Challenges of Ultra-low NOx Measurements

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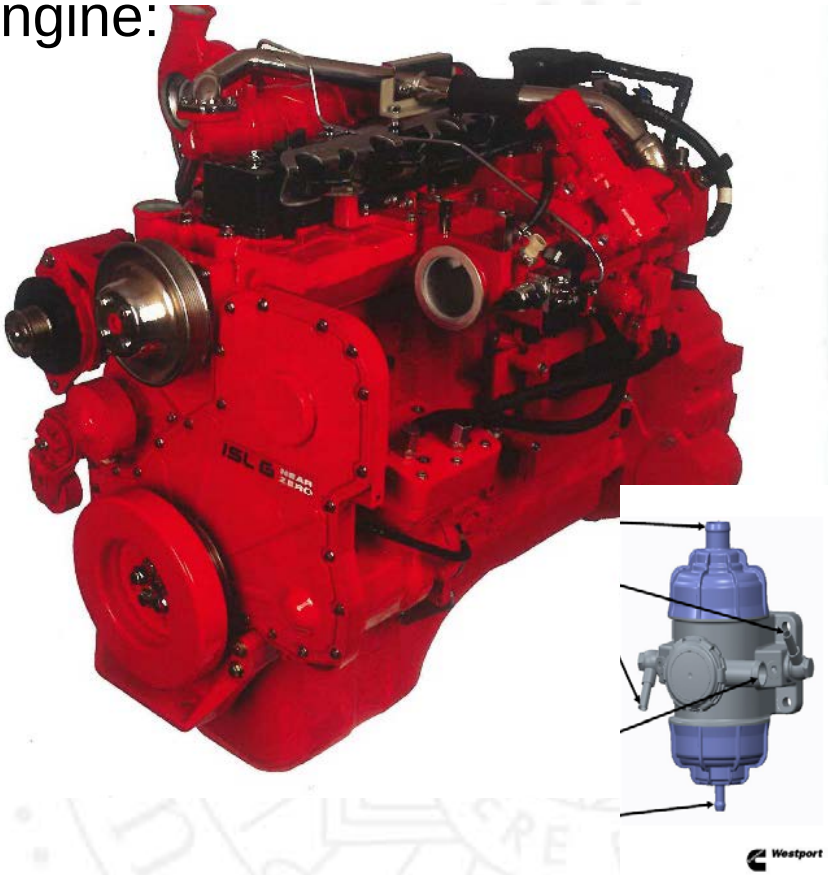
Outline

- Background
- Approach
- Results
- Summary

Advanced Natural Gas Engines are a Success

- California Optional Standards: 0.02 g/bhp-hr
- SCAQMD-managed $5M program to develop a 0.02 g/bhp-hr engine
- Cummins-Westport ISL G NZ 8.9L Engine:



Approach Refuse Truck: 0.02 g/bhp-hr Low NOx HD NG Engine

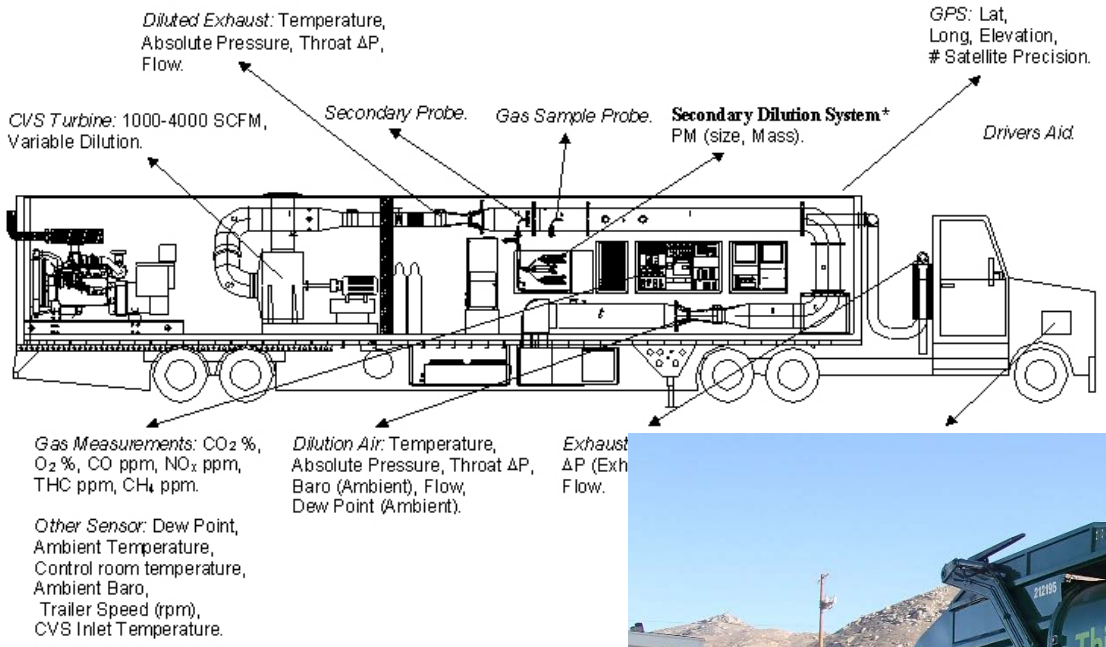
Mfg	Model	Year	Eng. Family	Rated Power (hp @ rpm)	Disp. (liters)	Adv NO_x Std g/bhp-h [1]	PM Std. g/bhp-h
CWI	ISL G NZ	2014	ECEXH0540LBH	320 @ 2100	8.9	0.02	0.01

[1] The family ECEXH0540LBH is on the engine label given its year of manufacture. The engine tested was produced under the ECEX… label but was later certified and upgraded to the GCEX… label. The engine tested is thus, based on the GCEX label and represents a 0.02 g/bhp-hr NO_x standard, see Appendix F Figure 4 for details.

- **Model year 2016 certified to 0.02 g/bhp-hr**
- **Vehicle equipped with a automatic transmission**

Day	Distance	Average Speed	Duration
Near Dock	5.61	6.6	3046
Local	8.71	9.3	3362
Regional	27.3	23.2	3661
UDDSx2	5.55	18.8	1061
CBDx3	3.22	20.2	560
AQMD Refuse	4.30	7.31	2997

Test Performed On UCRs Chassis Dyno With the Mobile Emissions Laboratory (MEL)



- **Added acid treated PM filters for high ammonia emissions**
- **Added three advanced NOx measurement methods**

- **Measured Global Warming Potential**
- **Measured PM and fines**

Approach: Measurement Upgrades

Type	Analyzer	Meth. ID	Description
Traditional	600 HCLD dil 600 HCLD amb	M1	Modal NO_x with ambient bag correction
Traditional	600 HCLD dil 600 HCLD amb	M2	Dilute bag NO_x with ambient bag correction
Upgrade	300 HCLD raw	M3	Raw NO_x no ambient bag correction
Upgrade	600 HCLD dil TECO amb	M4	Modal dilute NOx with ambient real time correction
Upgrade	TECO dil TECO amb	M5	Trace analyzer dilute bag with trace ambient bag correction

TECO - Trace level chemiluminescence NO-NO2-NOx analyzer modal 42C manufactured by Thermo Environmental Instruments Inc. Calibrated to 600 ppb.

$$NO_{x\_m3} = \sum_{ii=1}^{m} \left(\left(Q_{exh_{ii}} * M_{NO_{x\_ii}} \right) 1000 \right) * \left(\left(\left(C_{NO_{x\_dil}} - C_{NO_{x\_amb}} \left(1 - \frac{1}{DF_{ave}} \right) \right) \frac{1}{DF_{ave}} \right) \right)$$

From Johnson et al (2016), Final report to Cummins West Port via SC-AQMD funding “In-Use Ultra-Low NOx Natural Gas Vehicle Evaluation ISL G NZ 8.9”, Feb 2016.

