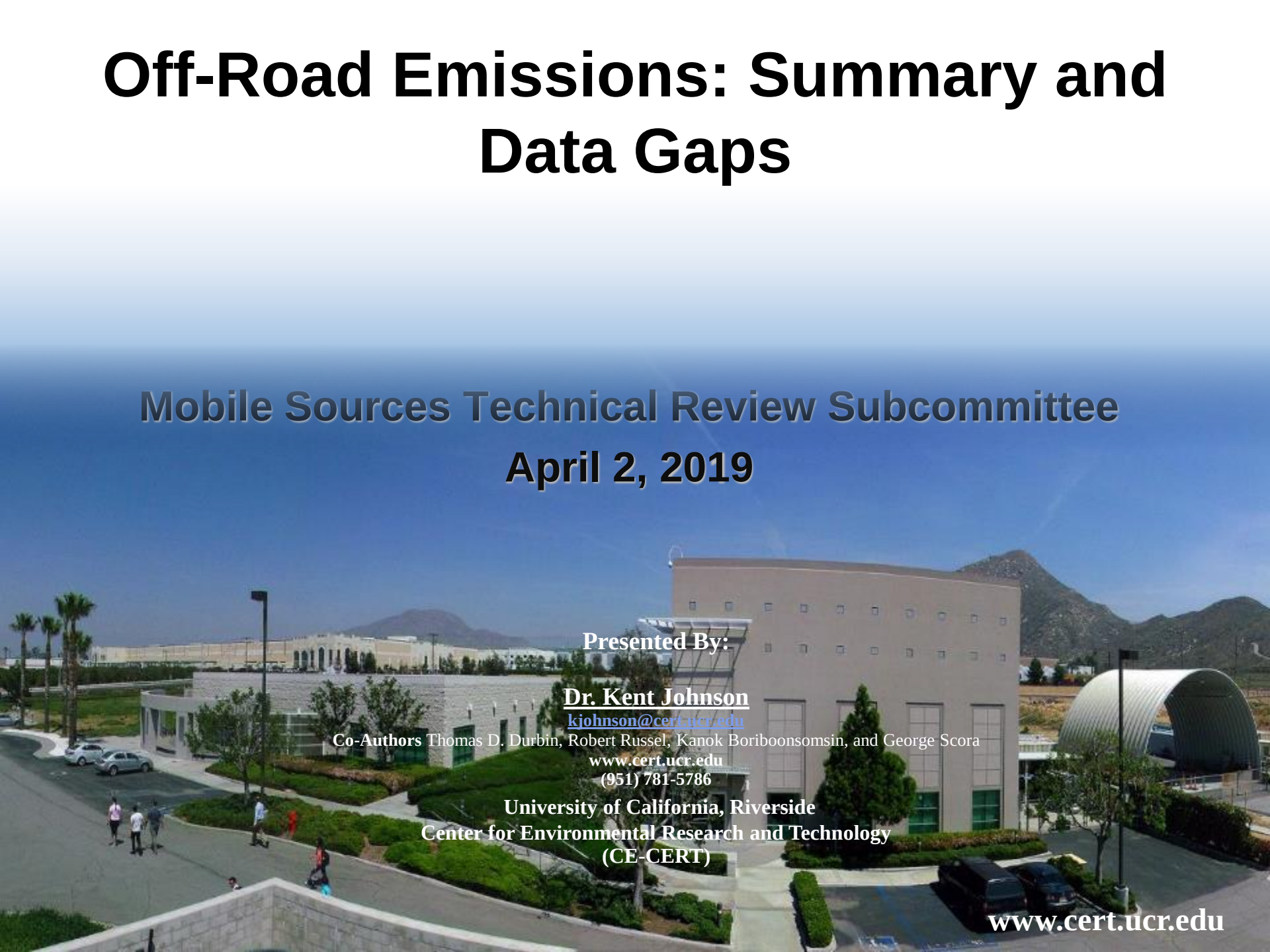
Off-Road Emissions: Summary and Data Gaps

Mobile Sources Technical Review Subcommittee

April 2, 2019



Presented By:

Dr. Kent Johnson
kjohnson@cert.ucr.edu
Co-Authors Thomas D. Durbin, Robert Russel, Kanok Boriboonsomsin, and George Scora
www.cert.ucr.edu
(951) 781-5786
University of California, Riverside
Center for Environmental Research and Technology
(CE-CERT)

Past Projects (114 units tested)

• **2001**	EPA Activity	18 units [1]	Loggers
• **2006**	Caltrans	12 units	PEMS [2]
• **2006**	Port of LA/LB	2 cranes	MEL
• **2012**	Caltrans/CARB	27 units	PEMS/PAMS
• **2013**	CARB/AQIP	5 units	PEMS/PAMS/Video
• **2013**	Caltrans	5 units	PEMS
• **2013**	Caltrans	45 units	PAMS

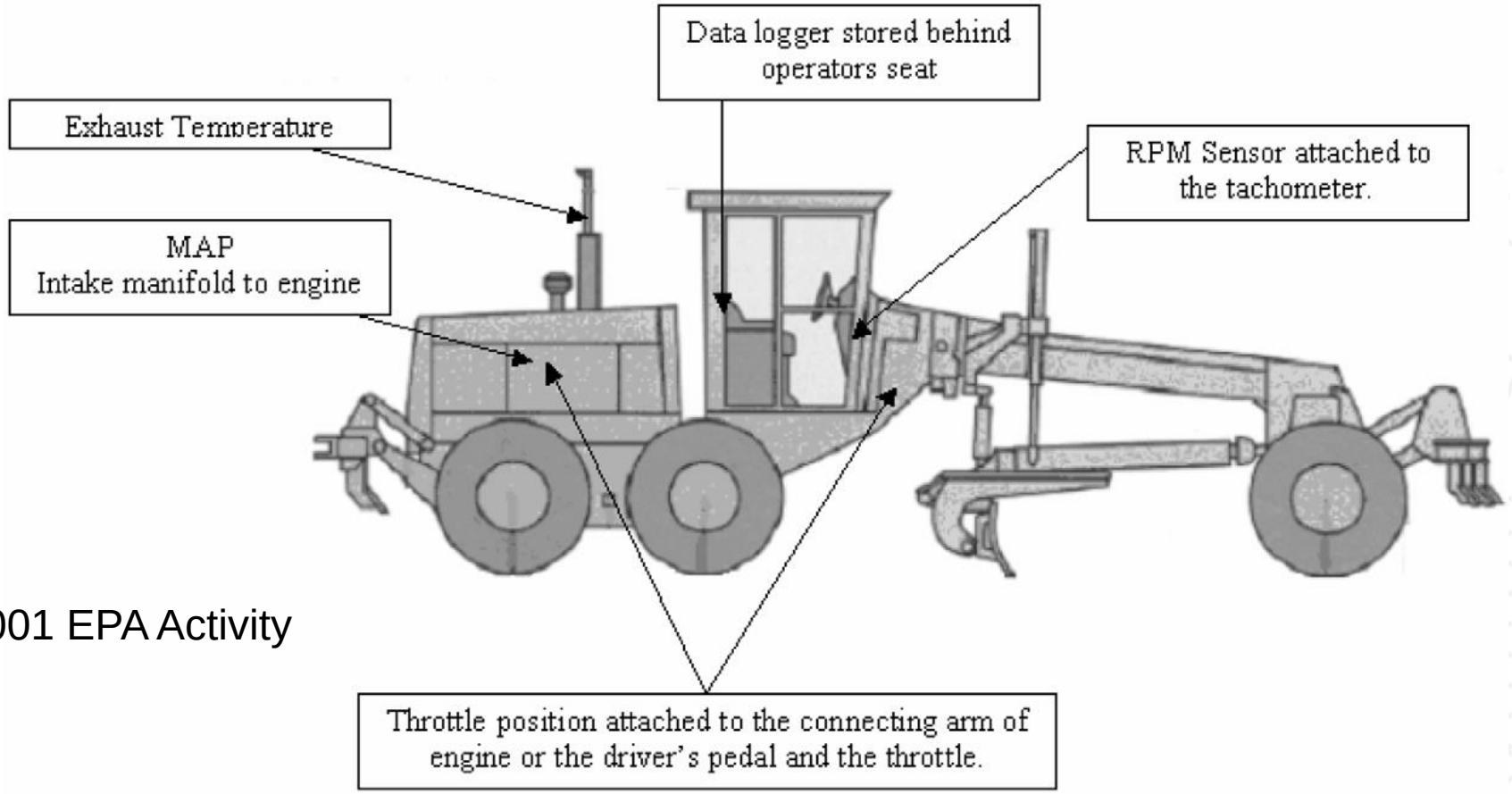
Current Projects (150 units)

