Assessing the Ability of On-Board NOx Sensors to Reflect Full Cycle NOx Emissions

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Using On-Board NO_x Sensors to Monitor In-Use Emissions

- The Real Emissions Assessment Logging ("REAL") concept uses NOx sensors to monitor in-use emissions
- For 2016 and subsequent model year engines, the OBD system shall illuminate MIL when NOx emissions exceed 0.4 g/bhp-hr
- The performance of on-board NOx sensors will affect the understanding of in-use emissions

REAL bins in HD OBD regulation

Total (Bin 1)	% of Rated Power	Vehicle Speed (km/h) 0	> 0 ≤ 16	> 16 ≤ 40	> 40 ≤ 64	> 64
	≤ 25%	Bin 2	Bin 3	Bin 4	Bin 5	Bin 6
	> 25% ≤ 50%		Bin 7	Bin 8	Bin 9	Bin 10
	> 50%		Bin 11	Bin 12	Bin 13	Bin 14

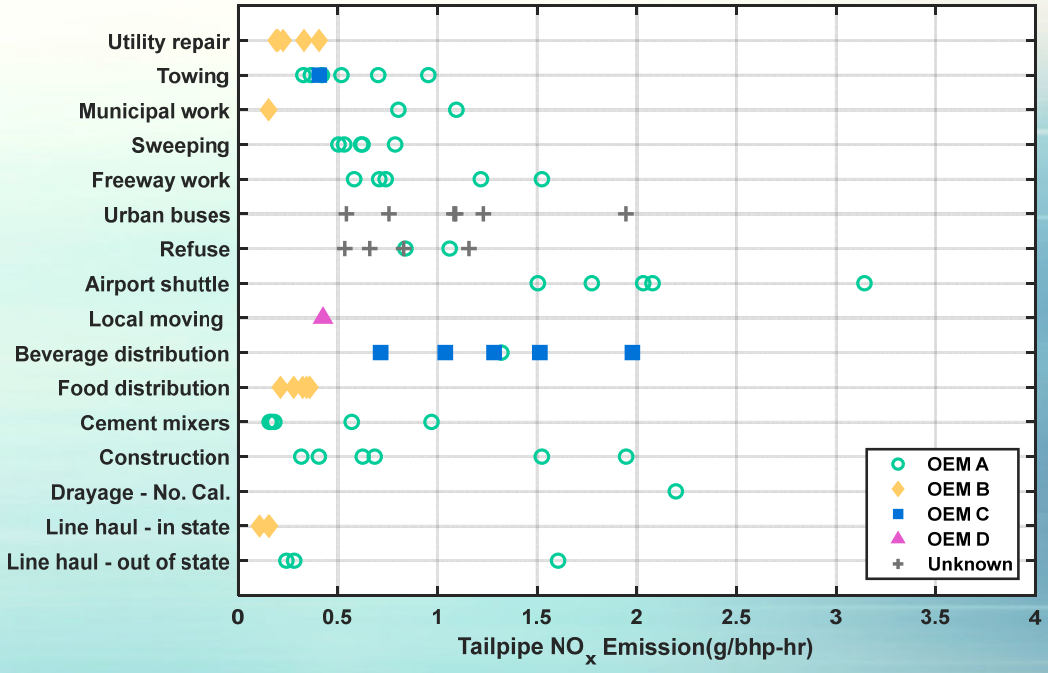
NTE Bin 15

DPF regen Bin 16

MIL on Bin 17

$$NOx\left(\frac{g}{s}\right) = 0.001588 * [NOx]\text{ppm} * \text{Exhaust Flow}\left(\frac{\text{kg}}{\text{hr}}\right) * \frac{1}{3600}$$

Using On-Board NOx Sensors to Monitor In-Use Emissions



Tan et al. (2019)