Comparison of Method Calculations

$$NO_{x\_m1} = \sum_{i=1}^{n} (Q_{cvs_i} * \Delta t_{\_i}) * \rho_{NO_x} * \left(C_{m\_i} - C_a * \left(1 - \frac{1}{DF_i}\right)\right)$$

$$NO_{x\_m2} = (Q_{cvs\_ave} * \Delta t) * \rho_{NO_x} * \left(C_d - C_a * \left(1 - \frac{1}{DF_{\_ave}}\right)\right)$$

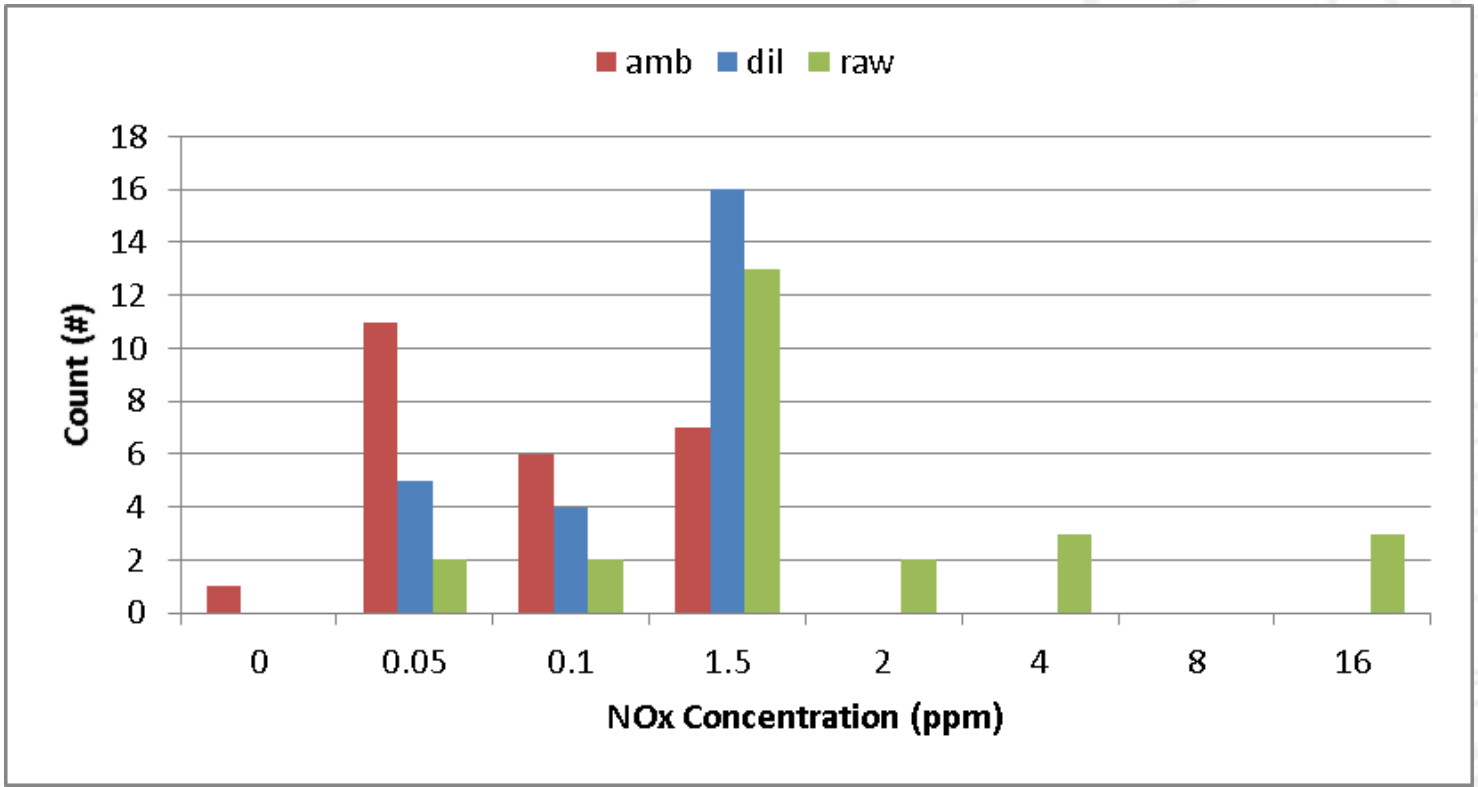
$$NO_{x\_m3} = \sum_{i=1}^{n} (Q_{exh_i} * \Delta t_{\_i}) * \rho_{NO_x} * \left(C_{r\_i}\right)$$

$$NO_{x\_m4} = \sum_{i=1}^{n} (Q_{cvs_i} * \Delta t_{\_i}) * \rho_{NO_x} * \left(C_{m\_i} - C_{a\_adv\_i} * \left(1 - \frac{1}{DF_i}\right)\right)$$