• **2019**	Caltrans	10 units	PEMS (2days)
• **2020**	ARB	100 units	PAMS
• **2021**	ARB	50 port	PAMS some PEMS

PEMS – portable emission measurement system (1 day)
PAMS – portable activity measurement system (1-4 weeks)
MEL – mobile emissions laboratory (1 day)
Logger – simple logger GPS and RPM plus other (1 day)
AQIP – Air Quality Incentive Program
Caltrans – California Department of Transportation

[1] Unit is a piece of construction equipment
[2] early version of PEMS so data is limited

UCR Tested Off-Road Equipment Logging RPM, Temps, and Other



2001 EPA Activity

From Huai et al "MEASUREMENT OF OPERATIONAL ACTIVITY FOR NONROAD DIESEL CONSTRUCTION EQUIPMENT", International Journal of Automoti

UCR Tested Construction Equipment Before 1065 PEMS

2006 CalTrans

From Barth et al “Evaluating the Emissions from Heavy-Duty Construction Equipment”, Final Report CalTrans June 2008

UCR Tested Cargo Cranes with Its MEL

From Jayaram et al “Measurement of the Effectiveness of the CCST Emissions Control Technology on a Rubber Tyre Gantry Crane”, Final Report J&J Environmental Corporation Sep 2009

From Miller et al “Measurement of the Effectiveness of the CCST Emissions Control Technology on a Rubber Tyre Gantry Crane”, Final Report Vycon Inc. Sep 2007

UCR Testing Now Involves 1065 Gas and PM PEMS

Barth et al “Measuring and Modeling PM Emissions from Heavy-Duty Construction Equipment”, Final Report CalTrans June 2012
Durbin et al “Study of In-Use Emissions from Diesel Off-Road Equipment” Final Report to ARB April 2013

Time Laps Video Setup To Capture Operation Front and Rear Facing Automatic, 3 Mo Operation

2012 CARB/AQIP

From Johnson et al “Hybrid Off-Road Equipment In-Use Emissions Evaluation”, Final Report CARB June 2013

Time Laps Video Capture Unique Modes With Long Term Logging (2-3 mo): Track Dozer

2012 CARB/AQIP

From Johnson et al “Hybrid Off-Road Equipment In-Use Emissions Evaluation”, Final Report CARB June 2013

Time Laps Video Capture Unique Modes With Long Term Logging (2-3 mo): Excavator

2012 CARB/AQIP

From Johnson et al “Hybrid Off-Road Equipment In-Use Emissions Evaluation”, Final Report CARB June 2013

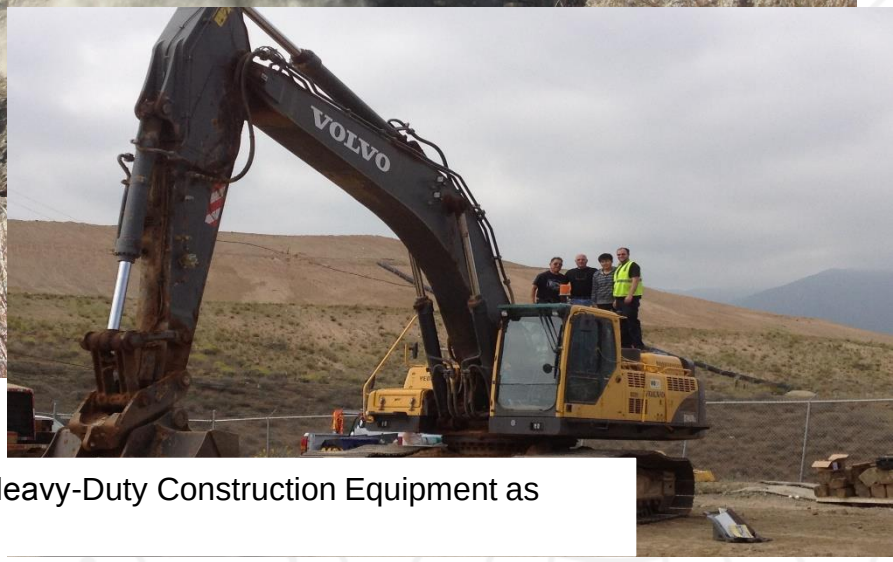
Testing Under In-Service Conditions
Complex and Difficult → Low Relative Data Yield

2012 CARB/AQIP

From Johnson et al “Hybrid Off-Road Equipment In-Use Emissions Evaluation”, Final Report CARB June 2013

Testing Under In-Service Conditions
Complex and Difficult → Low Relative Data Yield

