



# New NO<sub>x</sub> Emission Factors for Off-road Diesel Engines *based on real-world engine testing*

CRC Real World Emissions Workshop

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# Concept Overview

**Goal:** To update and refine *off-road diesel emission inventories* using *real-world* engine test data  
(*On-road emissions have been 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

# Two-Part Analysis

## Data collected includes:

- 1. Emissions in load bin** from PEMS units on **50 pieces** of off-road equipment  
(same engine families, testing was simulated to represent real-world conditions)
- 2. Activity/time in load bin** from HEM data loggers on **156 pieces** of off-road equipment during real-world equipment operation  
(plus activity data from 50 PEMS units)



PEMS

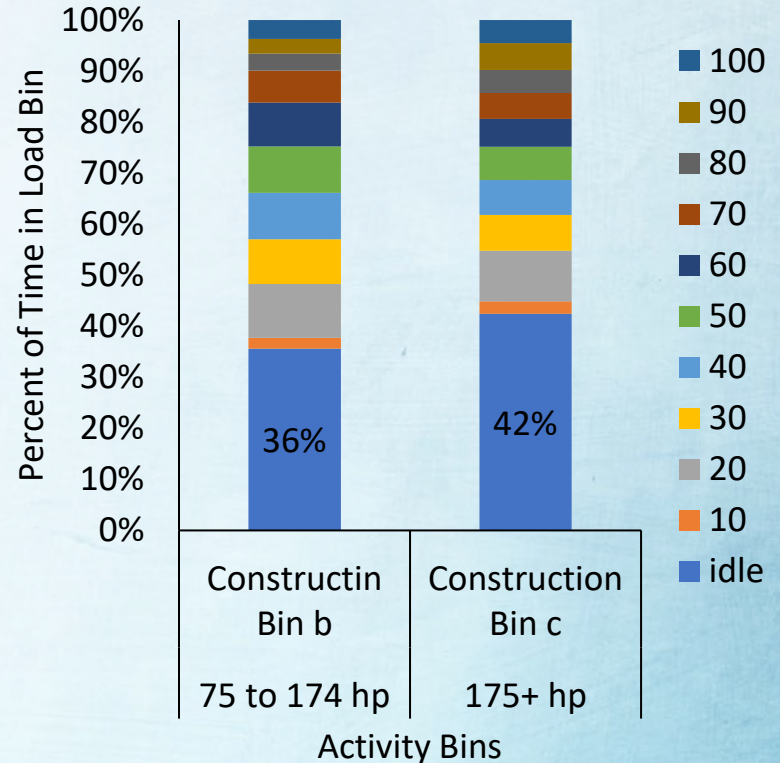


HEM Data Logger

# Activity Groups: Time in Load Bin

- HEM logger data + PEMS data
- Bins specific to engine *horsepower*
- Horsepower groupings are based on equipment profiles analysis from CARB's 2021 Agricultural Emission Inventory

	0 to 74 hp (25, 50, 75 hp bin)	75 to 174 hp (100, 175 hp bin)	175+ hp (300, 600, 750 hp bin)
Off-road Sector	Bin a	Bin b	Bin c



# US EPA Off-Road Diesel Engine Standards

- Number of PEMS data points not sufficient to group by each Tier and horsepower bin
- Grouping similar NOx standards (g/bhp-hr) into new NOx Groups