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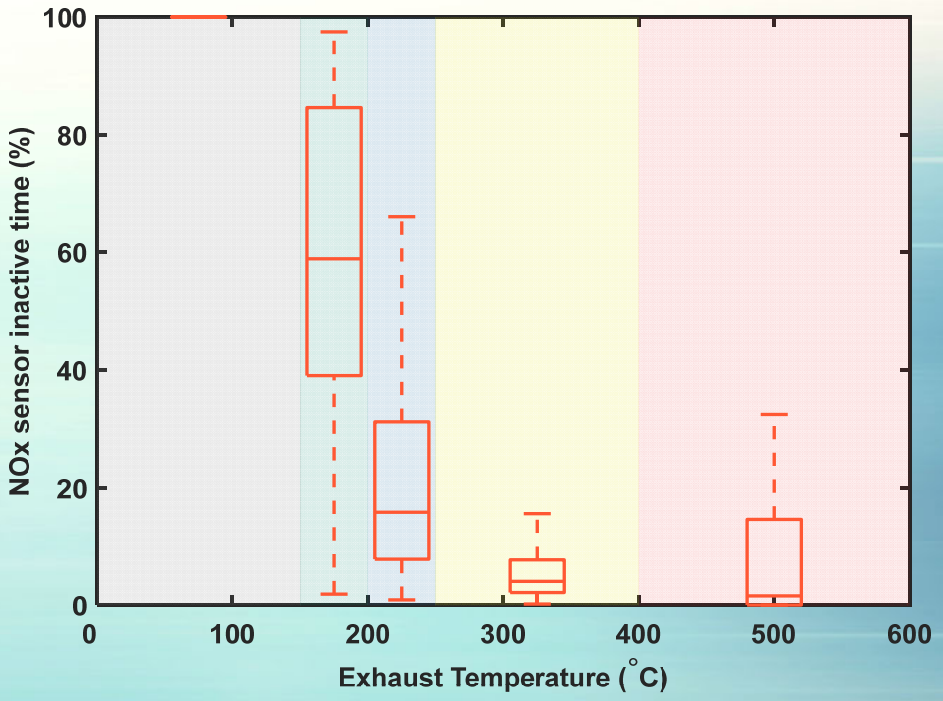
Inactive NOx sensors

- NOx sensors are turned off when the exhaust temperature is low
- NOx sensors are not always reporting valid data even when the exhaust is hot (250 – 400°C)
- High NOx emissions could occur when NOx sensors are not reporting valid data



Aggregated results of 110 trucks from activity studies (CARB contracts 13-301 and 14-302)

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Objectives

- To examine the ability of current on-board NOx sensors to reflect full cycle NOx emissions
  - Direct comparison between NOx sensor readings with concurrent PEMS measurements
  - Monte Carlo simulations with PEMS testing data

Data Sources – Heavy-Duty Diesel Trucks

- CE-CERT HDV activity study
  - 72 out of 90 trucks, mostly vocational trucks
- CE-CERT tractor and trailer study
  - 38 out of 77 newer trucks, mostly line-haul trucks
- OEM HDIUT & CARB HDIUC
  - 210 MY 2010+ HDDVs
- In-house PEMS testing

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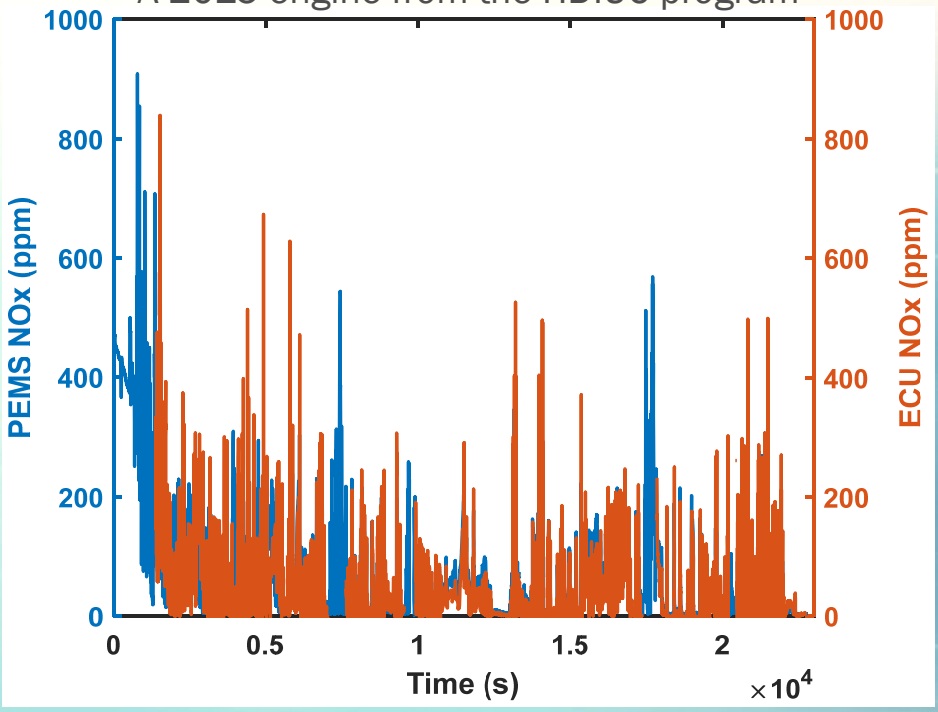
Understand Measurement Uncertainty Associated with Inactive NOx Sensors – Direct Comparison

- SCR outlet NOx sensor did not report valid data for 3,024s (13%) during the 22,637s testing

