



# Preliminary Off-road Diesel Emission Factor Updates

*based on real-world engine testing*

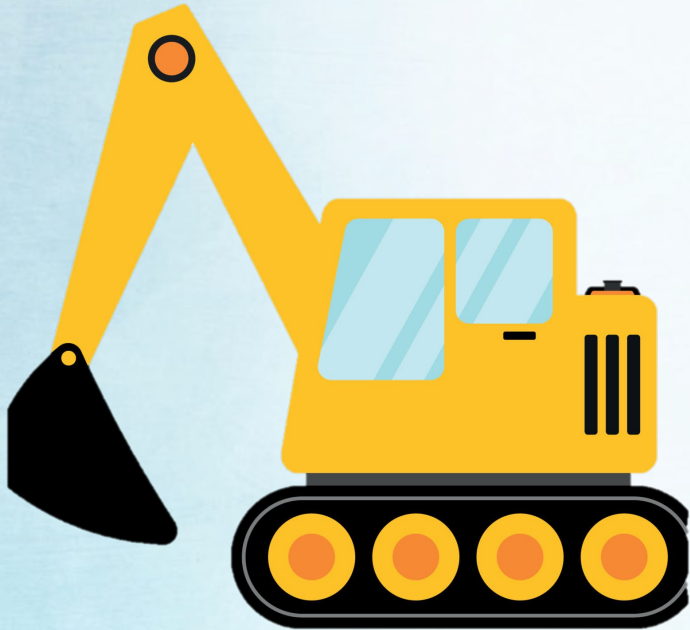
Tier 5 Rulemaking Workshop II  
October 31, 2023

# Concept Overview

Use *real-world off-road diesel* equipment data to quantify activity patterns & NOx emissions  
(*On-road emissions are based on real-world testing for 30+ years!*)

- **Current method:** no variation in engine load, one Emission Factor, and load factor based on equipment type grouping
- **New method:** reflects time and emissions at different engine loads, and load factor based on engine horsepower grouping

# Goals



To collect

- **Emissions in load bin** from PEMS units (simulated activity)
- **Activity/time in load bin** from data loggers during real-world equipment operation

To combine **emissions** and **activity** in load bin for

- **new composite NO<sub>x</sub> emission profiles**
- **new Load Factors**

# Data Logger and PEMS: Working Together

## Data Logger

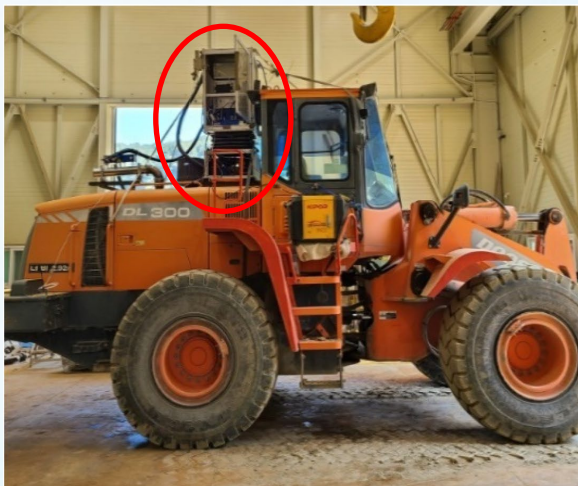
- Small, inexpensive, easy to install
- Captures months of real-world activity and load data, but no emissions data



Data Logger

## PEMS

- Large, difficult to install
- Each PEMS tested 4-8 hours of simulated activity
- Captures emissions at different loads, but very limited real world activity data