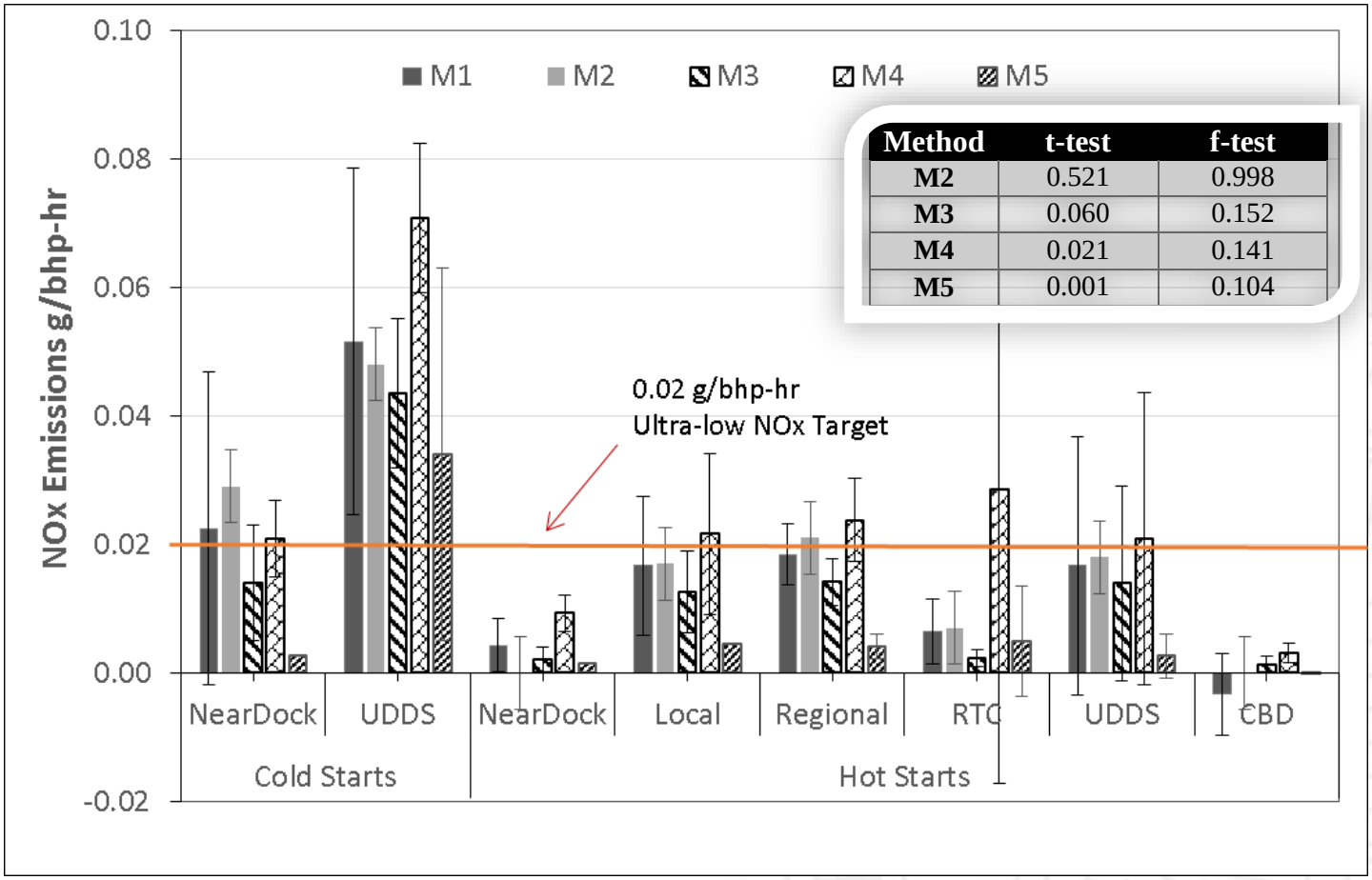
$$NO_{x\_m5} = (Q_{cvs\_ave} * \Delta t) * \rho_{NO_x} * \left(C_{d\_adv} - C_{a\_adv} * \left(1 - \frac{1}{DF_{\_ave}}\right)\right)$$

Source and Ambient Concentrations Are Converging

Percentile	Amb	Dilute	Raw	Amb/Dil %
10th	0.234	0.632	6.533	105%
50th	0.070	0.168	0.554	54%
90th	0.021	0.033	0.070	10%



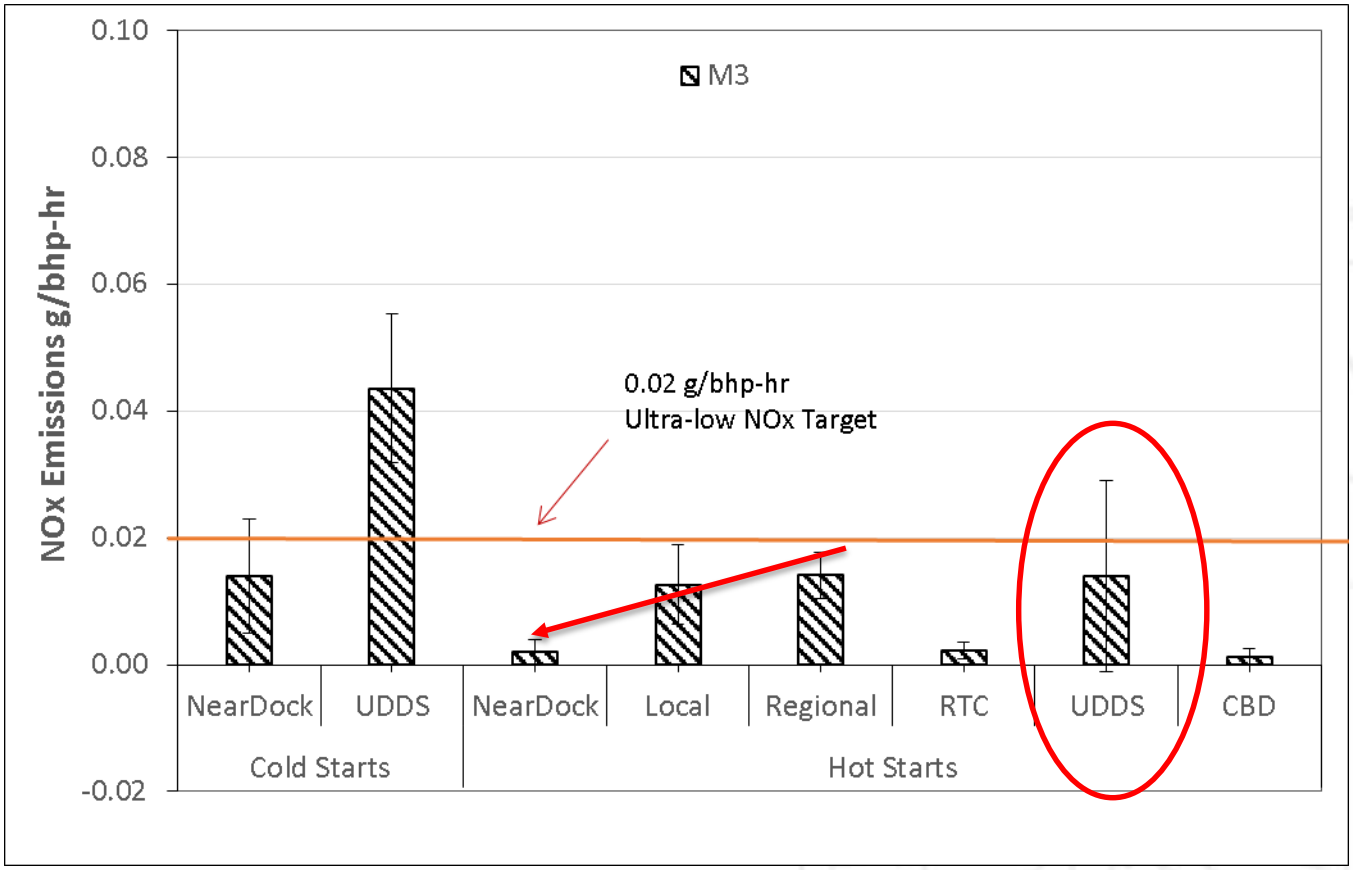
Method 3 (Raw Sampling) Shows Lowest Variability