		2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015+
100	< 75 (56)													
	≥ 75 (56) < 100 (75)			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)			
175	≥ 100 (75) < 175 (130)			5.6 / 4.9 / 0.60 (7.5 / 6.6 / 0.80)							5.6 / 4.9 / 0.30 (7.5 / 6.6 / 0.40)			
				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)		
300	≥ 175 (130) < 300 (225)			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)		
									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)		0.14 (0.19) 0.30 (0.40) 3.7 (5.0) 0.01 <sup>b</sup> (0.02)	
600	≥ 300 (225) < 600 (450)			4.9 / 3.7 / 0.22 (6.6 / 5.0 / 0.30)						3.0 / 3.7 / 0.22 (4.0 / 5.0 / 0.30)				
				4.9 / 2.6 / 0.15 (6.6 / 3.5 / 0.20)										
750	≥ 600 (450) < 750 (560)			1.0 / 6.9 / 8.5 / 0.40 <sup>b</sup> (1.3 / 9.2 / 11.4 / 0.54)						3.0 / 2.6 / 0.15 <sup>c</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)		0.14 (0.19) 0.30 (0.40) 2.6 (3.5) 0.01 <sup>b</sup> (0.02)



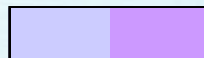
: Tier 1



: Tier 2



: Tier 3



: Tier 4 Interim / Final

# 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 49 Hp	NOx04	7.1	9.52
Tier 2 - Over 300 Hp	NOx05	4.8	6.44
Tier 2 - 100 to 299 Hp	NOx06	4.9	6.57
Tier 2.4i.4F - Under 100 Hp	NOx07	5.6	7.51
Tier 3 -100 to 750 Hp	NOx08	3.0	4.02
Tier 3.4i.4F - 25 to 99 Hp	NOx09	3.5	4.69
Tier 4i - 175 to 750 Hp	NOx10	1.5	2.01
Tier 4i - Over 750 Hp	NOx11	2.6	3.49
Tier 4i - 75 to 174 Hp	NOx12	2.5	3.35
Tier 4F - 76 to 750 Hp	NOx13	0.3	0.40

# New NOx Emissions Groups

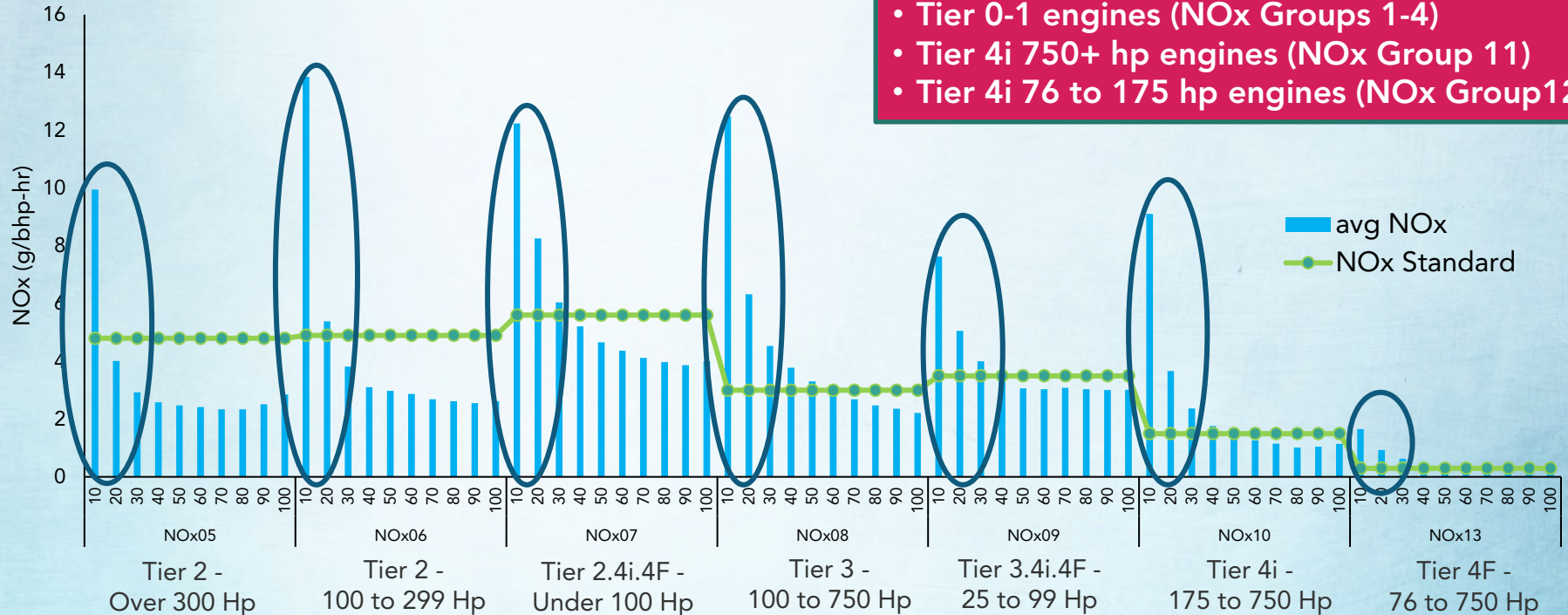
New NOx Emission Calculations based on:

- Activity Group
- NOx Group
- Idle & Non-Idle Bins

HP Bin	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	<b>Activity Bin a</b>			NOx04	NOx04	NOx04	NOx04	NOx07	NOx07	NOx07	NOx07	NOx07	NOx07	NOx07	NOx07	NOx07	NOx09	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	<b>Activity Bin b</b>			NOx02	NOx02	NOx02	NOx02	NOx07	NOx07	NOx07	NOx07	NOx07	NOx09	NOx09	NOx09	NOx09	NOx12	NOx12	NOx12	NOx13	NOx13
175	100 to 174	NOx01	NOx01	<b>Activity Bin b</b>			NOx02	NOx02	NOx02	NOx06	NOx06	NOx06	NOx06	NOx08	NOx08	NOx08	NOx08	NOx08	NOx08	NOx12	NOx12	NOx12	NOx13	NOx13
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	NOx13
600	300 to 599	NOx01	NOx02	<b>Activity Bin c</b>			NOx02	NOx05	NOx05	NOx05	NOx05	NOx05	NOx08	NOx08	NOx08	NOx08	NOx08	NOx08	NOx10	NOx10	NOx10	NOx13	NOx13	NOx13
750	600 to 750	NOx01	NOx02	NOx02	NOx02	NOx02	NOx02	NOx02	NOx05	NOx05	NOx05	NOx05	NOx08	NOx08	NOx08	NOx08	NOx08	NOx10	NOx10	NOx10	NOx13	NOx13	NOx13	NOx13
9999	750 +	NOx01	NOx01	NOx01	NOx01	NOx01	NOx02	NOx02	NOx02	NOx02	NOx02	NOx02	NOx05	NOx05	NOx05	NOx05	NOx05	NOx11	NOx11	NOx11	NOx11	NOx11	NOx11	NOx11

# NOx Emissions by Load Bin

**Finding:** NOx emissions are higher at low loads across all horsepower groups



No data for

- Tier 0-1 engines (NOx Groups 1-4)
- Tier 4i 750+ hp engines (NOx Group 11)
- Tier 4i 76 to 175 hp engines (NOx Group 12)