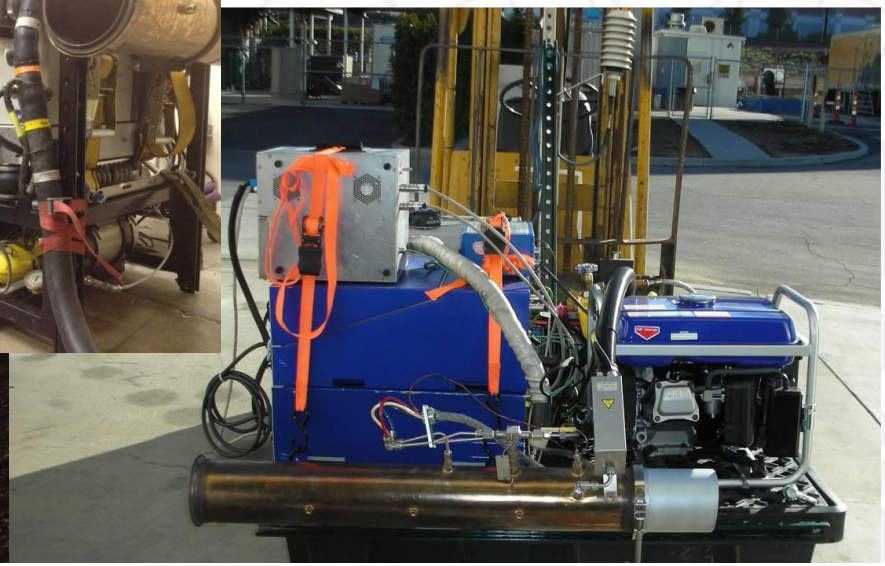
2014 CalTrans



From Russell et al “Developing a Model to Quantify Emissions from Heavy-Duty Construction Equipment as Related to Job Site Activity Data”, Final Report CalTrans June 2014

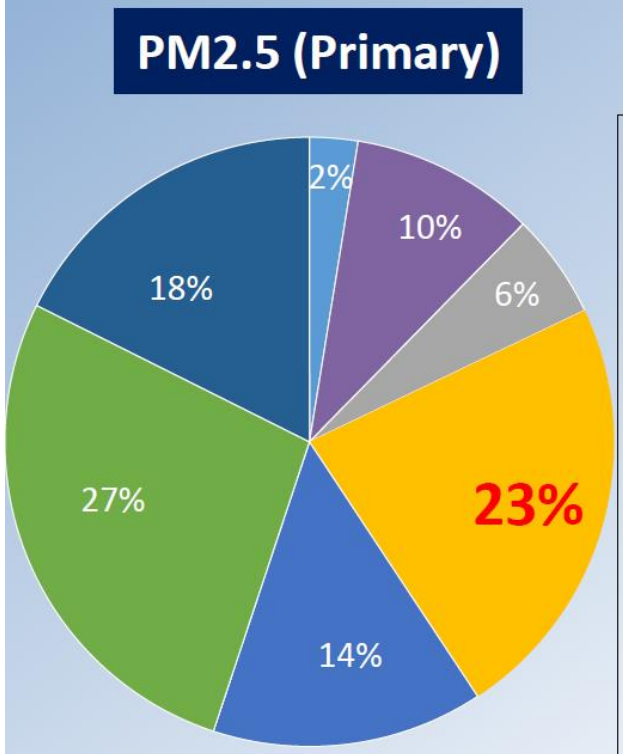
Portable Emission Measurement Systems (PEMS) Are Accurate, but Complex

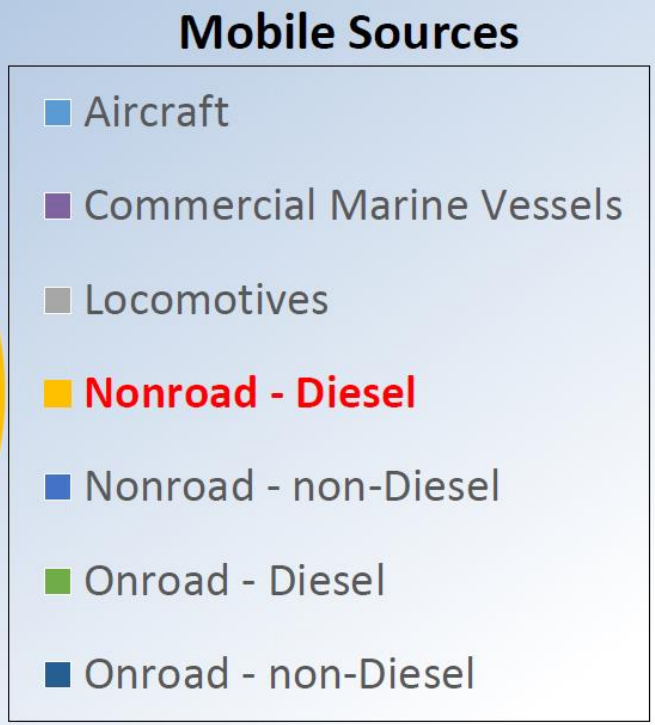
- **Accurate and meets reference method (40 CFR part 1065)**
- **Pre and post calibration required**
- **Generators or large batteries are needed**
- **Report support needed (cranes and or forklifts)**
- **Install times min 4 hr and limited operation 6-8 hrs**

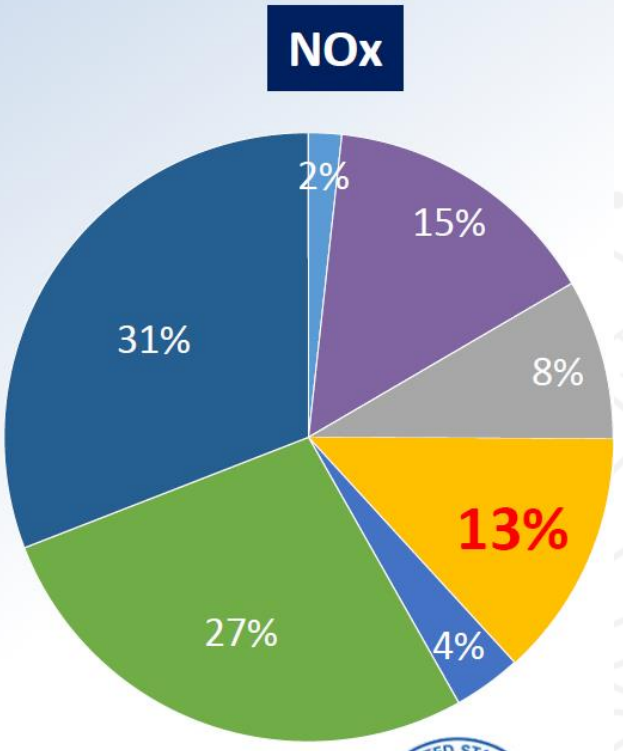


Accurate, but Not Easy to Perform and Minimizes Data Capture

Primary Pollutants Of Concern NO_x and PM
So Lets Focus More on NO_x and PM Measurements