PEMS Units on Off-Road Equipment

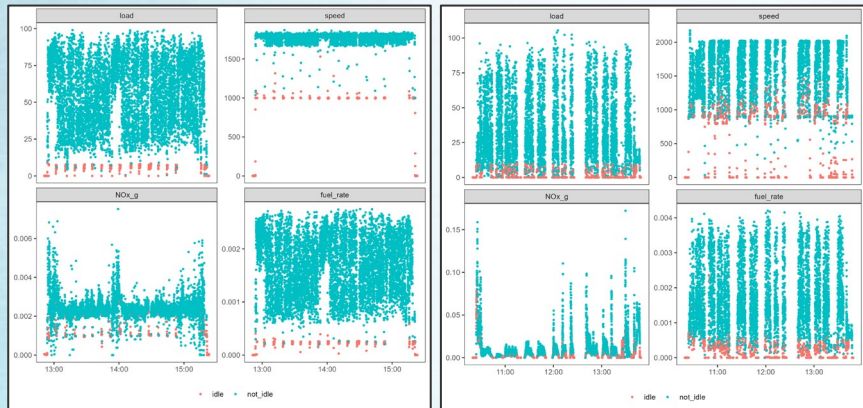
# Data Sets

Collection of Tier 2 – 4F Equipment

## Emissions: PEMS

➤ PEMS Test Duration: ~1 day simulated

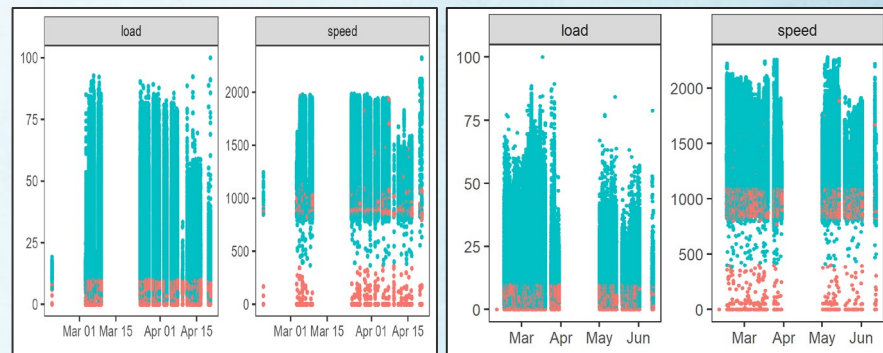
1. 2011 Construction (27 pieces)
2. 2019 Construction (23 pieces)



## Activity: HEM Data Loggers + PEMS

➤ Logger Test Duration: ~12 months real-world

1. 2022 Construction (64 pieces)
2. All PEMS data
3. (Next Steps) Ag Data Logging



# New Activity Groups

## Activity Groups

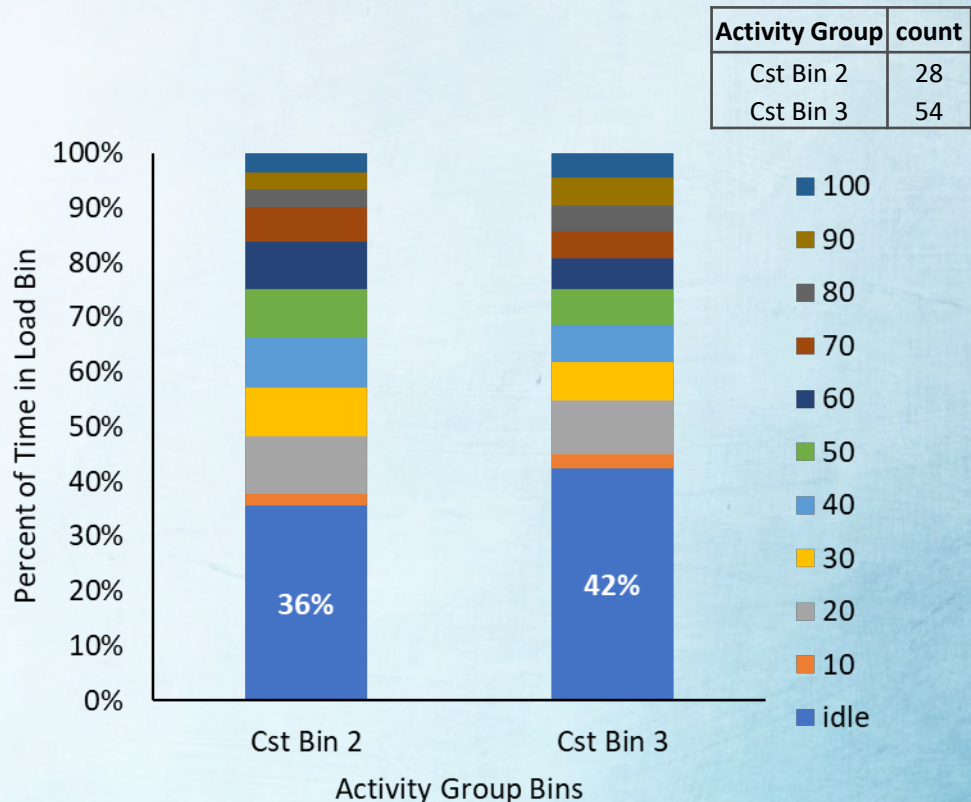
	0 to 74 hp (25, 50, 75 hp bin)*	75 to 174 hp (100, 175 hp bin)*	175+ hp (300, 600, 750 hp bin)*
Construction	Construction Bin 1	Construction Bin 2	Construction Bin 3
Potential for Agriculture (study in progress)	Ag Bin 1	Ag Bin 2	Ag Bin 3
+ Future Sectors (when available)	Bin 1	Bin 2	Bin 3

\*Groupings for all sectors are based on equipment profile analysis, which can be found in more detailed explanation in CARB's 2021 Agricultural Equipment Emission Inventory Technical Document

[https://ww2.arb.ca.gov/sites/default/files/2021-08/AG2021\\_Technical\\_Documentation\\_0.pdf](https://ww2.arb.ca.gov/sites/default/files/2021-08/AG2021_Technical_Documentation_0.pdf)