# Emission Inventory Analysis of Data Loggers for Idling Periods

Idling: Load = 0

-or-

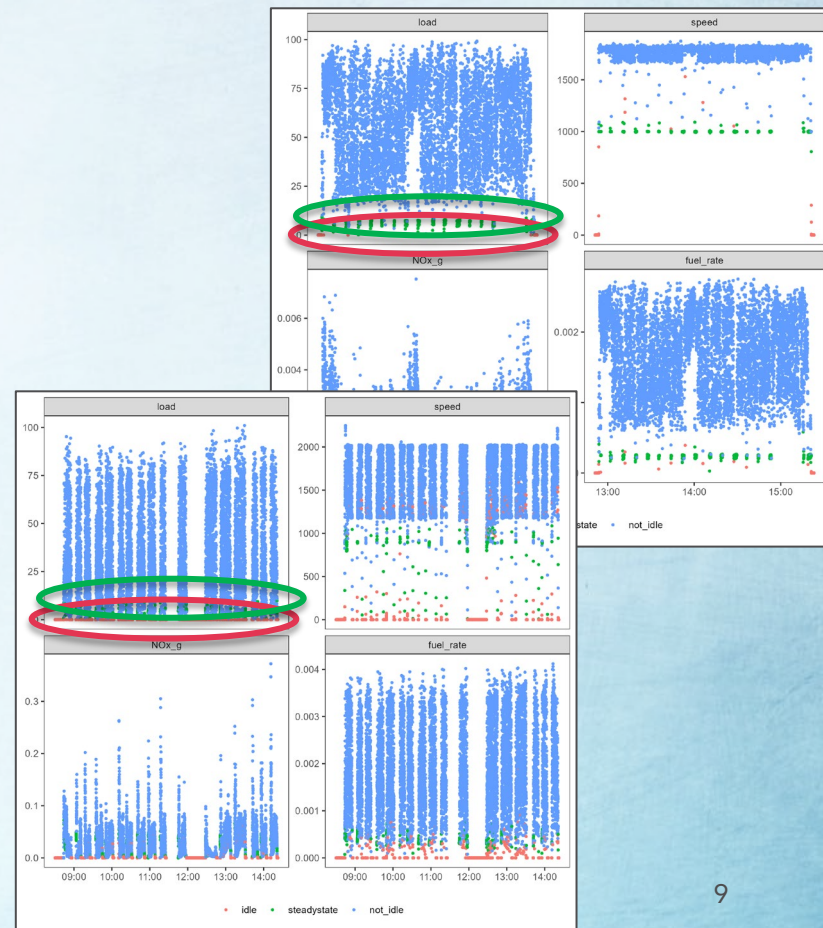
Steady State Idling

1. Calculate **average speed (engine rpm)** in **15-second** groupings
2. Look at the ratio of instantaneous speed to average speed

If  $\frac{\text{speed}}{\text{avg speed}} \leq 5\%$  AND  $\text{speed} \leq 1100 \text{ rpm}$

➔ **steadystate idling**

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



# Process Visualization (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

### Using HEMS & PEMS:

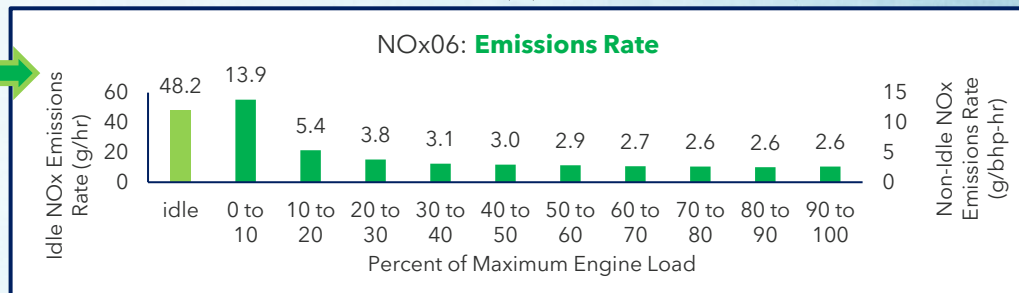
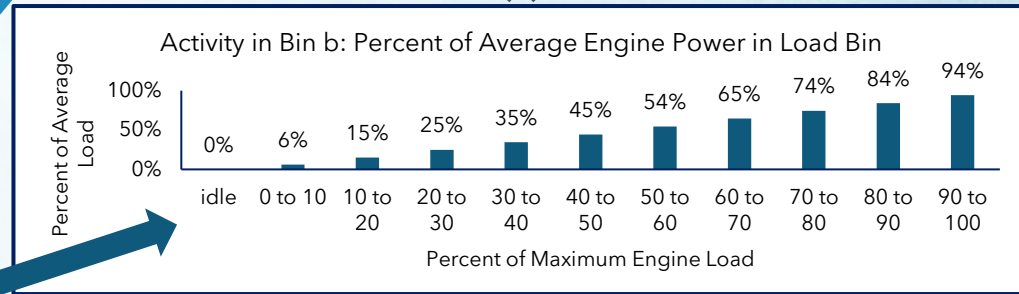
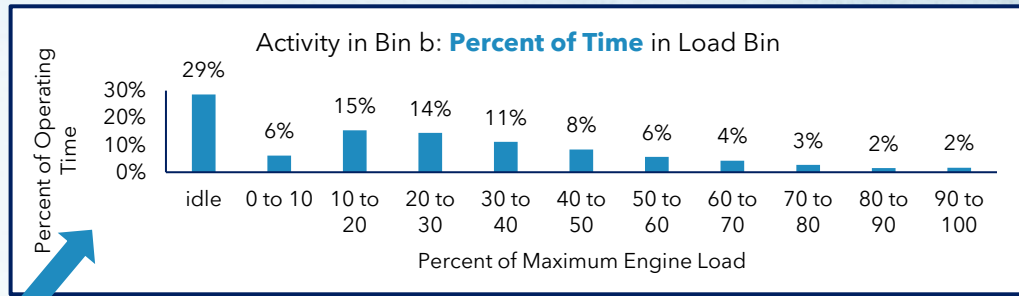
- Activity time by load (**Activity Group**)
- Find average power by load (**Average Load**)