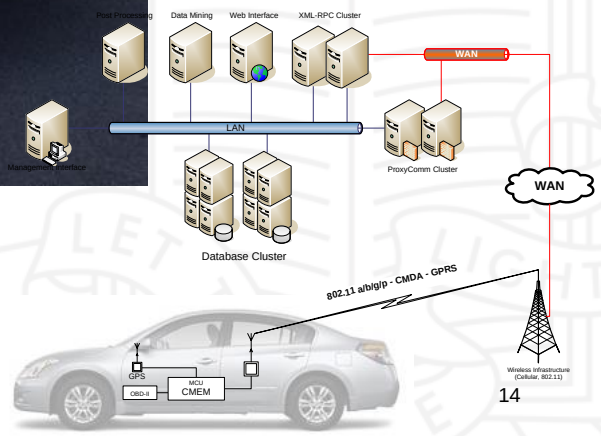




Source CRC 2019

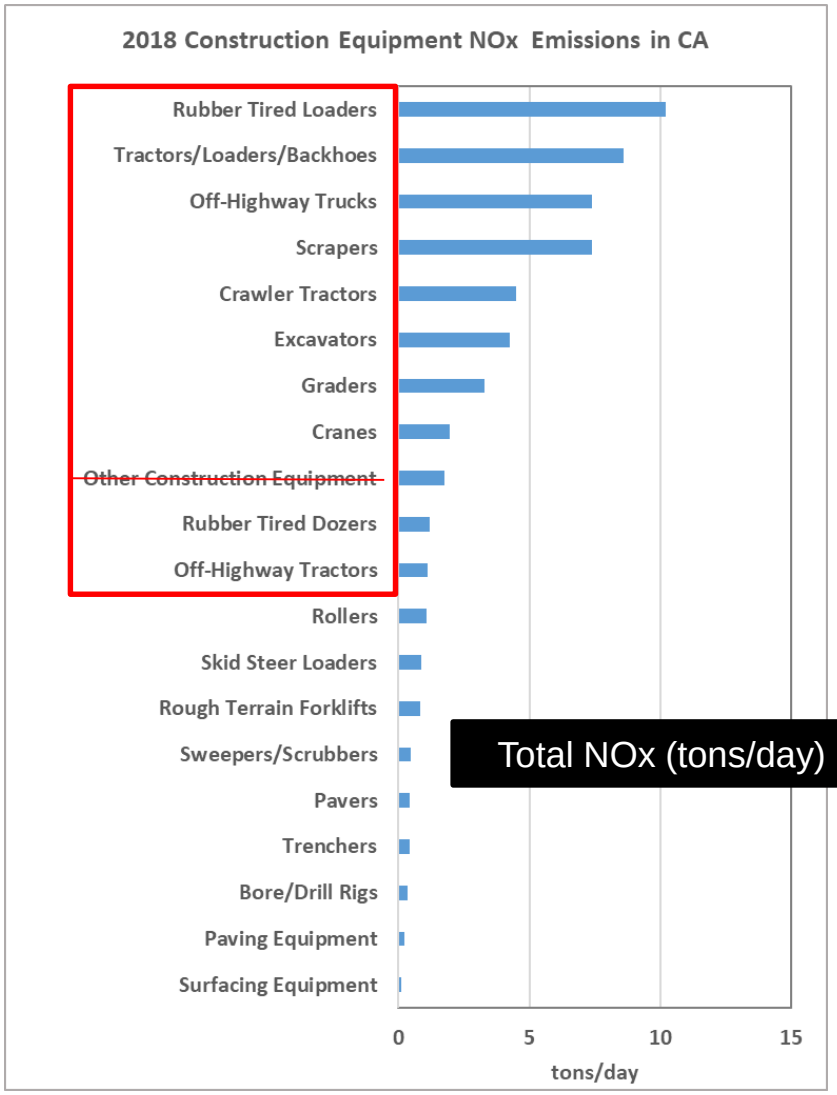
Simple Emissions Measurement Systems (SEMS) Simplifies Testing

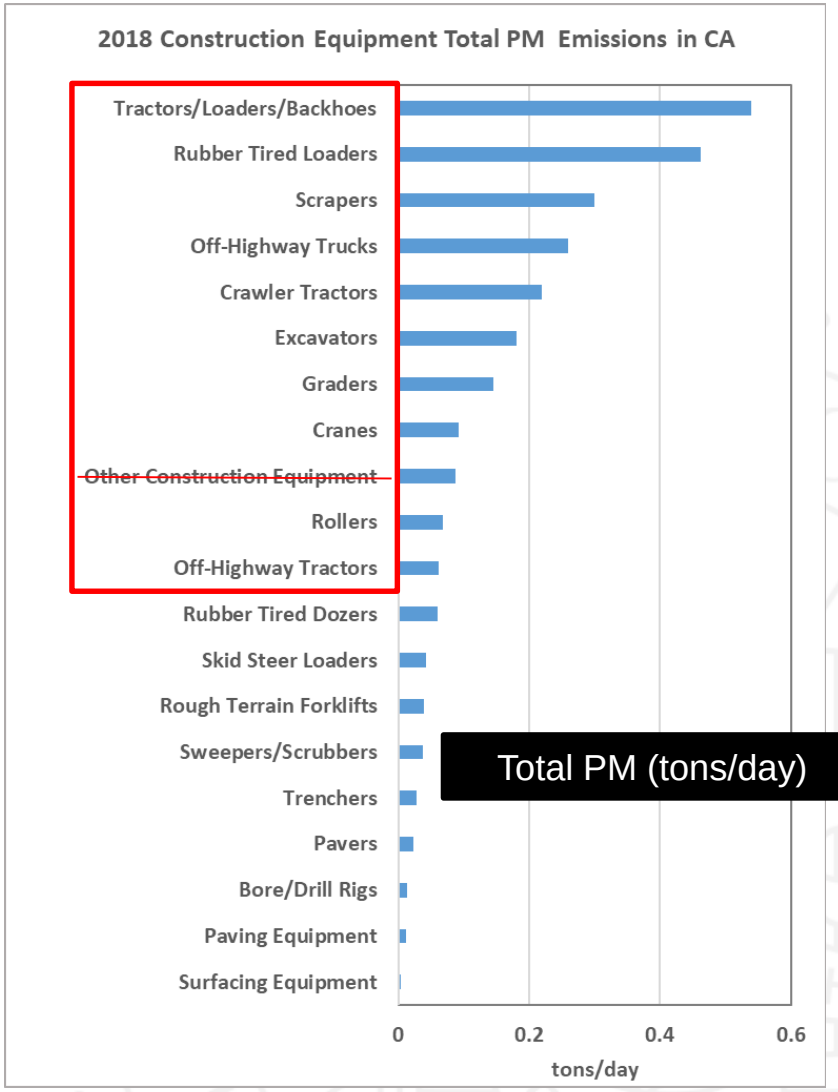
- **NOx Sensors Commercially available**
- **PM shows promise and is available (5 years devel.)**
- **Autonomous operation (multiple days, weeks, mo…)**
- **Regulatory pathway for sensors**
  - Real Emissions Assessment Logging (REAL)
  - UCR's version Onboard Sensing, Analysis, and Reporting (OSAR)