Method	t-test	f-test
M2	0.521	0.998
M3	0.060	0.152
M4	0.021	0.141
M5	0.001	0.104

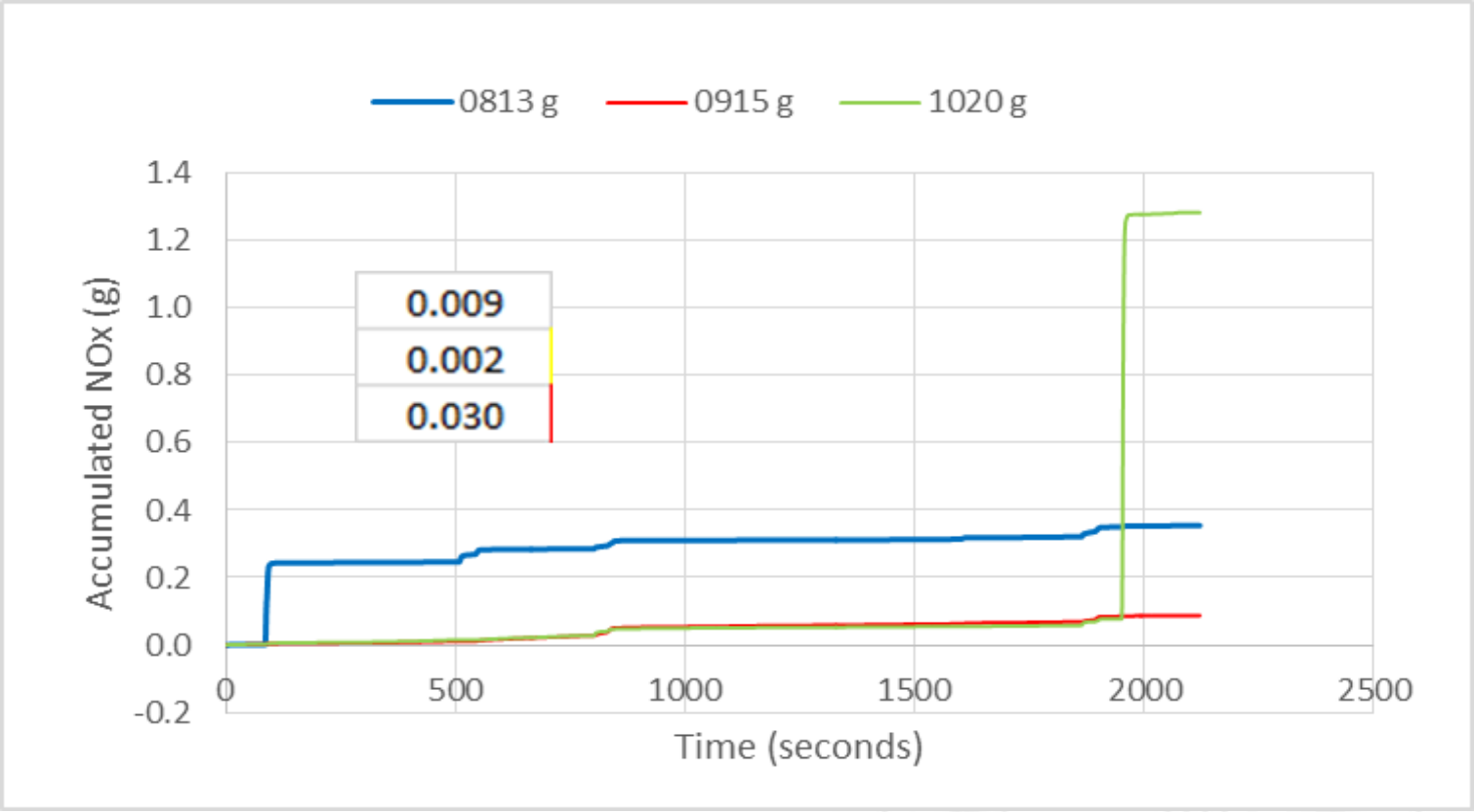
- Traditional methods lower signal/noise, reasonable means
- M4 showed poor repeatability and M5 low response

Meets Optional CA Standard And Even Lower For Lower Power Duty Cycles



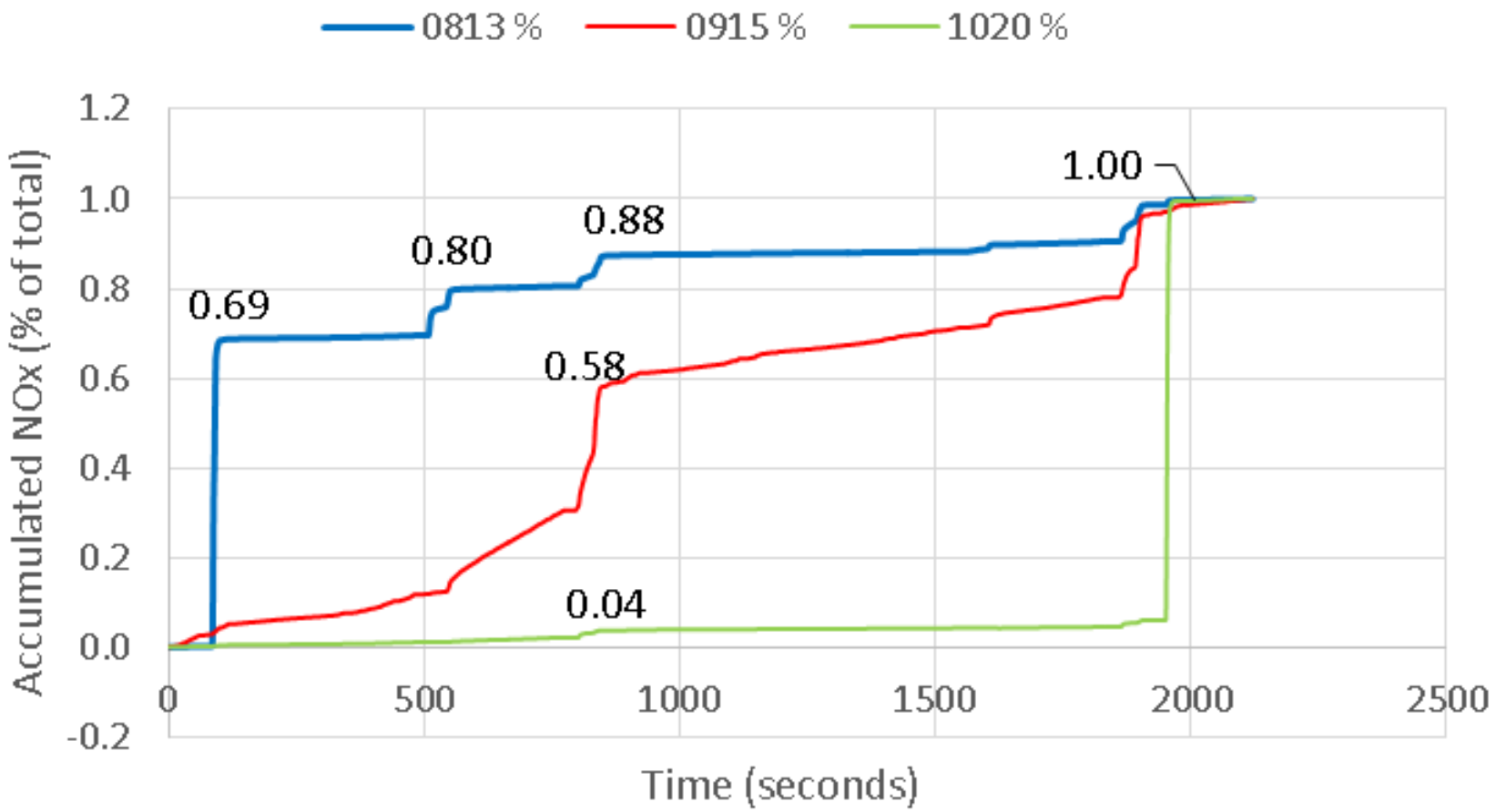
- NOx emissions drop with decreasing load
- The weighted NO_x hot/cold emissions 0.018 g/bhp-hr

