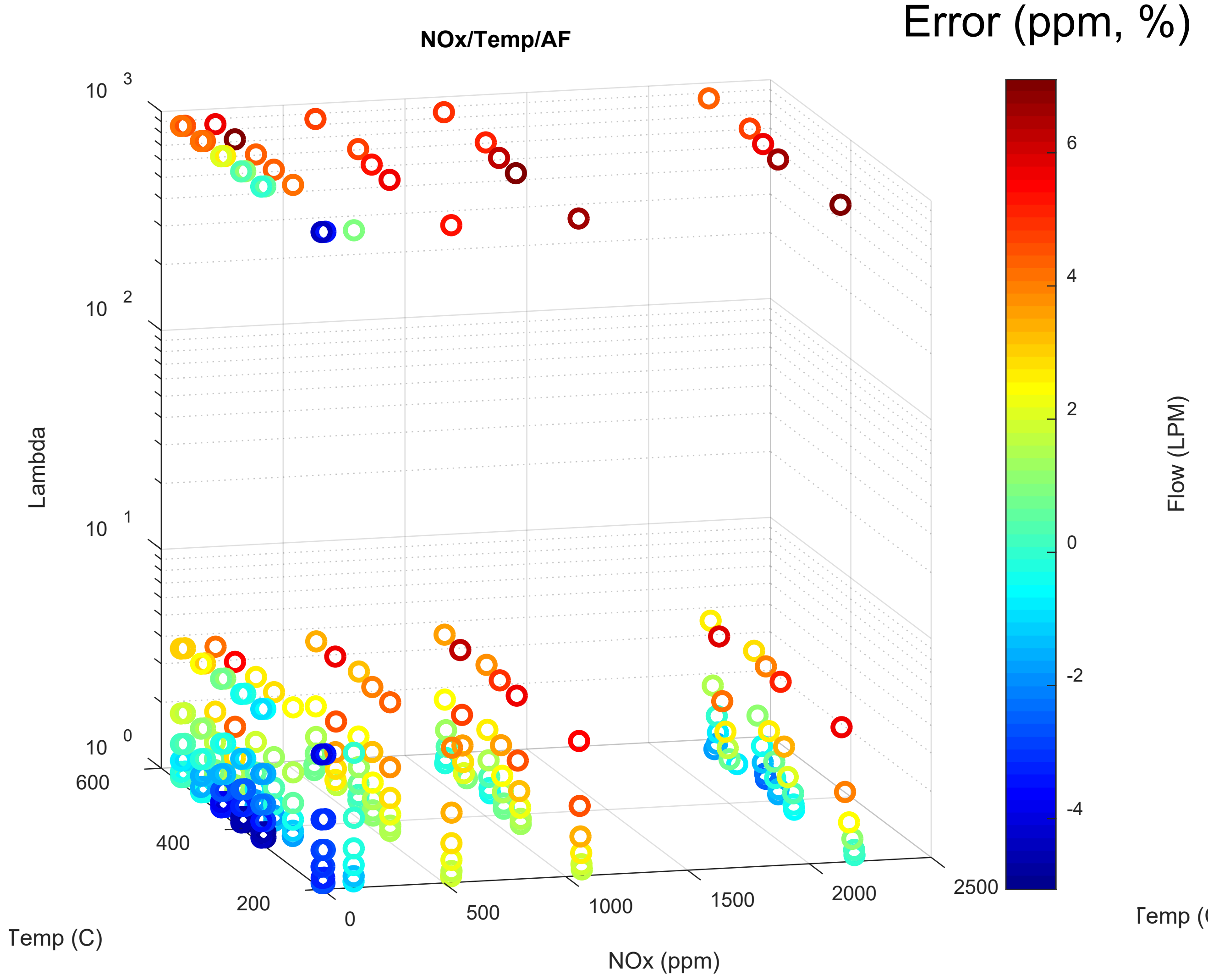


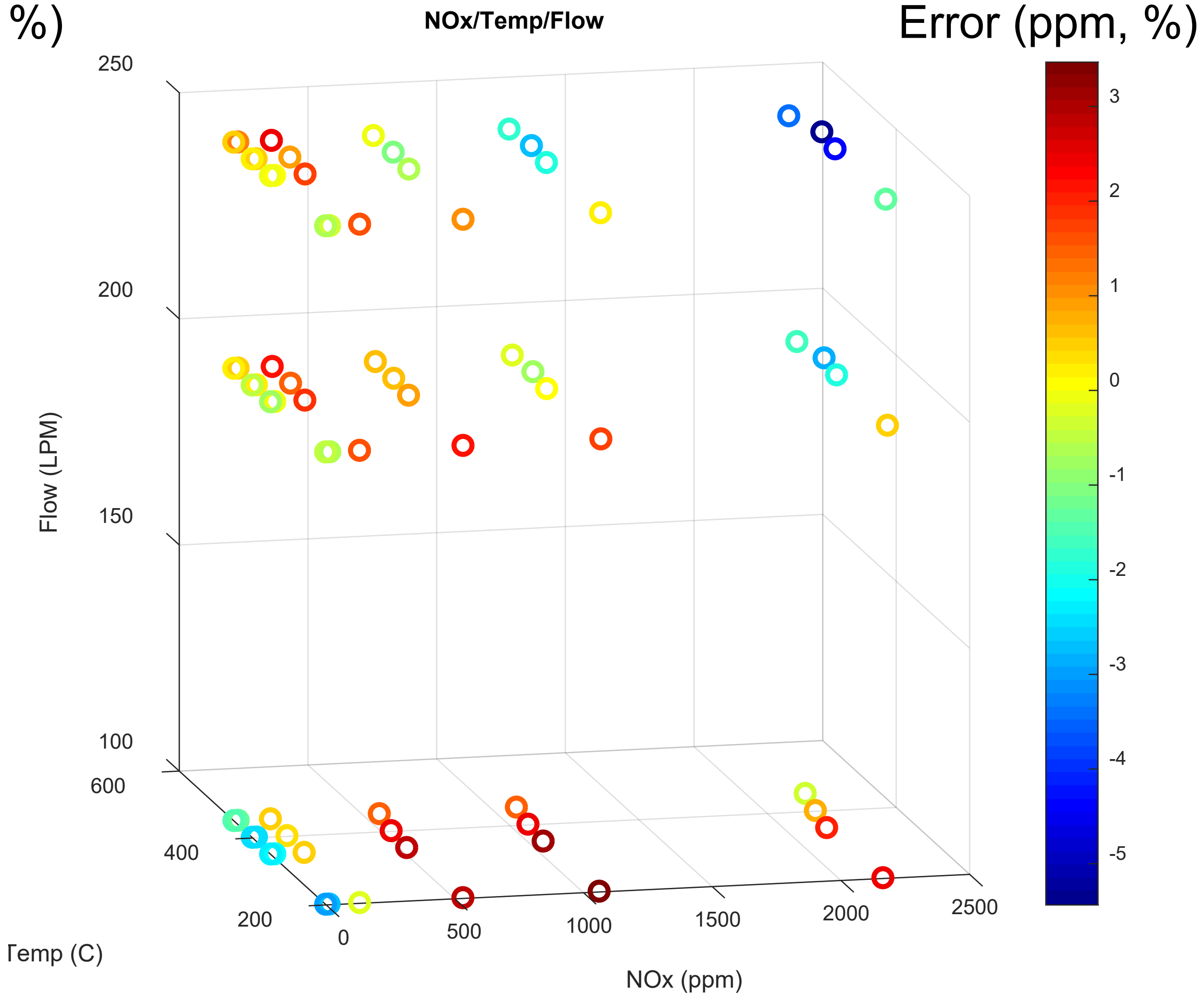
Fuel Map Simulation