NOx, PM, AFR, CO2, and ECM SEMS

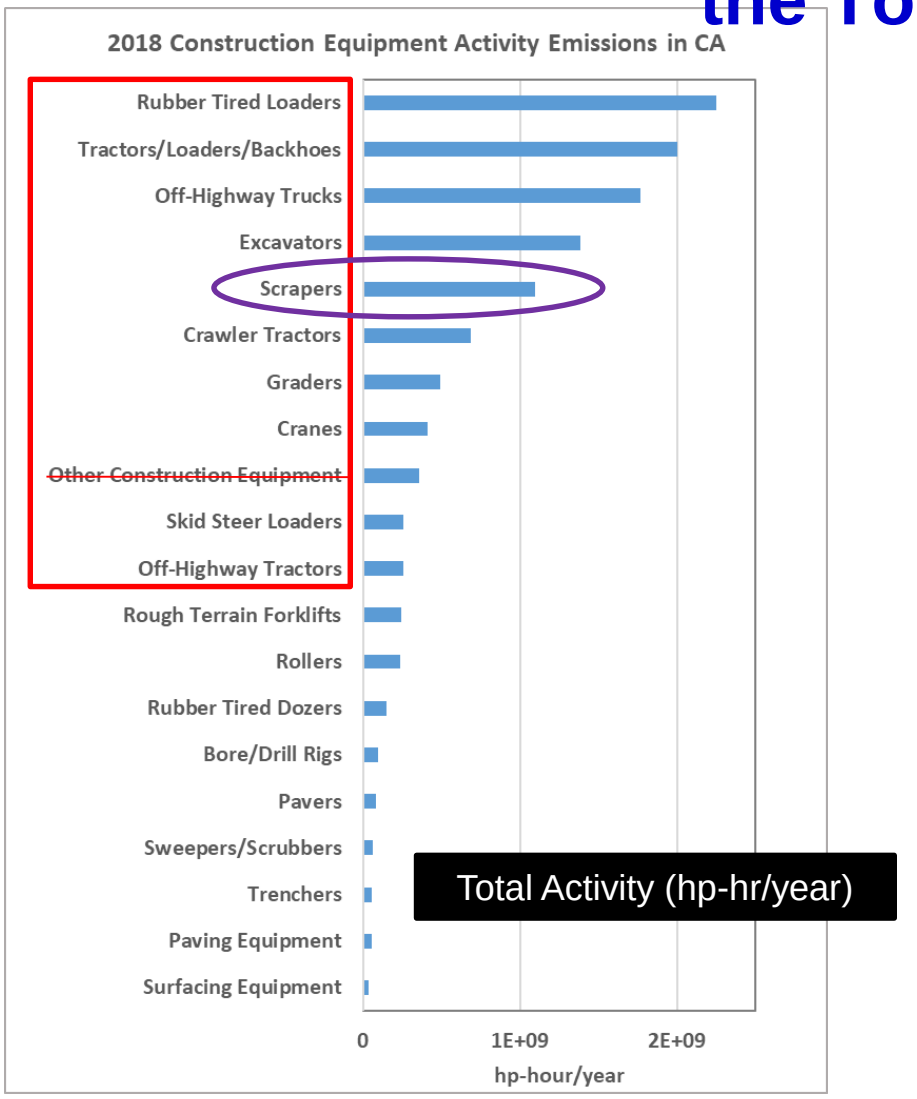
CA Emission Inventories Similar for the Top 10

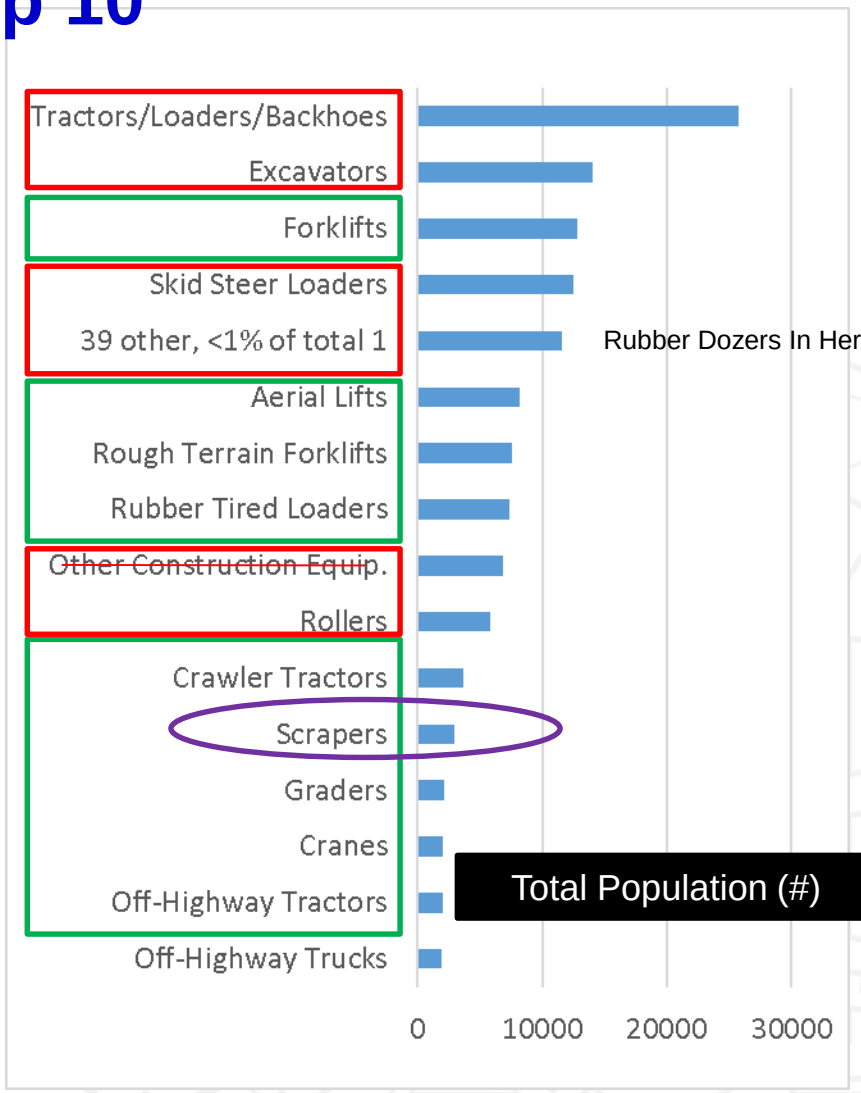




Source OFFROAD2017; CA Statewide; Calendar Year 2018

CA Load/Activity and Population Inventories Vary for the Top 10





Source OFFROAD2017; CA Statewide; Calendar Year 2018

Source 2017 CA Doors database

National Population Shows Trends by Tier

Model Year

Engine Power Category

kW (HP)	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
<8 (11)					7.5 --- 0.80			7.5 --- 0.40							
≥8 (11) <19 (25)					7.5 --- 0.80			7.5 --- 0.40							
≥19 (25) <37 (50)				7.5 --- 0.60				7.5 --- 0.30					4.7 --- 0.03		
≥37 (50) <56 (75) Opt 1				7.5 --- 0.40				4.7 --- 0.30					4.7 --- 0.03		
Opt 2								4.7 --- 0.40				4.7 --- 0.03			
≥56 (75) <75 (100)				7.5 --- 0.40				4.7 --- 0.40				3.4 0.19 0.02			0.40 0.19 0.02
≥75 (100) <130 (175)			6.6 --- 0.30				4.0 --- 0.30					3.4 0.19 0.02			0.40 0.19 0.02
≥130 (175) <225 (300)			6.6 --- 0.20			4.0 --- 0.20					2.0 0.19 0.02			0.40 0.19 0.02	
≥225 (300) <450 (600)	6.4 --- 0.20														
≥450 (600) <560 (750)		6.4 --- 0.20													
≥560 (750)						6.4 --- 0.20					3.5 0.19 0.10				3.5 0.19 0.04