# Activity Only: Data Logging Time in Load Bin

- Combines all data sets: PEMS + HEM loggers
- New **Activity groups** based on *sector* and engine *horsepower*
- With additional testing, will add more sector-specific Activity group bins



# US EPA Off-Road Diesel Engine Standards

- Number of PEMS data points not sufficient to group by each Tier and horsepower bin
- Grouping similar NO<sub>x</sub> standards (g/bhp-hr) into new **NO<sub>x</sub> Groups**

		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015+
		7.8 / 6.0 / 0.75 (10.5 / 8.0 / 1.0)			5.6 / 6.0 / 0.60 (7.5 / 8.0 / 0.80)			5.6 / 6.0 / 0.30 <sup>a</sup> (7.5 / 8.0 / 0.40)									
		7.1 / 4.9 / 0.6 (9.5 / 6.6 / 0.80)			5.6 / 4.9 / 0.60 (7.5 / 6.6 / 0.80)			5.6 / 4.9 / 0.30 (7.5 / 6.6 / 0.40)									
50	≥ 25 (19) < 50 (37)	7.1 / 4.1 / 0.60 (9.5 / 5.5 / 0.80)			5.6 / 4.1 / 0.45 (7.5 / 5.5 / 0.60)			5.6 / 4.1 / 0.22 (7.5 / 5.5 / 0.30)				3.5 / 4.1 / 0.02 (4.7 / 5.5 / 0.03)					
75	≥ 50 (37) < 75 (56)	- / 6.9 / - / - <sup>b</sup> (- / 9.2 / - / -)			5.6 / 3.7 / 0.30 (7.5 / 5.0 / 0.40)			3.5 / 3.7 / 0.22 <sup>c</sup> (4.7 / 5.0 / 0.30)				3.5 / 3.7 / 0.02 <sup>c</sup> (4.7 / 5.0 / 0.03)					
100	≥ 75 (56) < 100 (75)							3.5 / 3.7 / 0.30 (4.7 / 5.0 / 0.40)				0.14 / 2.5 / 3.7 / 0.01 <sup>b,d</sup> (0.19 / 3.4 / 5.0 / 0.02)					
175	≥ 100 (75) < 175 (130)				4.9 / 3.7 / 0.22 (6.6 / 5.0 / 0.30)			3.0 / 3.7 / 0.22 (4.0 / 5.0 / 0.30)				0.14 (0.19) 0.30 (0.40) 3.7 (5.0) 0.01 <sup>b</sup> (0.02)					
300	≥ 175 (130) < 300 (225)				4.9 / 2.6 / 0.15 (6.6 / 3.5 / 0.20)							0.14 (0.19) 0.30 (0.40) 2.6 (3.5) 0.01 <sup>b</sup> (0.02)					
600	≥ 300 (225) < 600 (450)	1.0 / 6.9 / 8.5 / 0.40 <sup>b</sup> (1.3 / 9.2 / 11.4 / 0.54)			4.8 / 2.6 / 0.15 (6.4 / 3.5 / 0.20)			3.0 / 2.6 / 0.15 <sup>e</sup> (4.0 / 3.5 / 0.20)				0.14 / 1.5 / 2.6 / 0.01 <sup>b,d</sup> (0.19 / 2.0 / 3.5 / 0.02)					
750	≥ 600 (450) < 750 (560)																



# New NOx Groupings

based on engine standards

NOx Description	NOx Group	NOx Standard (g/bhp-hr)	NOx Standard (g/kw-hr)
Tier 0	NOx01	15	20.12
Tier 1 - Over 50 Hp	NOx02	6.9	9.25
Tier 1 - Under 11 Hp	NOx03	7.8	10.46
Tier 1 - 11 to 50 Hp	NOx04	7.1	9.52
Tier 2 - Over 300 Hp	NOx05	4.8	6.44
Tier 2 - 101 to 300 Hp	NOx06	4.9	6.57
Tier2.3.4i.4f - Under 100 Hp	NOx07	5.6	7.51
Tier3 -101 to 750 Hp	NOx08	3.0	4.02
Tier3.4i.4F - 101 to 750 Hp	NOx09	3.5	4.69
Tier4i - 176 to 750 Hp	NOx10	1.5	2.01
Tier4i - Over 750 Hp	NOx11	2.6	3.49
Tier4i - 76 to 175 Hp	NOx12	2.5	3.35
Tier4F - 76 to 750 Hp	NOx13	0.3	0.40