Emissions Spikes are Significant

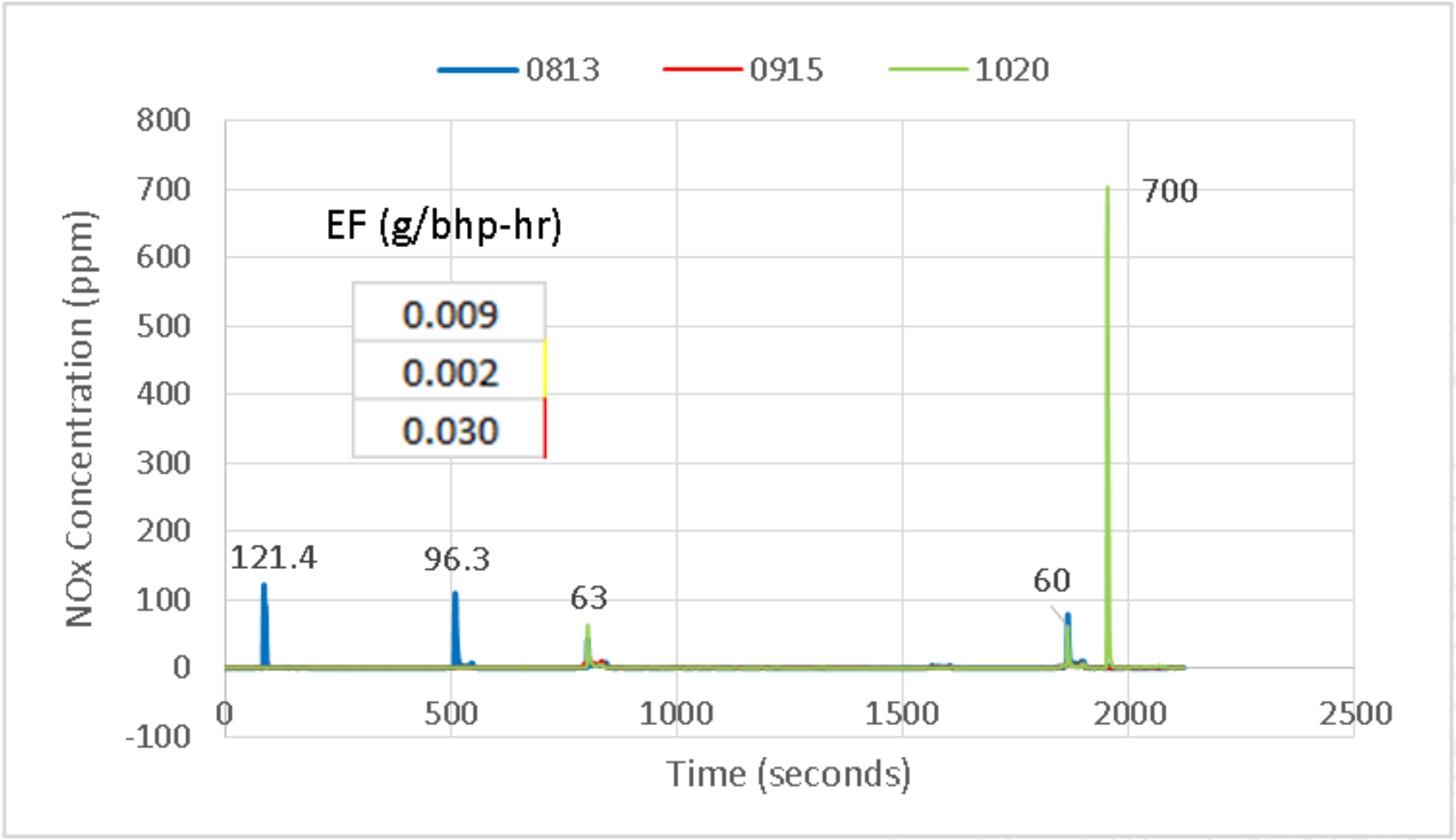


- Spikes show most of the emission increases
- Variability is not the measurement, but the vehicle

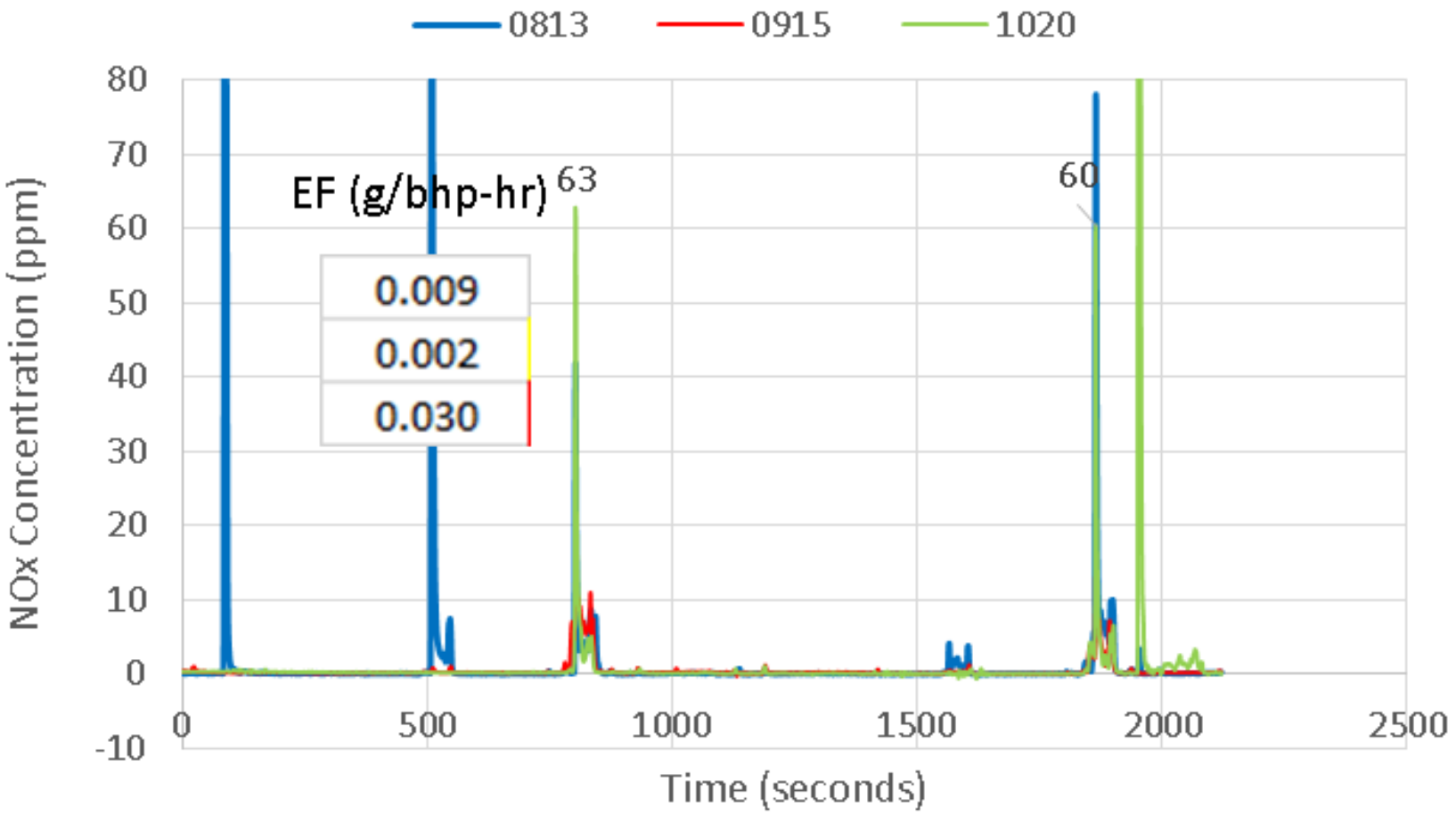
Up to 90% of The NO_x in One Acceleration