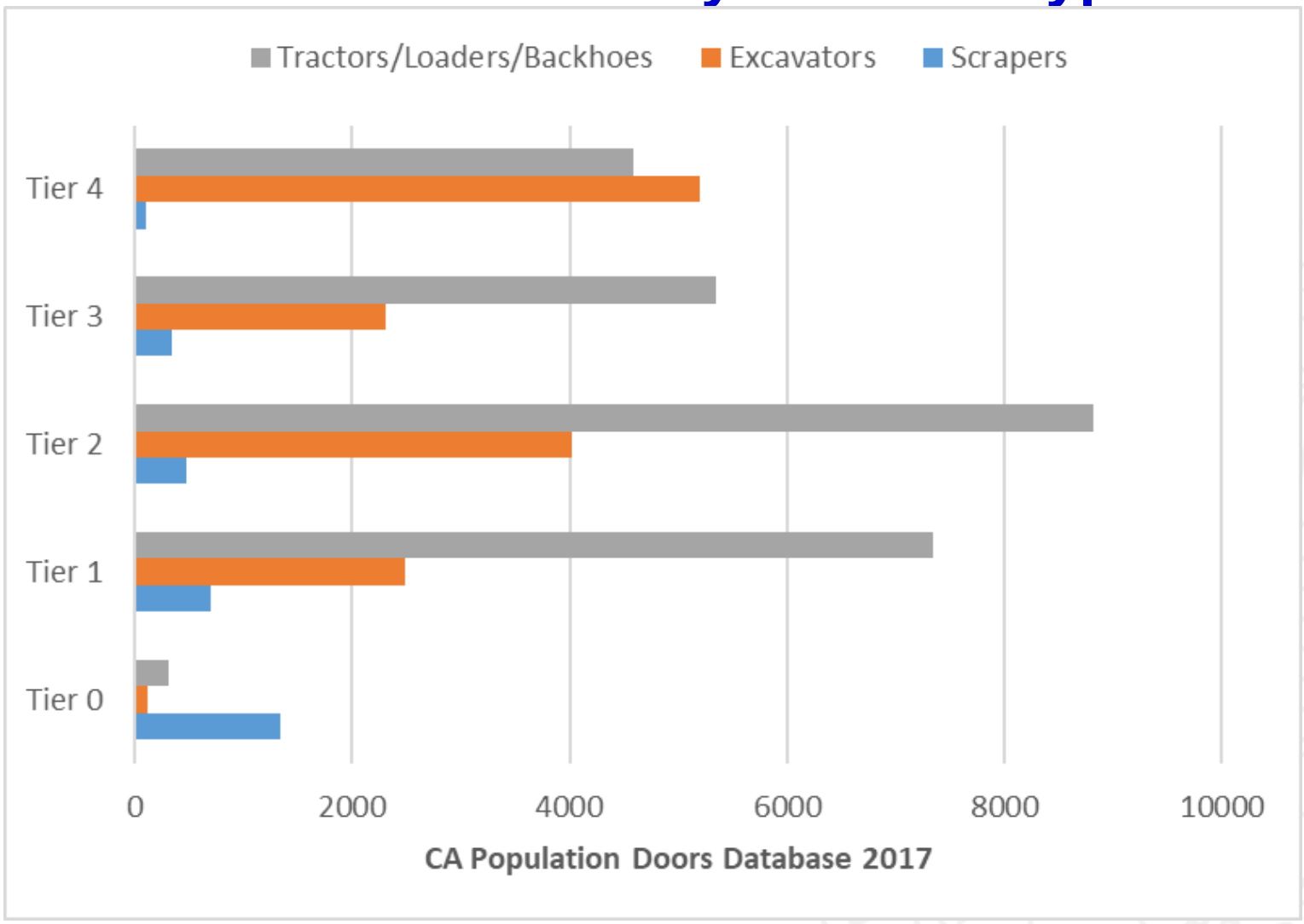
TIER Color Code
Tier 1
Tier 2
Tier 3
Tier 4 Transitional
Tier 4 Final

Rates [g/kW-hr]
NMHC+NOx --- PM
or
NOx NMHC PM

* EPA NRCI exhaust emission standards at https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100OA05.pdf