# New NOx Groups

## By Tier

HpBin	HP	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016+	
11	<11	0	0	0	0	0	1	1	1	1	1	2	2	2	4F	4F	4F	4F	4F	4F	4F	4F	4F	4F
25	11 to 24	0	0	0	0	0	1	1	1	1	1	2	2	2	4F	4F	4F	4F	4F	4F	4F	4F	4F	4F
50	25 to 49	0	0	0	0	1	1	1	1	1	2	2	2	2	4i	4i	4i	4i	4i	4i	4F	4F	4F	4F
75	50 to 74	0	0	0	1	1	1	1	1	1	2	2	2	2	4i	4i	4i	4i	4i	4i	4F	4F	4F	4F
100	75 to 99	0	0	0	1	1	1	1	1	1	2	2	2	2	3	3	3	3	3	4i	4i	4i	4F	4F
175	100 to 174	0	0	1	1	1	1	1	1	1	2	2	2	2	3	3	3	3	3	4i	4i	4i	4F	4F
300	175 to 299	0	1	1	1	1	1	1	1	1	2	2	2	2	3	3	3	3	3	4i	4i	4i	4F	4F
600	300 to 599	0	1	1	1	1	1	1	2	2	2	2	2	2	3	3	3	3	3	4i	4i	4i	4F	4F
750	600 to 750	0	1	1	1	1	1	1	2	2	2	2	2	2	3	3	3	3	3	4i	4i	4i	4F	4F

## By NOx Group

HpBin	HP	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016+	
11	<11	NOx01	NOx01	NOx01	NOx01	NOx01	NOx03	NOx03	NOx03	NOx03	NOx03	NOx07	NOx07	NOx07	NOx07	NOx07	NOx07	NOx07	NOx07	NOx07	NOx07	NOx07	NOx07	NOx07
25	11 to 24	NOx01	NOx01	NOx01	NOx01	NOx01	NOx04	NOx04	NOx04	NOx04	NOx04	NOx07	NOx07	NOx07	NOx07	NOx07	NOx07	NOx07	NOx07	NOx07	NOx07	NOx07	NOx07	NOx07
50	25 to 49	NOx01	NOx01	NOx01	NOx01	NOx01	NOx04	NOx04	NOx04	NOx04	NOx07	NOx07	NOx07	NOx07	NOx07	NOx07	NOx07	NOx07	NOx07	NOx07	NOx09	NOx09	NOx09	NOx09
75	50 to 74	NOx01	NOx01	NOx01	NOx01	NOx01	NOx02	NOx02	NOx02	NOx02	NOx07	NOx07	NOx07	NOx07	NOx07	NOx09	NOx09	NOx09	NOx09	NOx09	NOx09	NOx09	NOx09	NOx09
100	75 to 99	NOx01	NOx01	NOx01	NOx01	NOx01	NOx02	NOx02	NOx02	NOx02	NOx07	NOx07	NOx07	NOx07	NOx07	NOx09	NOx09	NOx09	NOx09	NOx09	NOx12	NOx12	NOx12	NOx13
175	100 to 174	NOx01	NOx01	NOx01	NOx01	NOx01	NOx02	NOx02	NOx02	NOx06	NOx06	NOx06	NOx06	NOx08	NOx08	NOx08	NOx08	NOx08	NOx08	NOx08	NOx12	NOx12	NOx12	NOx13
300	175 to 299	NOx01	NOx02	NOx02	NOx02	NOx02	NOx02	NOx02	NOx02	NOx06	NOx06	NOx06	NOx08	NOx08	NOx08	NOx08	NOx08	NOx08	NOx08	NOx10	NOx10	NOx10	NOx13	NOx13
600	300 to 599	NOx01	NOx02	NOx02	NOx02	NOx02	NOx02	NOx05	NOx05	NOx05	NOx05	NOx05	NOx08	NOx08	NOx08	NOx08	NOx08	NOx08	NOx08	NOx10	NOx10	NOx10	NOx13	NOx13
750	600 to 750	NOx01	NOx02	NOx02	NOx02	NOx02	NOx02	NOx02	NOx05	NOx05	NOx05	NOx05	NOx08	NOx08	NOx08	NOx08	NOx08	NOx08	NOx08	NOx10	NOx10	NOx10	NOx13	NOx13