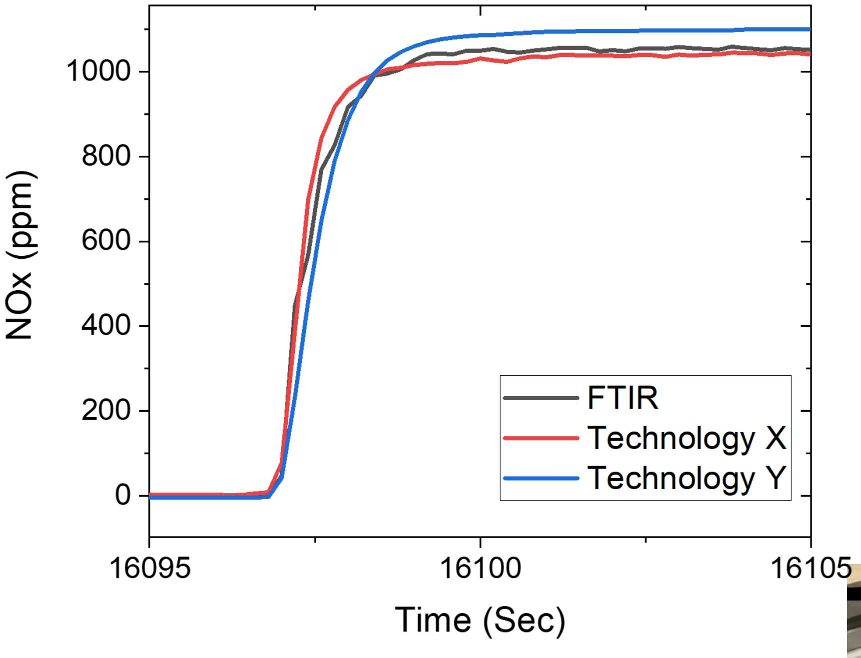


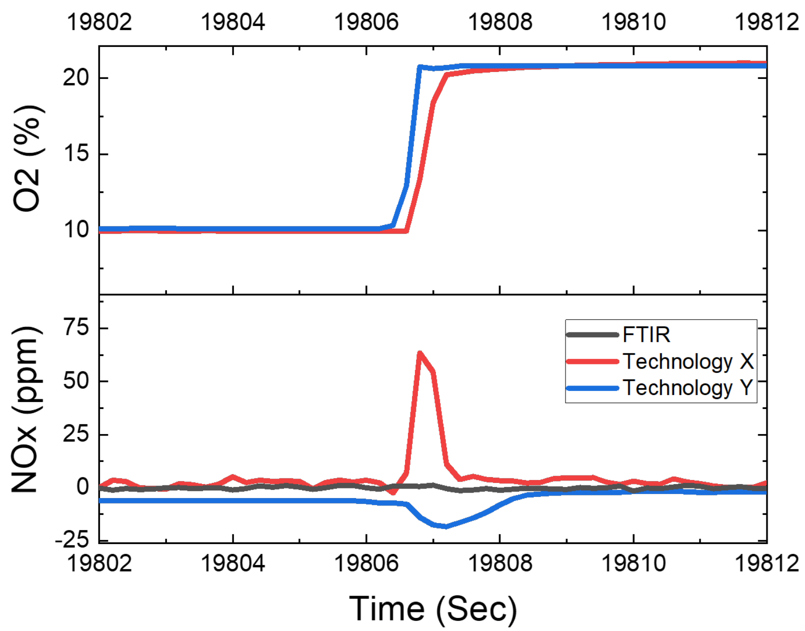