### Using PEMS:

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

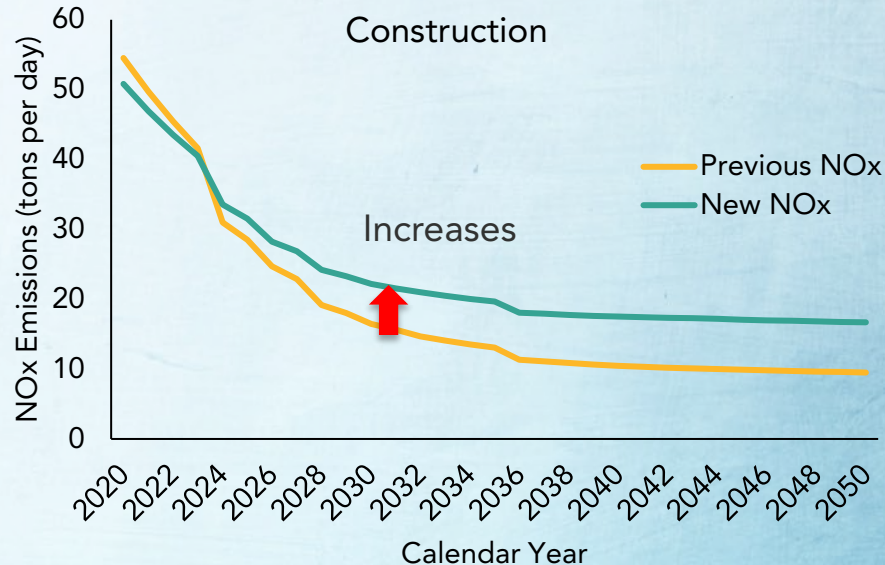
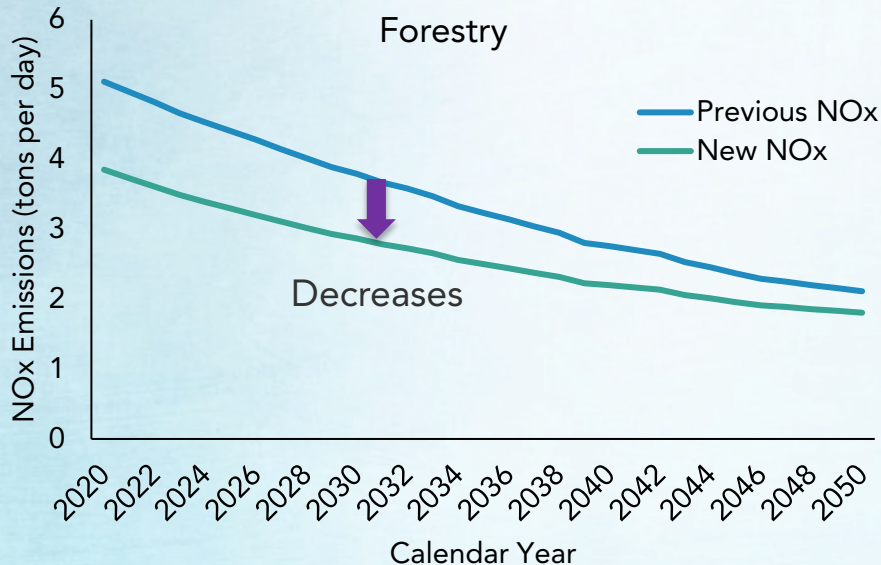
### New NOx EF:

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



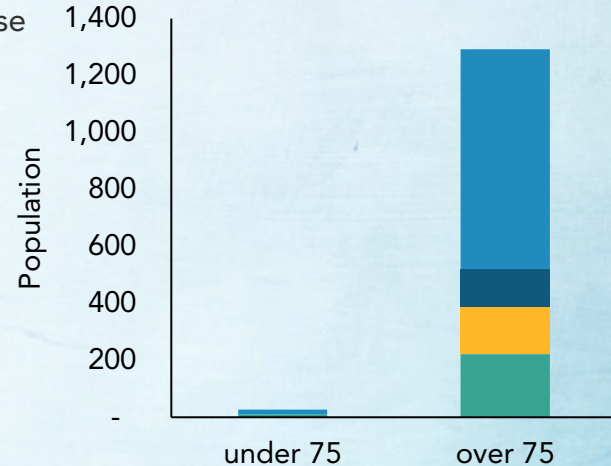
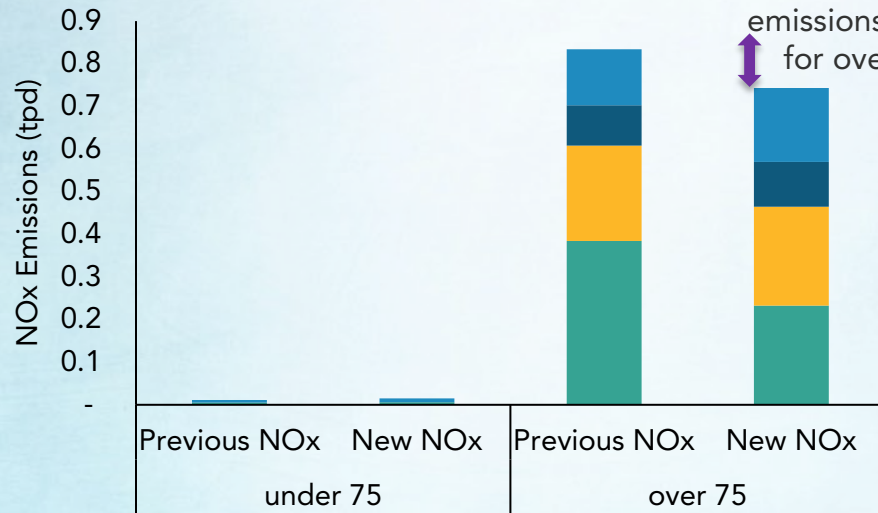
# Preliminary Results

- Overall impact on off-road emission inventories is still *under evaluation*
- With updated NOx methodology, inventories show opposite trends depending on the equipment within the sector