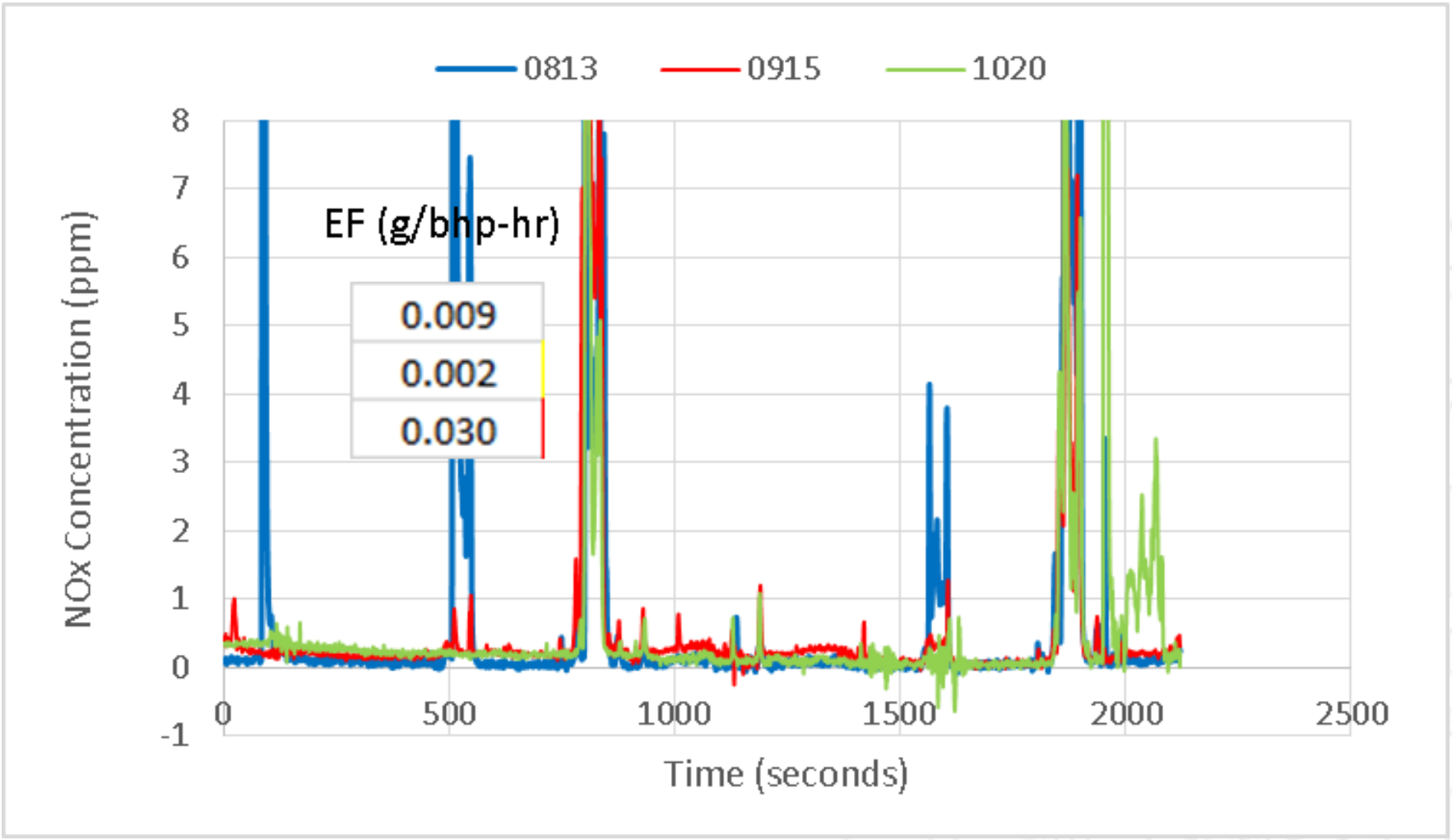
Can PEMS Capture Deviations In the Field? I/M?



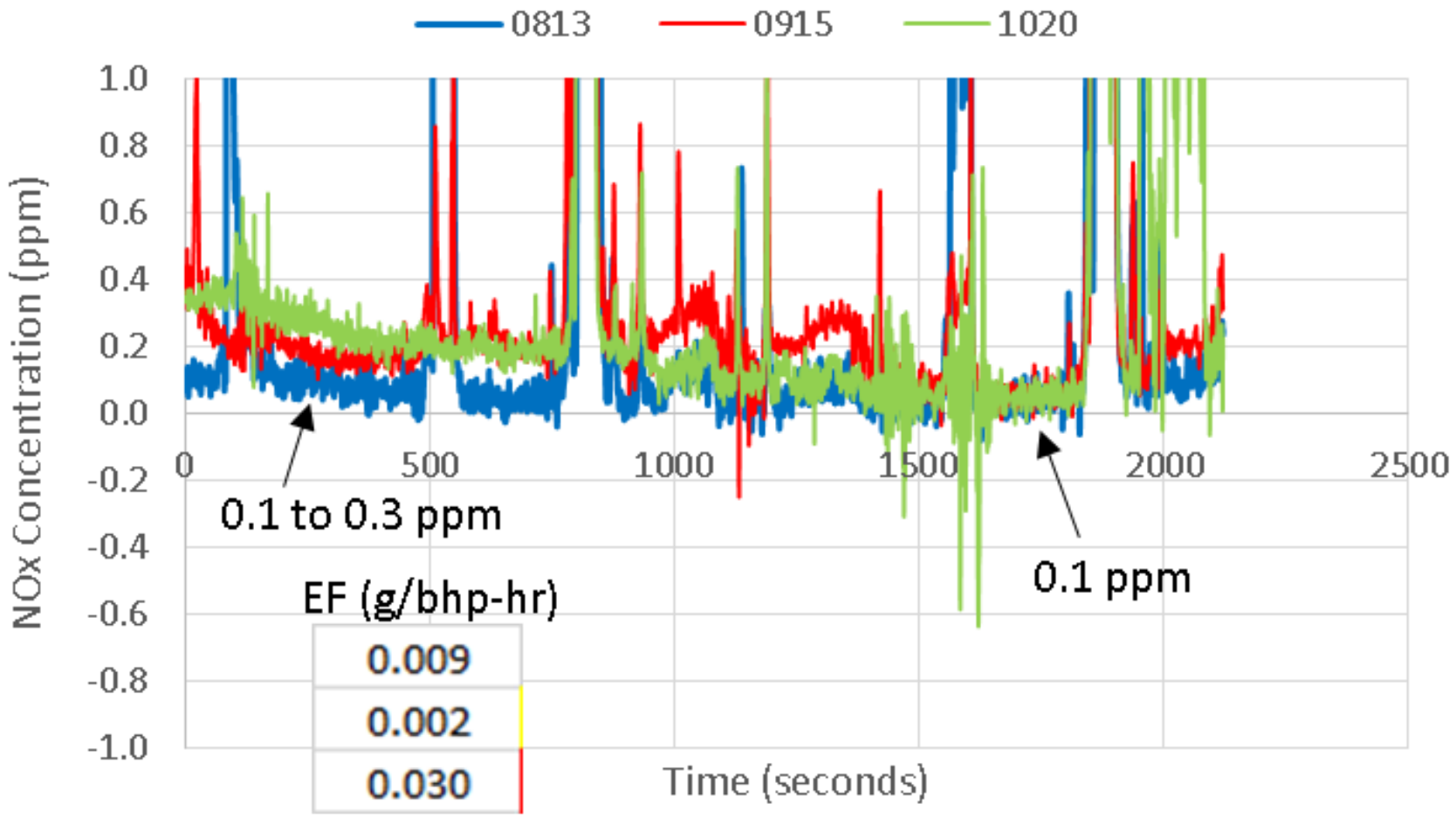
If We Zoom In 90% What Does It Look Like