Cummins Matrix Result





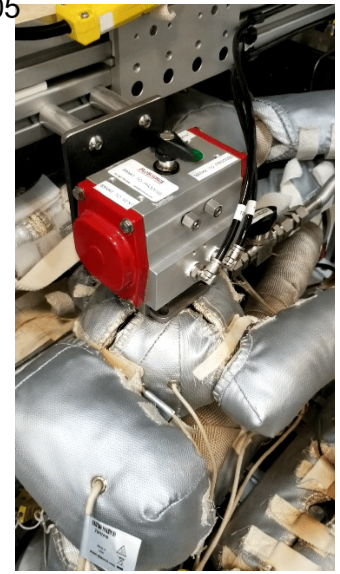
Response Time

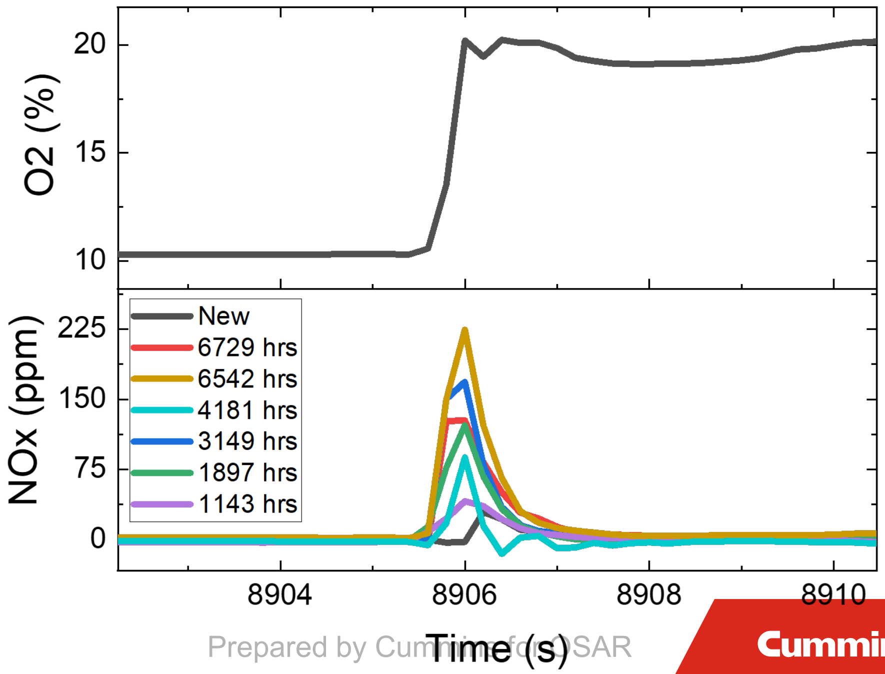