# New NOx Emissions: Activity & NOx Groups

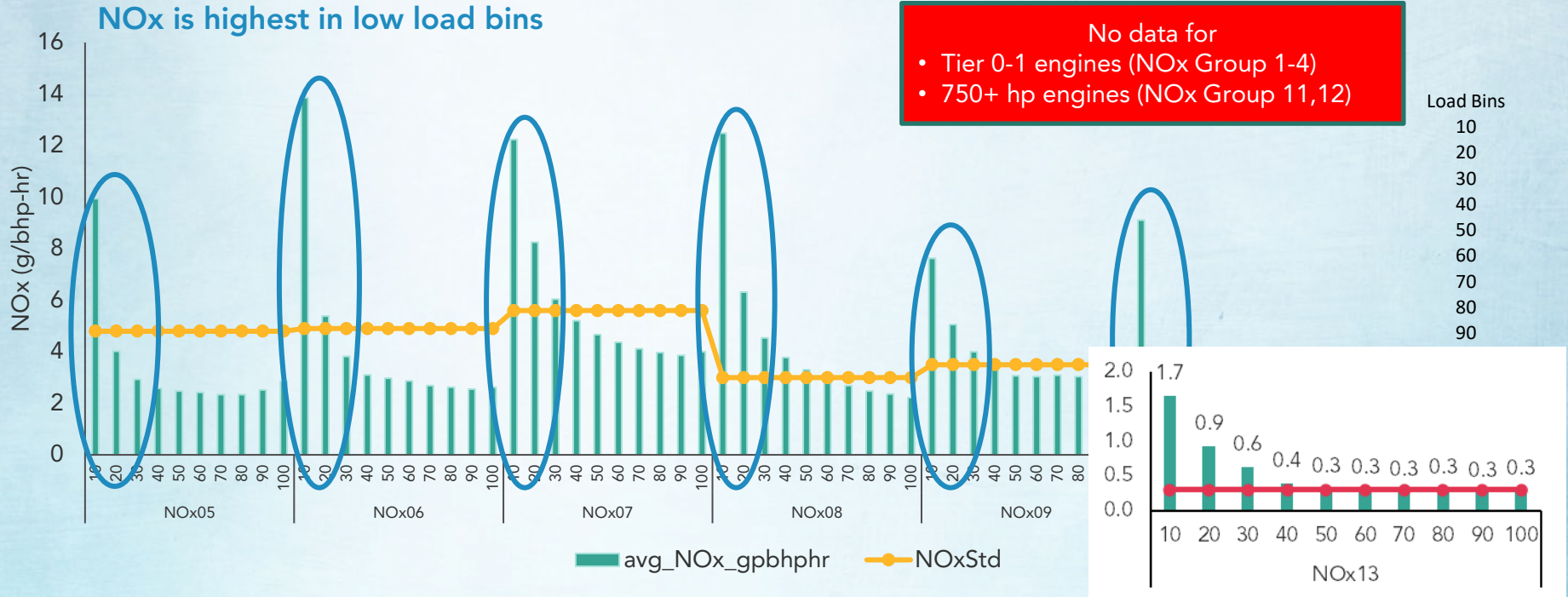
	HpBin	HP	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016+
Activity Bin 1	11	<11	NOx01	NOx01	NOx01	NOx01	NOx01	NOx03	NOx03	NOx03	NOx03	NOx03	NOx07	NOx07	NOx07	NOx07	NOx07	NOx07	NOx07	NOx07	NOx07	NOx07	NOx07	NOx07
	25	11 to 24	NOx01	NOx01	NOx01	NOx01	NOx01	NOx04	NOx04	NOx04	NOx04	NOx04	NOx07	NOx07	NOx07	NOx07	NOx07	NOx07	NOx07	NOx07	NOx07	NOx07	NOx07	NOx07
	50	25 to 49	NOx01	NOx01	NOx01	NOx01	NOx01	NOx04	NOx04	NOx04	NOx04	NOx04	NOx07	NOx07	NOx07	NOx07	NOx07	NOx07	NOx07	NOx07	NOx07	NOx09	NOx09	NOx09
Activity Bin 2	75	50 to 74	NOx01	NOx01	NOx01	NOx01	NOx01	NOx02	NOx02	NOx02	NOx02	NOx07	NOx07	NOx07	NOx07	NOx07	NOx09	NOx09	NOx09	NOx09	NOx09	NOx09	NOx09	NOx09
	100	75 to 99	NOx01	NOx01	NOx01	NOx01	NOx01	NOx02	NOx02	NOx02	NOx02	NOx07	NOx07	NOx07	NOx07	NOx07	NOx09	NOx09	NOx09	NOx09	NOx09	NOx12	NOx12	NOx12
	175	100 to 174	NOx01	NOx01	NOx01	NOx01	NOx01	NOx02	NOx02	NOx02	NOx06	NOx06	NOx06	NOx06	NOx08	NOx08	NOx08	NOx08	NOx08	NOx08	NOx12	NOx12	NOx12	NOx13
Activity Bin 3	300	175 to 299	NOx01	NOx02	NOx02	NOx02	NOx02	NOx02	NOx02	NOx02	NOx06	NOx06	NOx06	NOx08	NOx08	NOx08	NOx08	NOx08	NOx08	NOx10	NOx10	NOx10	NOx13	NOx13
	600	300 to 599	NOx01	NOx02	NOx02	NOx02	NOx02	NOx02	NOx05	NOx05	NOx05	NOx05	NOx05	NOx08	NOx08	NOx08	NOx08	NOx08	NOx08	NOx10	NOx10	NOx10	NOx13	NOx13
	750	600 to 750	NOx01	NOx02	NOx02	NOx02	NOx02	NOx02	NOx05	NOx05	NOx05	NOx05	NOx05	NOx08	NOx08	NOx08	NOx08	NOx08	NOx08	NOx10	NOx10	NOx10	NOx13	NOx13

## New NOx Emission Calculations based on:

- **Activity Group & NOx Group**
  - 22 combinations
- Each grouping has **Idle** (1 load bin) & **Non-Idle** (10 load bins)