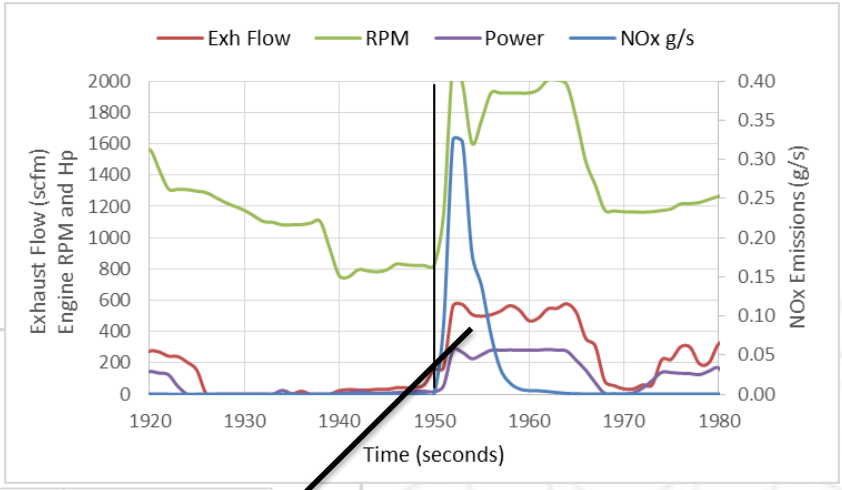
Lets Zoom In Another 90% (99%) What Do We See

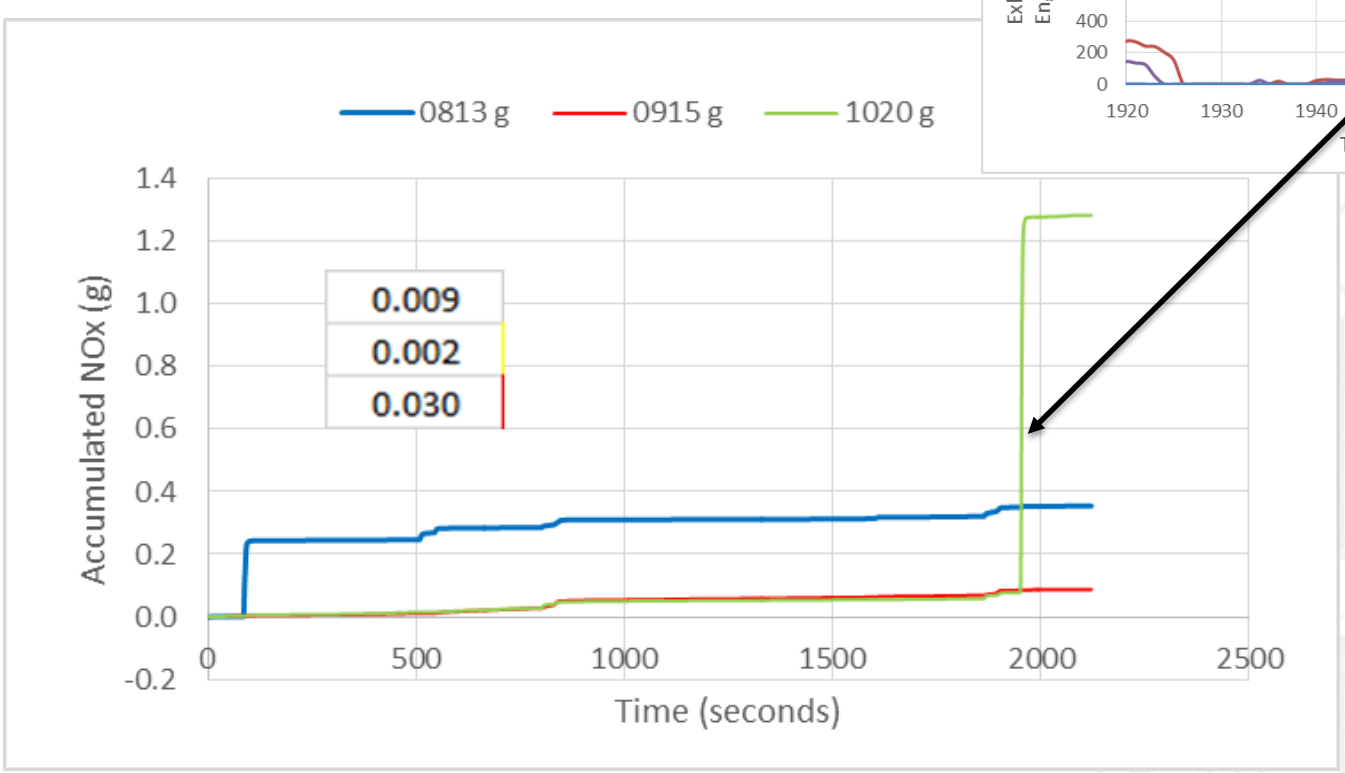


Okay Lets Zoom in Another 75% (99.47%)