# Forestry Emissions: Comparison

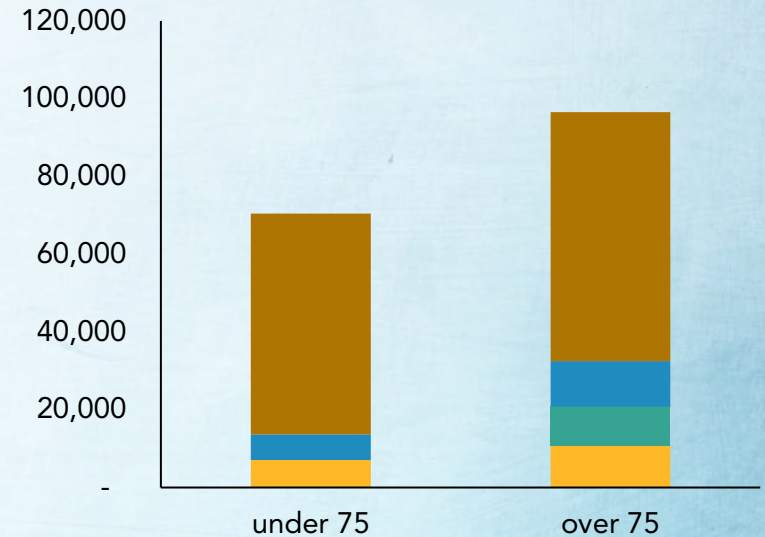
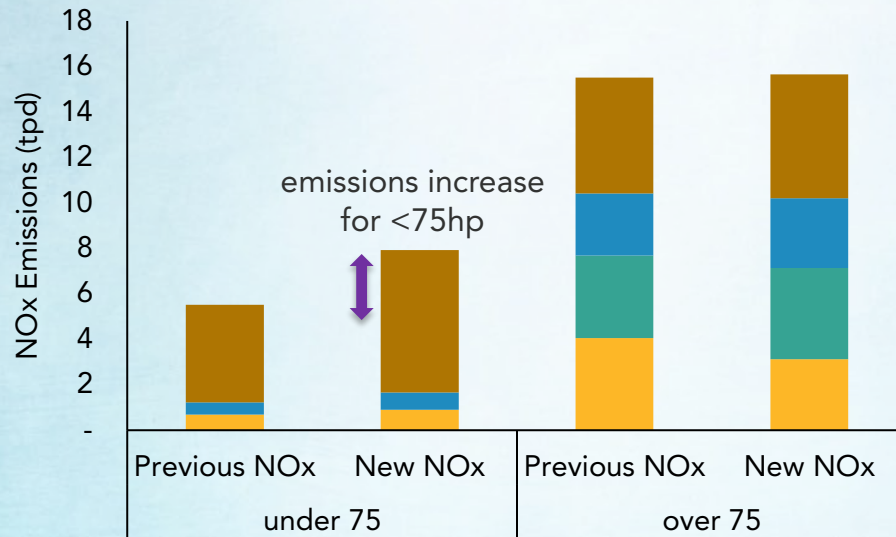
- Majority of equipment is over 75 hp
- Over 75 hp equipment emissions decrease, indicating larger equipment is cleaner than expected
- Overall NOx emissions **decrease** with the new methodology



■ tier2 ■ tier3 ■ tier4i ■ tier4F

# Construction Emissions: Comparison

- Large population of under 75 hp engines
- Under 75 hp emissions increase, while over 75 hp emissions are similar
- Overall NOx emissions **increase** with the new methodology

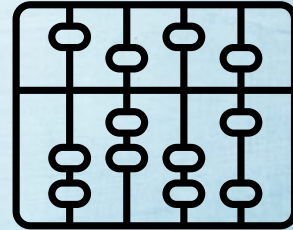


# Impacts of this Analysis

- 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

- Incorporate methodology into off-road emission inventories
- Update additional pollutants when data becomes available



# Thank you

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**Many thanks with all the data collection efforts:**

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