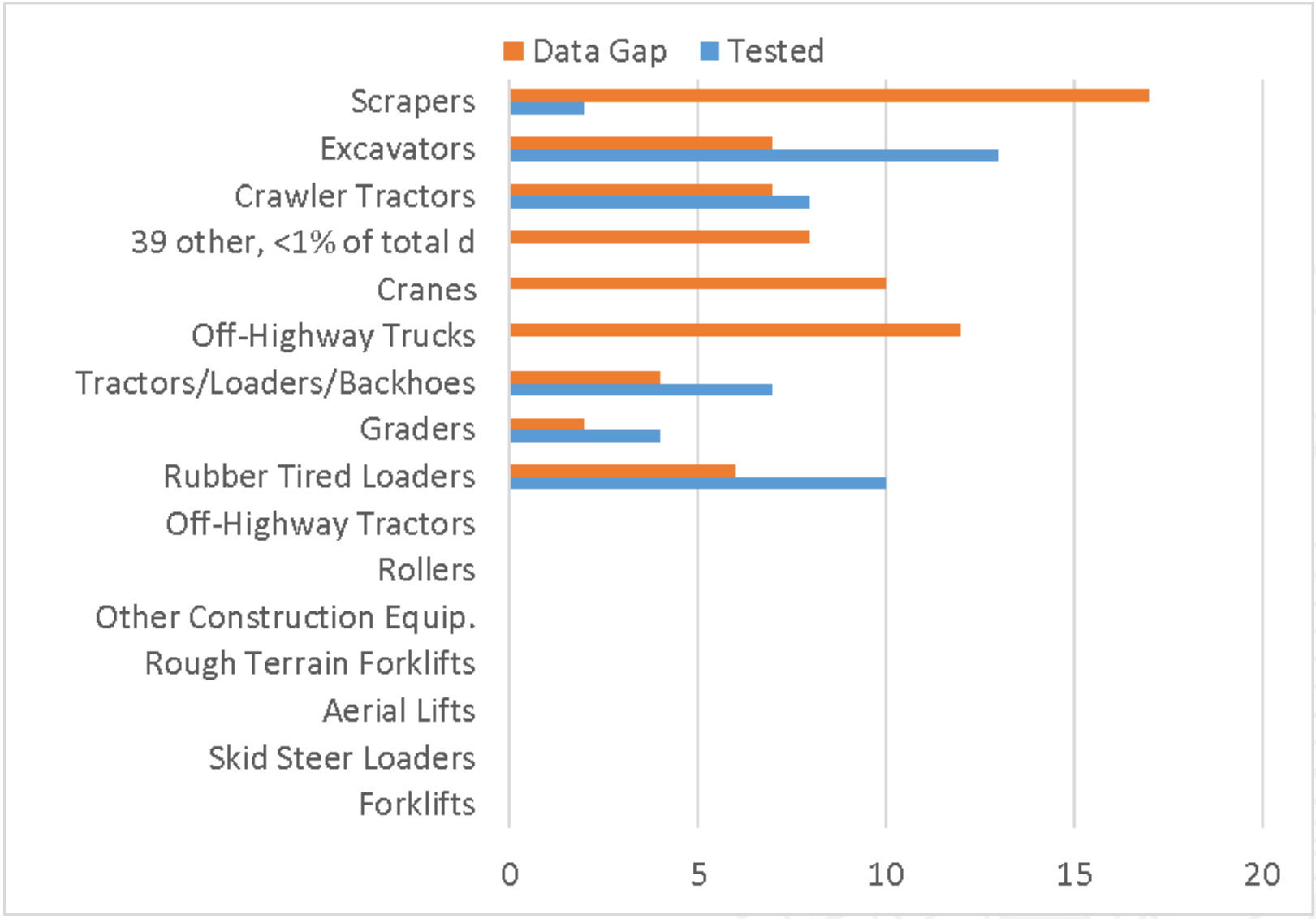
Source CRC 2019

California Equipment Population Shows Similar Trend as Federal by Tier and Type



Source 2017 CA Doors database

Overview of What Has Been Tested and The Data Gaps



Source 2017 CA Doors database

What Has Been Tested and Where Are The Data Gaps

				Tested							Data Gaps					
Vehicle Type in California	Number in CA	% > 1%	Tested W/ PEMS	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4I	Tier 4F	Recomnd To Test	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4I	Tier 4F
Forklifts	12862	10.1%	0							0						
Skid Steer Loaders	12480	9.8%	0							0						
Aerial Lifts	8242	6.5%	0							0						
Rough Terrain Forklifts	7561	5.9%	0							0						
Other Construction Equip.	3340	2.6%	0							0						
Rollers	5799	4.5%	0							0						
Off-Highway Tractors	2005	1.6%	0							0						
Rubber Tired Loaders	7375	5.8%	10			1	6		3	6			3		3	
Graders	2160	1.7%	4				4 [b]			2					x	2
Tractors/Loaders/Backhoes	25784	20.2%	7			3	1	1	2	4				2	2	
Off-Highway Trucks	1910	1.5%	0							12	2	2	2	2	2	2
Cranes	2024	1.6%	0							10	2	2	2	2	x	2
39 other, <1% of total [d]	11611	9.3%	0							8			2	2	2	2
Crawler Tractors	3714	2.9%	8			1	1	4 [b]	2	7	2	2	2			1
Excavators	14079	11.0%	13				10 [1]		3	7			2	3	1	1
Scrapers	2934	2.3%	2			1 [c]	1			17	5	5	3	2	x	2
Total	127632	97%	44							73						

a) hybrids (3), b) one with a DPF, c) 2 engines in the scraper (280 and 540 hp), d) There are 39 units in other. One of which is the rubber dozer.

Source 2017 CA Doors database

UCR Collaborations with EPA

- **EPA is providing data loggers and support funding for CARB study to data log 100 pieces of construction equipment.**
- **EPA is providing funding for UCR to identify non-road database sources on equipment type, size range, and any usage information.**
- **UCR has provided EPA costing information for additional data logging and mini-PEMS and PEMS measurements of fleets UCR is already working with.**

CARB study of Potential Electrification of Non-road Applications

- UCR is in contracting for a program to evaluate the potential for the electrification or hybridization of non-road applications.
- Hybridization/electrification feasibility analysis.
- Off-road activity and emissions analysis.
- Hybridization/electrification cost/benefit analysis.
- Development recommendations for future activity collection and demonstration programs.

Studies of Non-Road Equipment being used at Ports

- UCR is supporting a several different demonstration programs for non-road equipment being used at Ports in LA, Long Beach, Oakland, and Stockton.
- Work being done in support of CARB Low Carbon Transportation and Fuels Investment and Air Quality Improvement Programs.
- Activity characterization from over 50 pieces of port-related non-road equipment, including yard tractors, top handlers, rubber tire gantry cranes, and forklifts.
- Emissions testing on a smaller subset of this equipment.

THANK YOU

Acknowledgement

- California Department of Transportation (CalTrans)
- California Air Resources Board
- Environmental Protection Agency

Previous Studies Details

- CARB – Caltrans – Study #2
  - PEMS on 27 pieces of equipment (2003 – 2012) – 1 day of testing (some from AQIP below)
- CARB AQIP Study of Hybrid bulldozers and excavators
  - PEMS on 5 pieces of equipment (2007 – 2012) – 1 day of testing (video + logger)

Project	Agency	Model Year	Type of Equipment	Tier	Tech Group	Rated Power (hp)	PEMS	PAMS	Video
Study of In-Use Emissions from Diesel Off-Road Equipment	CARB, Caltrans	2007	Backhoe	Tier 2	non-hybrid	99	x	x	
		2010	Backhoe	Tier 3	non-hybrid	99	x	x	
		2007	Wheel Loader	Tier 3	non-hybrid	225	x	x	
		2006	Backhoe	Tier 2	non-hybrid	92	x	x	
		2006	Backhoe	Tier 2	non-hybrid	92	x	x	
		2009	Wheel Loader	Tier 3	non-hybrid	273	x	x	
		2004	Wheel Loader	Tier 2	non-hybrid	156	x	x	
		2008	Excavator	Tier 3	non-hybrid	520	x	x	
		2006	Scraper	Tier 2	non-hybrid	280	x	x	
		2006	Scraper	Tier 2	non-hybrid	540	x	x	
		2006	Excavator	Tier 3	non-hybrid	269	x	x	
		2003	Bulldozer	Tier 2	non-hybrid	338	x	x	
		2008	Road Grader	Tier 3	non-hybrid	163	x	x	
		2011	Wheel Loader	Tier 3	non-hybrid	171	x	x	
		2010	Road Grader	Tier 3	non-hybrid	163	x	x	
		2008	Road Grader	Tier 3	non-hybrid	163	x	x	
		2010	Road Grader w/DPF	Tier 3	non-hybrid	168	x	x	
		2011	Wheel Loader	Tier 3	non-hybrid	171	x	x	
		2010	Scraper	Tier 3	non-hybrid	193	x	x	
		2011	Wheel Loader	Tier 3	non-hybrid	171	x	x	
Hybrid Off-Road Equipment In-Use Emissions Evaluation Air Quality Improvement Plan (AQIP)	CARB	2012	Bulldozer	Tier 4i	hybrid	204	x	x	x
		2011	Bulldozer	Tier 4i	non-hybrid	296	x	x	x
		2012	Bulldozer	Tier 4i	non-hybrid	347	x	x	x
		2012	Bulldozer	Tier 4i	hybrid	204	x	x	x
		2011	Bulldozer	Tier 4i	non-hybrid	296	x	x	x
		2007	Excavator	Tier 3	non-hybrid	155	x	x	x
		2011	Excavator	Tier 3	hybrid	148	x	x	x