NOx Group	Activity Group
NOx01	Bin 1
NOx02	Bin 1
NOx03	Bin 1
NOx04	Bin 1
NOx07	Bin 1
NOx09	Bin 1
NOx01	Bin 2
NOx02	Bin 2
NOx06	Bin 2
NOx07	Bin 2
NOx08	Bin 2
NOx09	Bin 2
NOx12	Bin 2
NOx13	Bin 2
NOx01	Bin 3
NOx02	Bin 3
NOx05	Bin 3
NOx06	Bin 3
NOx08	Bin 3
NOx10	Bin 3
NOx11	Bin 3
NOx13	Bin 3

# NOx Emissions (g/bhp-hr) in Load Bin



# Visualization of Goals (Example Only)

**Old Method (example)**

- Assume 100% of activity uses these values
- NOx Emission Factor: 2.3 g/bhp-hr
- Average Load: 0.48

**New Method (composite NOx)**

Using data loggers & PEMS:

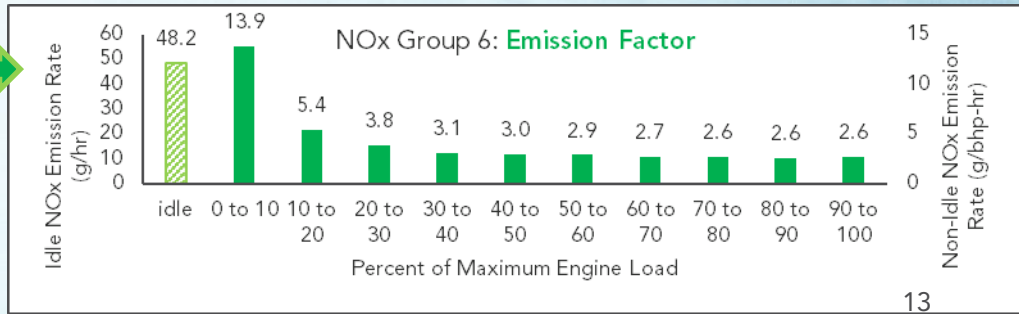
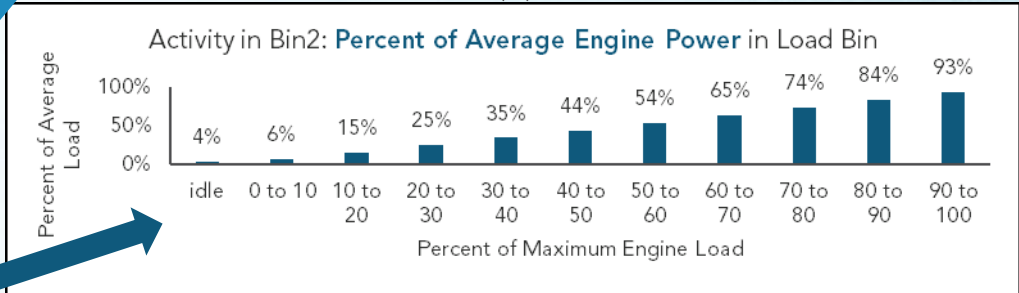
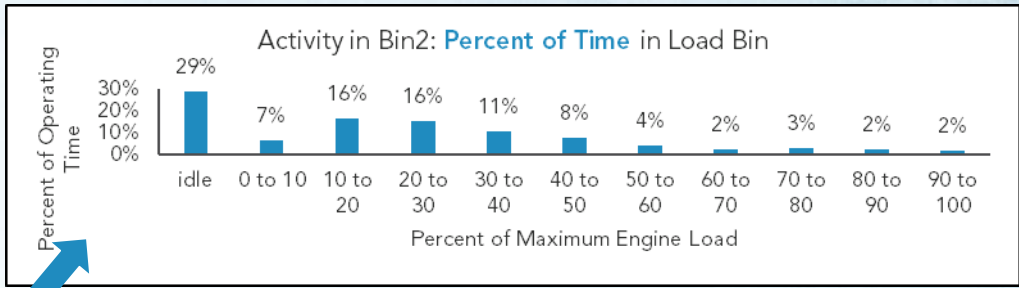
- Split activity time by load (**Activity Group**)
- Find average power by load (**Average Load**)

Using PEMS:

- Find NOx emission rate (**NOx Group**)

**New NOx EF:**

$$[\text{Time in Load Bin}] \times [\text{Power in Load Bin}] \times [\text{Emission Factor in Load Bin}]$$