	<150°C	150 – 200°C	200 – 250°C	250 – 400 °C	≥400°C
Total time (s)	1389	1362	6591	13,261	99
Inactive NOx sensor (s)	1388	812	622	295	0

- Reasonable agreement between PEMS (417 g, 0.45 g/bhp-hr) and NOx sensor (413 g, 0.43 g/bhp-hr) when the sensor was active
- Total NOx measured by PEMS: 563 g, 0.55 g/bhp-hr – sensor would miss >26% NOx

A 2015 engine from the HDIUC program



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Understand Measurement Uncertainty Associated with Inactive NOx Sensors – Direct Comparison (2)

- Pros
  - Directly quantify the impact of turning off NOx sensors
- Cons
  - Limited number of vehicles
  - Most vehicles were not very clean
  - Similar driving patterns that represent the operation of line-haul trucks
  - Complicated time alignment

Understand Measurement Uncertainty Associated with Inactive NOx Sensors – Monte Carlo Simulation (1)

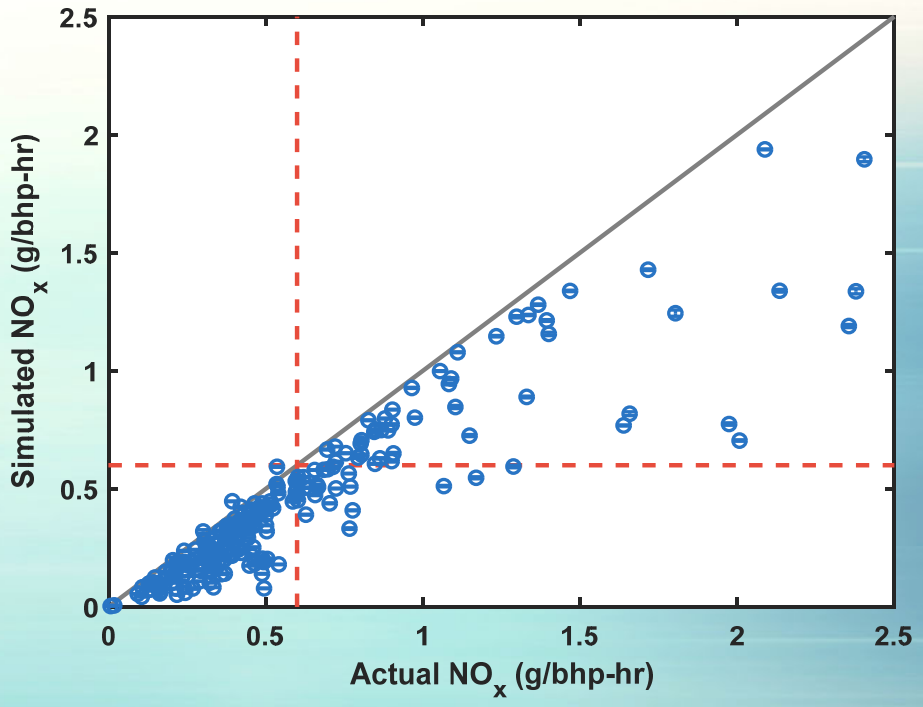
- Use instantaneous NOx emissions from PEMS testing as the input
- Assume some random data will be missed by the NOx sensor, depending on the exhaust temperature

	<150°C	150 – 200°C	200 – 250°C	250 – 400 °C	≥400°C
Data not monitored by NOx sensor	100%	60%	20%	10%	10%

- Calculate brake specific NOx emissions using data captured by the sensor
- Repeat the simulation for 10,000 times for each truck
- Compare the average of simulation results with the actual brake specific emission

Understand Measurement Uncertainty Associated with Inactive NOx Sensors – Monte Carlo Simulation (2)

- The analysis of 210 trucks found that NOx sensors typically underestimate in-use emissions
- The underestimation can be significant when low exhaust temperature operations were substantial
- For identifying high emitters, NOx sensors have low possibilities to report “false positives”



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Understand Measurement Uncertainty Associated with Inactive NOx Sensors – Monte Carlo Simulation (3)

- Pros
  - Can assess a large number of vehicles with different operating conditions
- Cons
  - The simulation might not represent real-world sensor operations
    - The simulation randomly picks data that are not monitored by the sensor
    - In reality, NOx sensor would be off continuously

Preliminary Findings and Next Steps

- Preliminary findings
  - OBD can be a reliable tool to identify high emitters
  - Turning off NOx sensors at low temperatures often underestimates in-use emissions
  - Improved sensors are needed to monitor full cycle NOx emissions
- Next steps
  - Understand other factors that contribute to the measurement uncertainty
  - Additional comparison between PEMS and PAMS with trucks from the HDIUC program and in-house research projects
  - Additional Monte Carlo simulation