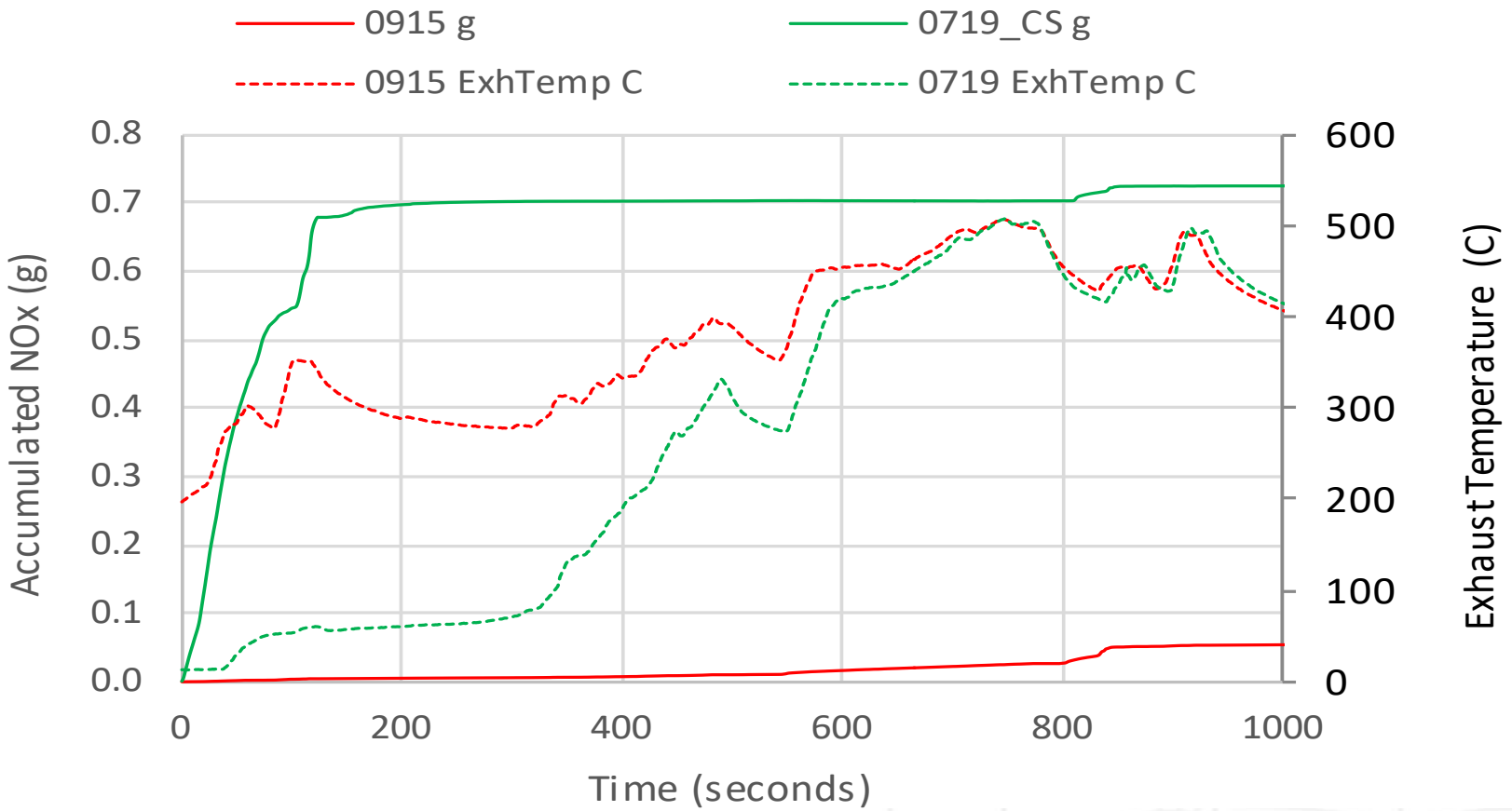


The Variability Is Real and Results from Shifting





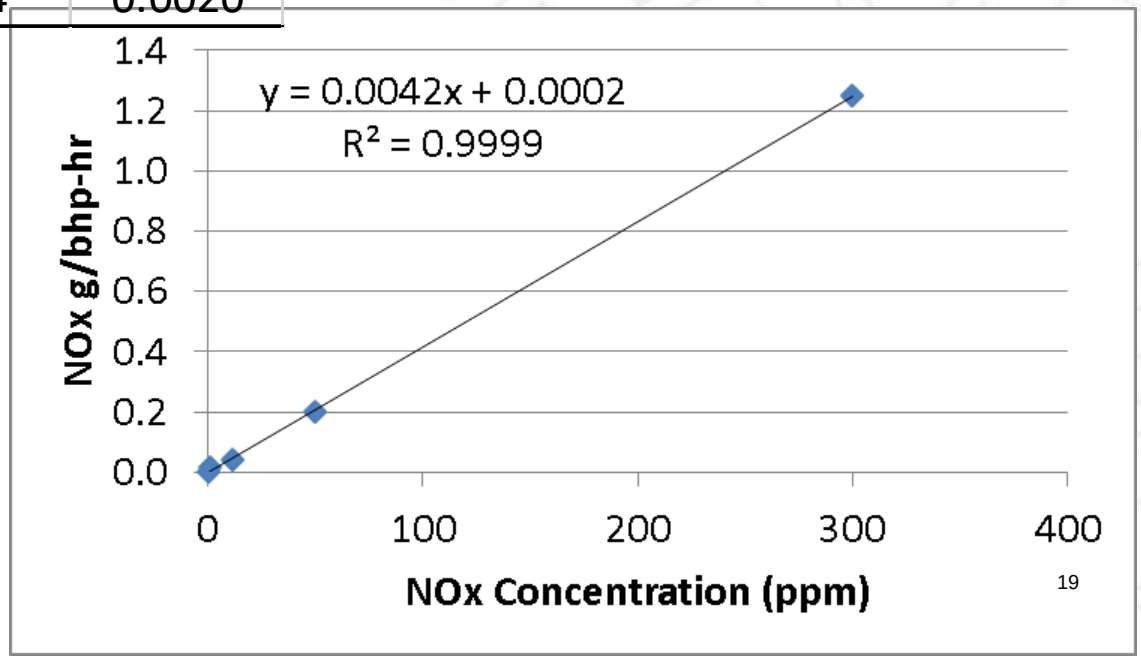
Cold Start Emissions are Significant



- 90% of the NO_x emission result in fist 100 seconds.
- PEMS can easily capture this large NOx spike. RSD?
- Hybrid applications need to manage cold starts

With On Board Sensors Can we Estimate NO_x from Concentration?

		NOx table	
Vehicle	Cycle	ppm	bsNOx
Diesel 2008	FTP	300	1.25
Diesel SCR	FTP	50	0.2
NZ NG	CS_UDDSx	11.27	0.0435
NZ NG	UDDSx2	1.10	0.0139
NZ NG	DPT1	0.14	0.0020



Summary Thoughts: Measurements

- Raw NOx concentrations stabilized between 0.3 and 0.1 ppm where ambient NOx ranged from 0.23 to 21 ppm (10^{th} and 90^{th} percentile)
- NOx spikes ranged from 700 to 60 ppm. One spike > 90% of the emission level at 0.02 g/bhp-hr.
- NG engines with acceleration issues may not be captured by I/M, but would be captured by PEMS or an telematics reporting system (Air-To-Fuel) ratio
- Vehicle ATS remained active after light off (unlike diesel ATS). Great for hybrid applications.

Summary Thoughts: Emission Levels

- The 0.02 g/bhp-hr Optional NOx standard was a success.
- The NG ISLG NZ vehicle showed **lower** emissions as **load decreased** (an additional 90% 0.002 g/bhp-hr).
- Real world driving, aged systems, and fuel variability may show higher emission levels. Great system to hybridize.
- Other Emissions (see the report)
  - HC emissions below certification (closed crank case design)
  - Particulate mass emissions are very low (at method detection)
  - Black carbon emissions are very low (at method detection)
  - Particle number emissions are low