# New Method for Calculating NOx Emissions

$$\text{New NOx} \left( \frac{\text{tons}}{\text{day}} \right) = \{ \text{NOx Emissions}_{\text{idle}} \left( \frac{\text{tons}}{\text{day}} \right) + \text{NOx Emissions}_{\text{non-idle}} \left( \frac{\text{tons}}{\text{day}} \right) \} \times \text{Population}$$

where:

$$\text{NOx Emissions}_{\text{idle}} \left( \frac{\text{tons}}{\text{day}} \right) = \text{ActivityID}_{\text{idle}} (\% \text{time}) \times \text{NOxID}_{\text{idle}} \left( \frac{\text{g}}{\text{hr}} \right) \times \frac{\text{Annual hours}}{\text{yr}} \times \text{UnitConversion}$$

$$\text{NOx Emissions}_{\text{non-idle}} \left( \frac{\text{tons}}{\text{day}} \right) = \left[ \sum_{i = \text{load bin}} \text{ActivityID}_i (\% \text{time}) \times \text{NOxID}_i \left( \frac{\text{g}}{\text{bhphr}} \right) \times \text{AvgLoad}_i (\text{unitless}) \right] \times \frac{\text{Annual hours}}{\text{yr}} \times \text{EngineHp} (\text{hp}) \times \text{UnitConversion}$$

$$\text{UnitConversion} = \frac{1 \text{ lb}}{453.6 \text{ g}} \times \frac{1 \text{ ton}}{2000 \text{ lb}} \times \frac{1 \text{ yr}}{365 \text{ day}}$$

Emission factors are the emissions level that engines produce, usually measured in grams per unit of work.

# Emission Inventory Analysis of Data Loggers for Idling Periods

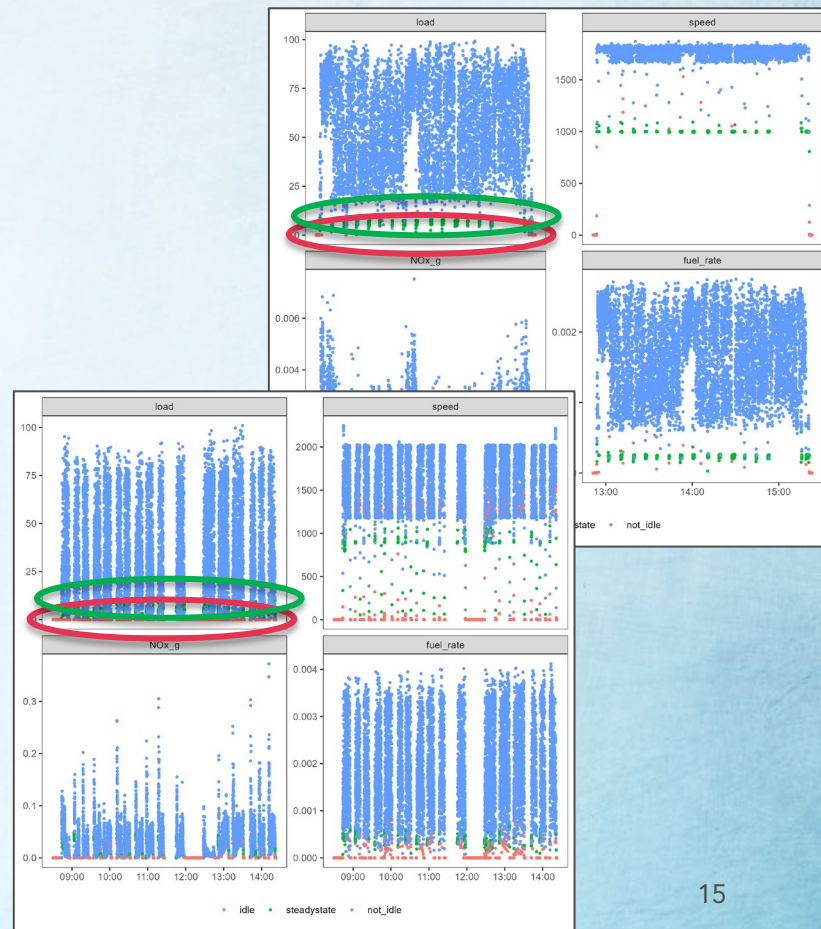
Idling: **Load = 0**

-or-

Steady State Idling

1. Assign **15-second** groupings
2. Calculate **avg speed (engine rpm)** in each grouping
3. Look at **ratio** of individual speed (engine rpm) to avg speed in grouping
4. If **ratio  $\leq$  5%** & **speed  $\leq$  1100 rpm**  
➔ **steadystate idling**