Previous Studies Details

- Caltrans PM modeling – PEMS 5 equipment (2011 – 2013) – PAMS 45 pieces of T2 to T4i equipment (many for only a few hours to one or more weeks)
- Caltrans – Emissions study #3
  - 10 pieces of equipment (Tier 4 final) – 2 days of staged testing

Project	Agency	Model Year	Type of Equipment	Tier	Tech Group	Rated Power (hp)	PEMS	PAMS	Video
Developing a Model to Quantify Emissions from Heavy-Duty Construction Equipment as Related to Job Site Activity Data	Caltrans	2013	Backhoe/Loader	Tier 4i	non-hybrid	127	x	x	
		2011	Bulldozer	Tier3	non-hybrid	174	x	x	
		2011	Wheel Loader	Tier3	non-hybrid	171	x	x	
		2013	Excavator	Tier3	non-hybrid	300	x	x	
		2011	Bulldozer	Tier 4i	non-hybrid	316	x	x	
		2011	Crawler Tractor	Tier 4i	non-hybrid	252		x	
		2011	Crawler Tractor	Tier 4i	non-hybrid	252		x	
		2011	Crawler Tractor	Tier 4i	non-hybrid	235		x	
		2006	Excavator	Tier 3	non-hybrid	155		x	
		2011	Excavator	Tier 3	non-hybrid	148		x	
		2011	Excavator	Tier 3	non-hybrid	148		x	
		2011	Excavator	Tier 3	non-hybrid	148		x	
		2011	Crawler Tractor	Tier 4i	non-hybrid	235		x	
		2011	Rubber Tired Loader	Tier 3	non-hybrid	149		x	
		2011	Rubber Tired Loader	Tier 3	non-hybrid	160		x	
		2011	Rubber Tired Loader	Tier 3	non-hybrid	149		x	
		2011	Rubber Tired Loader	Tier 3	non-hybrid	149		x	
		2003	Rubber Tired Loader	Tier 2	non-hybrid	174		x	
		2004	Rubber Tired Loader	Tier 2	non-hybrid	125		x	
		2013	Rubber Tired Loader	Tier 4i	non-hybrid			x	
		2011	Rubber Tired Loader	Tier 3	non-hybrid	160		x	
		2011	Rubber Tired Loader	Tier 3	non-hybrid	160		x	
		2008	Motor Grader	Tier 3	non-hybrid	267		x	
		2012	Motor Grader	Tier 4i	non-hybrid			x	
		NaN	Rubber Tired Loader	Tier 3	non-hybrid	149		x	
		2011	Rubber Tired Loader	Tier 3	non-hybrid	149		x	
		2011	Motor Grader	Tie 4i	non-hybrid			x	
		2012	Motor Grader	Tier 4i	non-hybrid			x	
		2011	Motor Grader	Tier 4i	non-hybrid			x	
		2008	Rubber Tired Loader	Tier 3	non-hybrid	129		x	
		2013	Rubber Tired Loader	Tier 4i	non-hybrid	124		x	
		2012	Motor Grader	Tier 4i	non-hybrid	240		x	
		2007	Rubber Tired Loader	Tier 3	non-hybrid	173		x	
		2013	Rubber Tired Loader	Tier 4i	non-hybrid	124		x	
		2012	Backhoe Loader	Tier 4i	non-hybrid	88		x	
		2014	Grade Roller	Tier 4i	non-hybrid	157		x	
		2011	Motor Grader	Tier 3	non-hybrid	158		x	
		2009	Motor Grader	Tier 3	non-hybrid	212		x	
		2010	Motor Grader	Tier 3	non-hybrid	153		x	
		2010	Motor Grader	Tier 3	non-hybrid	153		x	
		2009	Motor Grader	Tier 3	non-hybrid	153		x	
		2011	Motor Grader	Tier 3	non-hybrid	158		x	
		2009	Motor Grader	Tier 3	non-hybrid	153		x	
		2009	Motor Grader	Tier 3	non-hybrid	153		x	
		2010	Rubber Tired Loader	Tier 3	non-hybrid	197		x	
		2014	Rough Terrain Forklift	Tier 4i	non-hybrid	142		x	
		2014	Excavator	Tier 4i	non-hybrid	272		x	
		2012	Grade Roller	Tier 4i	non-hybrid	157		x	
		2013	Motor Grader	Tier 4i	non-hybrid	264		x	
		2014	Backhoe Loader	Tier 4i	non-hybrid	127		x	
		2014	Backhoe Loader	Tier 4i	non-hybrid	141		x	
		2014	Crane	Tier 4i	non-hybrid	260		x	
		2013	Rubber Tired Loader	Tier 4i	non-hybrid	219		x	
		2014	Crane	Tier 4i	non-hybrid	260		x	
		2013	Backhoe Loader	Tier 4i	non-hybrid	127		x	
		2011	Crawler Tractor	Tier 4i	non-hybrid			x	
			Rubber Tired Loader	Tier 3	non-hybrid			x	
		2011	Crawler Tractor	Tier 4i	non-hybrid	316		x	

Previous Studies Details

- Caltrans – Emissions study #3
  - 10 pieces of equipment (Tier 4 final) – 2 days of staged testing

Project	Agency	Model Year	Type of Equipment	Tier	Tech Group	Rated Power (hp)	PEMS	PAMS
Updating Off-Road Equipment Prototype to Include Tier 4 Final Heavy-Duty Construction Equipment as Related to Job Site Activities	Caltrans	2015	Excavator	Tier 4 final	non-hybrid	204	x	x
		2015	Wheel Loader	Tier 4 final	non-hybrid	188	x	x
		2015	Backhoe Loader	Tier 4 final	non-hybrid	115	x	x
		2016	Excavator	Tier 4 final	non-hybrid	318	x	x
		2017	Wheel Loader	Tier 4 final	non-hybrid	365	x	x
		2017	Backhoe Loader	Tier 4 final	non-hybrid	126	x	x
		2014	Crawl dozer	Tier 4 final	non-hybrid	397	x	x
		2017	Excavator	Tier 4 final	non-hybrid	172	x	x
		2014	Wheel Loader	Tier 4 final	non-hybrid	397	x	x
		2014+	Crawl dozer	Tier 4 final	non-hybrid		x	x