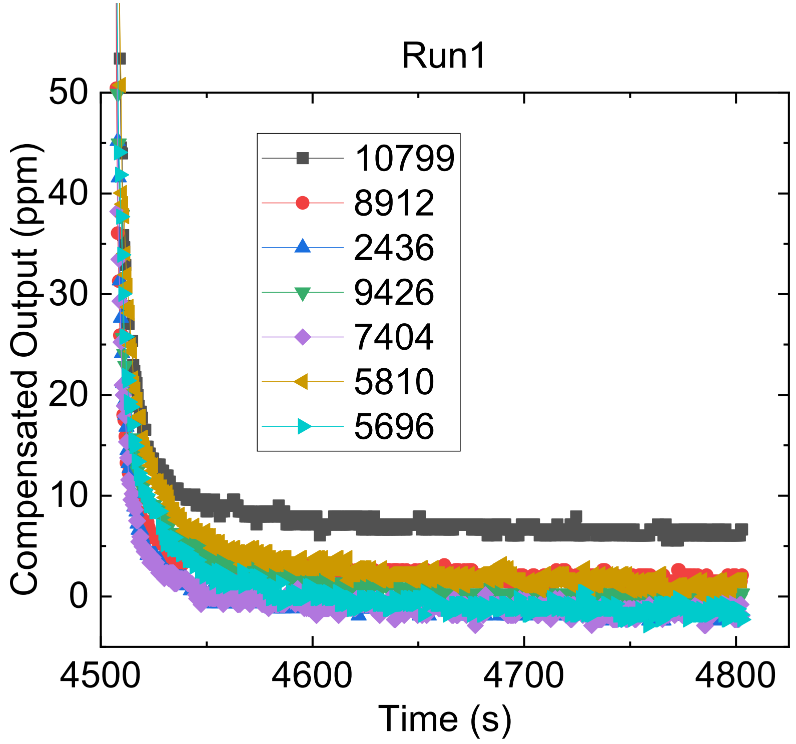
Performance comparison between:

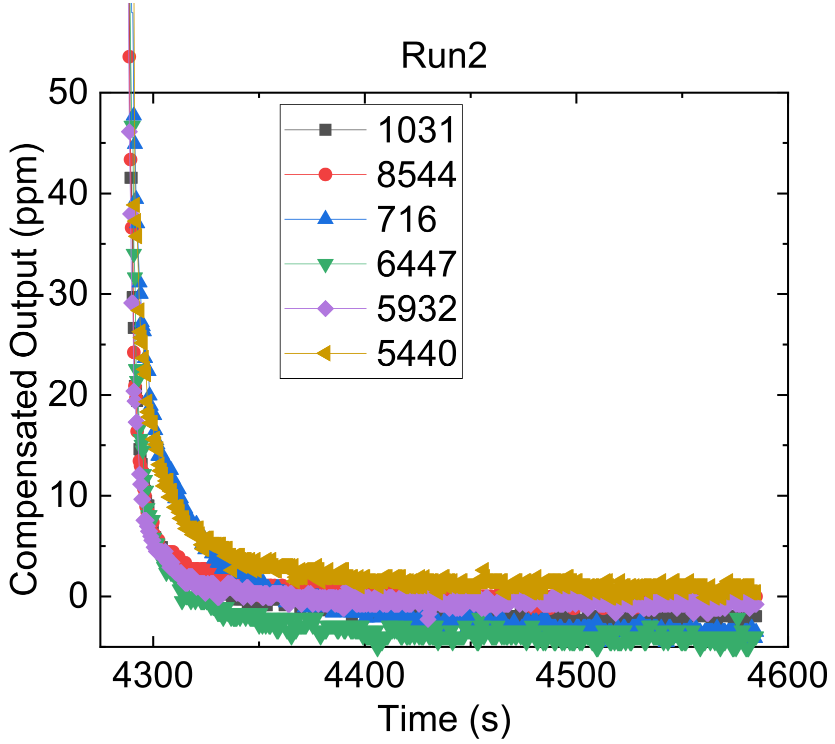
1. different technologies
2. new vs aged

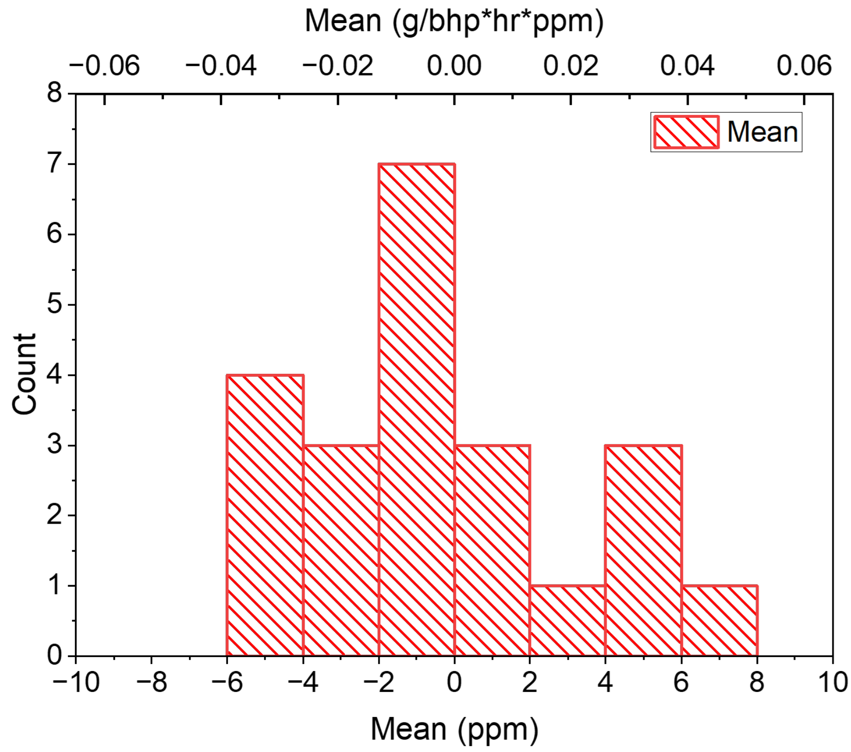




NOx Sensor Broadcasting Zero:

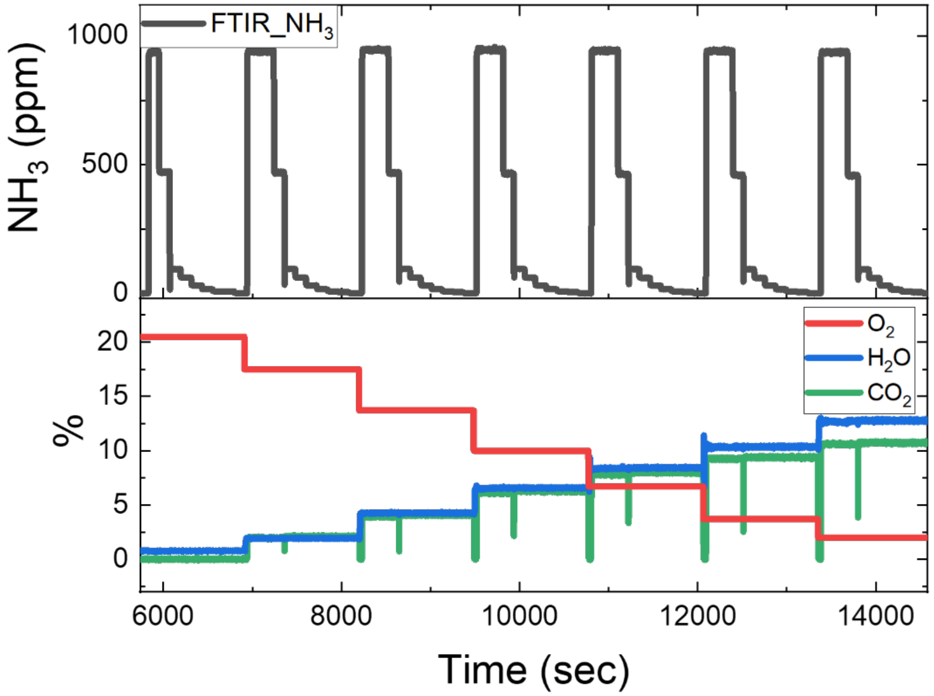


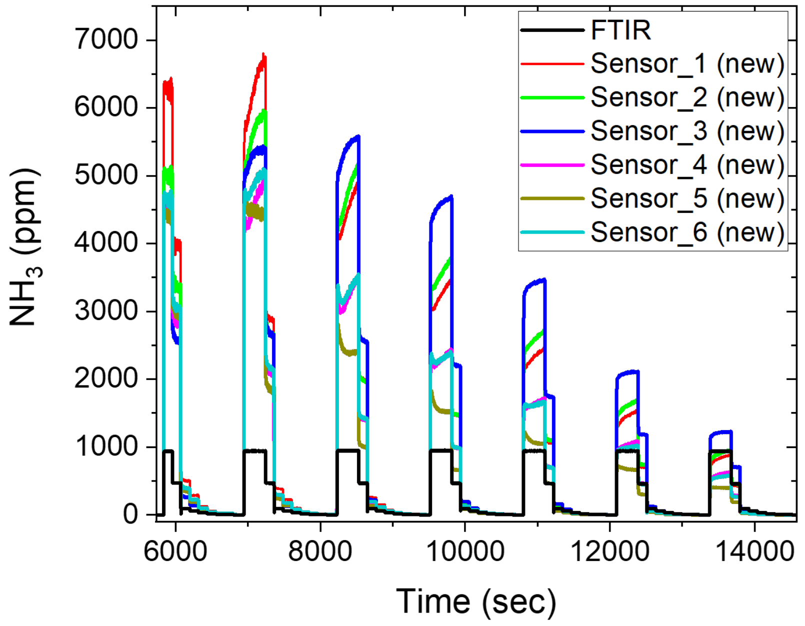


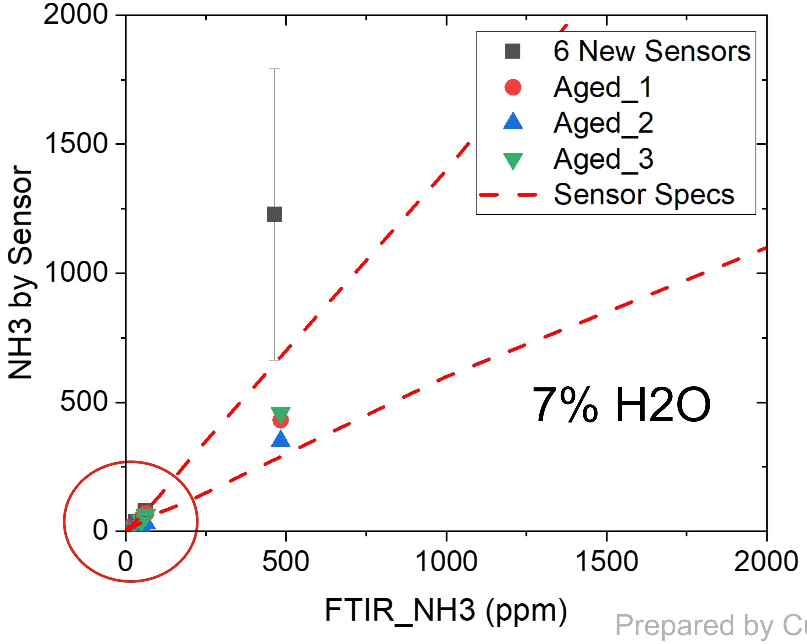


- The Average mean was computed by computing the mean for the last 15 s for each sensor for each of the runs and averaging them.
- The calculated NOx emission is based on a CO_2 emission of 503 g/bhp-hr and engine operating at $\lambda = 1.7$.

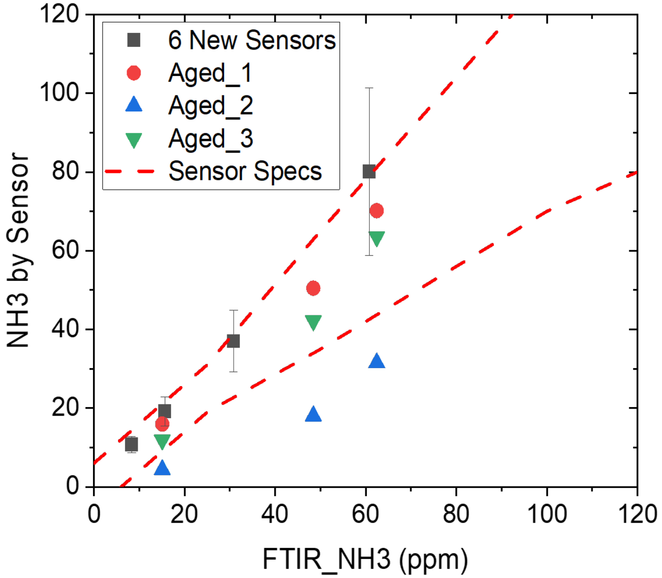
NH_3 Sensor







- Strong dependence on the air to fuel ratio.
- Large part-to-part variation.
- Decreased readings for aged sensors.



Implications and Conclusions

- Critical factors which impact sensor performance include temperature, pressure, lambda, NH_3, *etc.*
- Fuel economy and lambda determines the impact of NOx sensor errors on OBM/OBD-REAL type results. 1 ppm of NOx can be translated into 0.0065 g/bhp-hr under CO2 emission of 503 g/bhp-hr and engine operating at $\lambda = 1.7$.
- Empirically derived sensor models could be used to improve OBM/OBD-REAL type results, with qualitatively agreement being demonstrated between flow bench and test cell results.
- NOx sensor zero offset is sensitive to the sensor's age, type, and operating conditions (steady state and transient).
- OBM/OBD-REAL for NH3 would be a challenge.

Q+A