\*\* Idling NOx is measured in grams/hour, not grams/horsepower-hour



# Proposed Tier 5 NOx Groupings

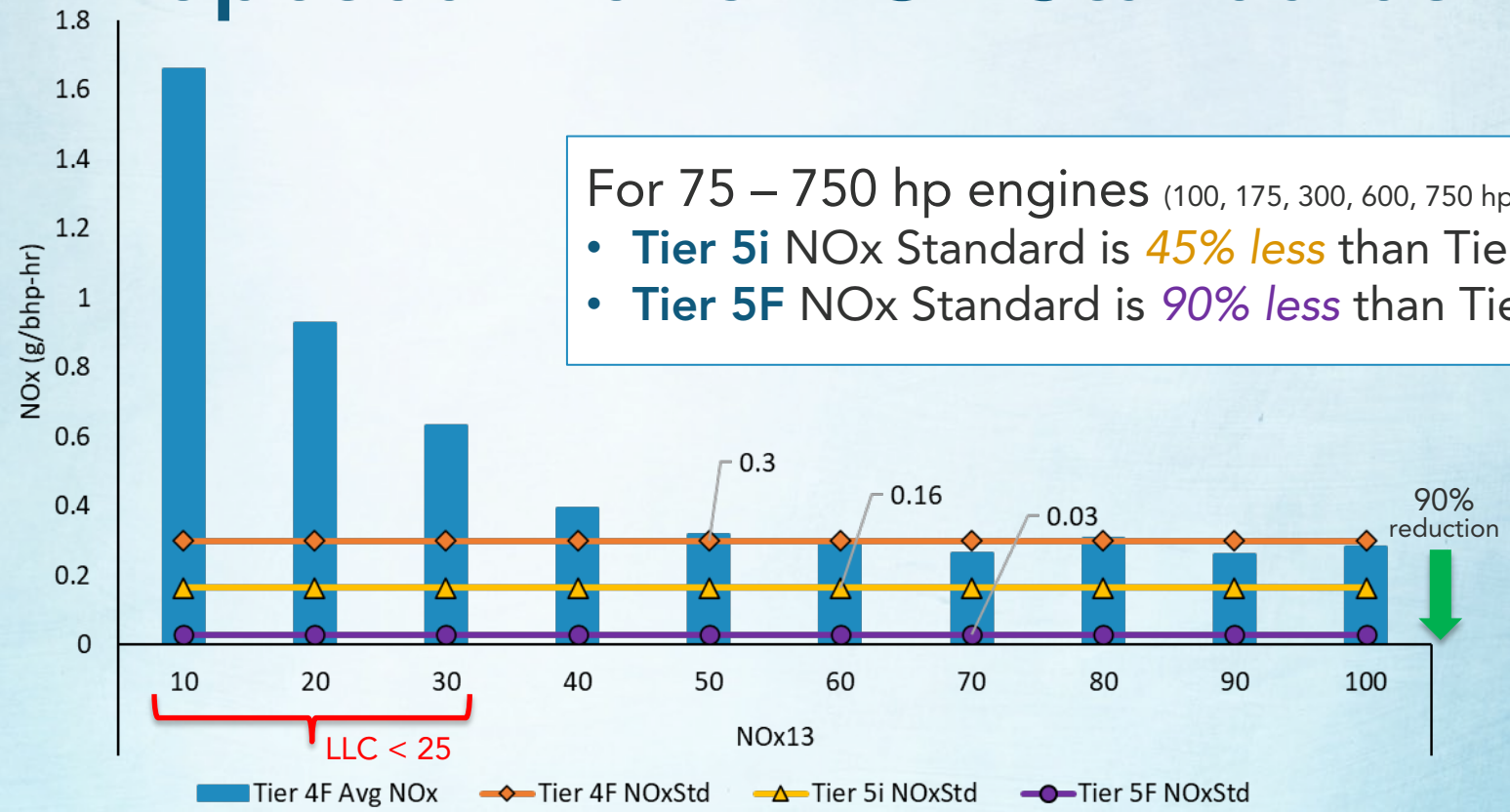
HP Description	HP Bin	Proposed T5i NOx Standard (g/bhp-hr)	Proposed T5F NOx Standard (g/bhp-hr)	Proposed Estimated Reduction from T4F to T5i	Proposed Estimated Reduction from T4F to T5F
<11	25	4.47	3.73	16%	30%
11 to 24	25	4.10	2.98	23%	44%
25 to 74	50, 75	2.76	1.86	17%	44%
75 to 750 *LLC	100, 175, 300, 600, 750	0.16	0.03	45%	90%
750+ Mobile Machines	750+	2.61	2.24	0%	14%
750+ GenSets	750+	0.37	0.26	25%	48%

Low Load Cycle (LLC)  
applied when load < 25%

This analysis will be used to quantify Tier 5 impacts



# Proposed Tier 5 NOx Standards

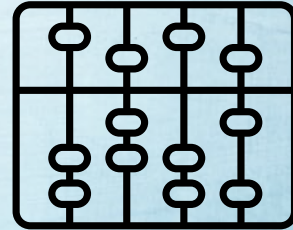


# Impacts of this Analysis

- First time quantifying:
  - *Idle* vs *non-idle* NOx emissions
  - *Low-load* engine cycles
- Will be able to model low-load cycles in off-road diesel emission inventories
- Quantify potential Tier 5 impacts

## Next Steps

- Completion of ag data logging contract
- Further discussion with industry
- Update additional pollutants when data becomes available (likely after Tier 5 rulemaking)



# Questions, Comments, Feedback

**Deadline for Comments: November 30, 2023**

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