CALIFORNIA
AIR RESOURCES BOARD

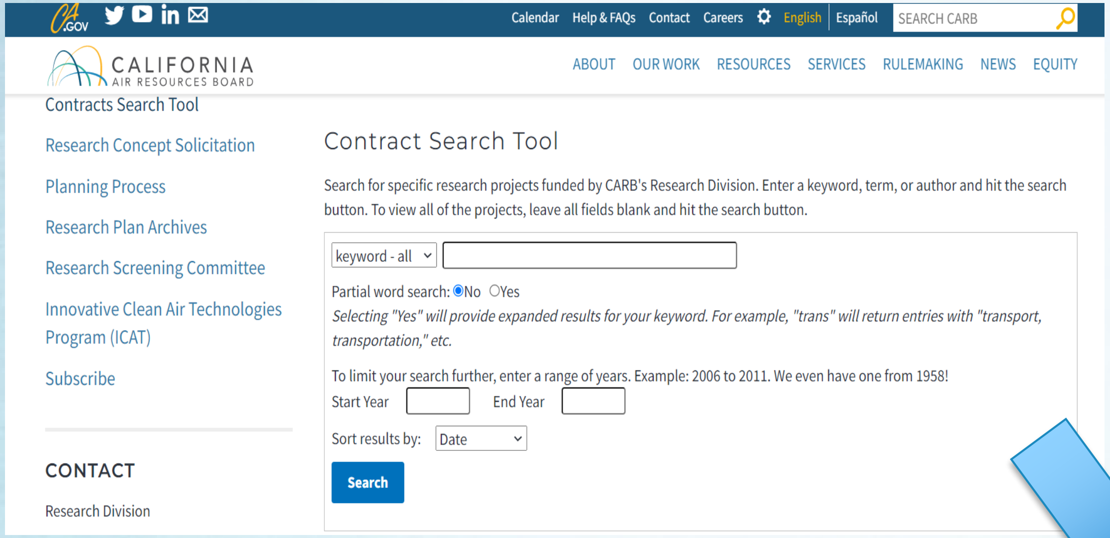
Hybridization and Full Electrification Potential in Off-Road Applications

April 29, 2022
10:00 AM – 12:00 PM PST

Thank you for joining us!
Before we start

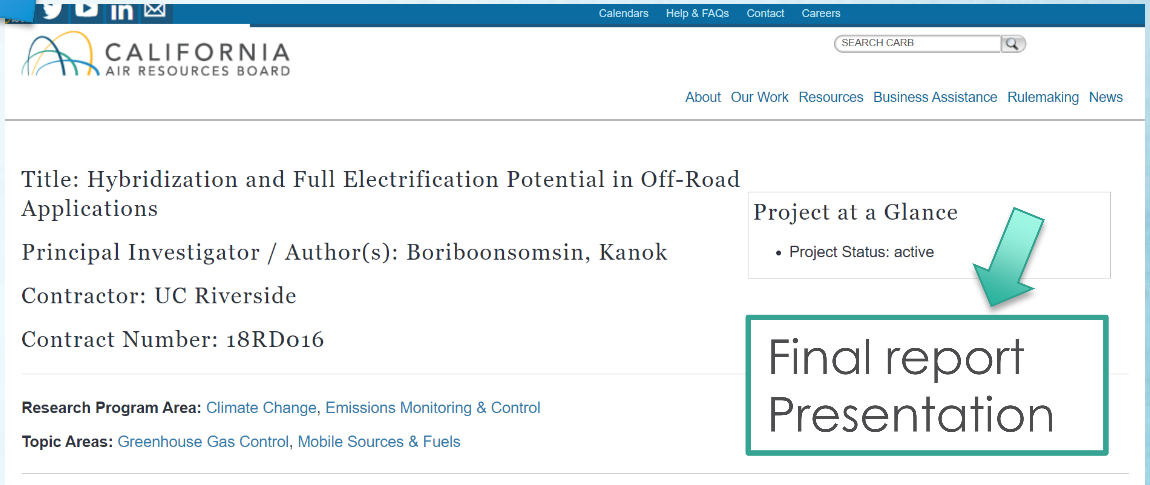
- This meeting will be recorded, final report and presentation slides will be available online
- We encourage questions AFTER the presentation
- Attendees will be muted during the presentation
- Use Chat to type in questions or Raise hand
- Email comments/questions to qi.yao@arb.ca.gov

Online Resource



https://ww2.arb.ca.gov/our-work/programs/research-planning/research-division-contracts

https://ww3.arb.ca.gov/research/single-project_ajax.php?row_id=67678



Final report
Presentation

CARB

Research Motivation

- Off-road equipment contributes to PM and NOx emissions
- 100% percent zero-emission from the off-road sector requires to be achieved by 2035 (N-79-20) in California
- Off-road representative operations, energy demands, and the feasibility of electrification and hybridization need to be characterized

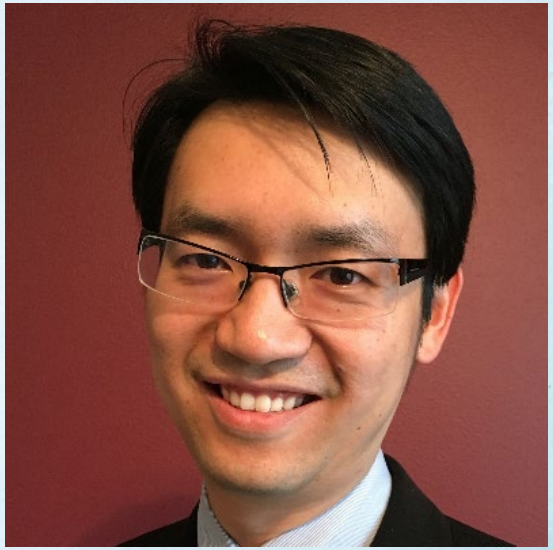
Exemplary Off-road EV/hybrid equipment*

CARB

* Caterpillar, 988K XE Wheel Loader. Available: https://s7d2.scene7.com/is/content/Caterpillar/CM20170815-25630-31787.
F. Lambert, This dumper truck is the world's largest electric vehicle with a massive 700 kWh battery pack. Available: https://electrek.co/2017/09/17/electric-dumper-truck-worlds-largest-ev-battery-pack/.

Today’s Speaker

Dr. Kanok Boriboonsomsin
Research Engineer,
University of California, Riverside.



Research Interest:

- sustainable transportation
- transportation electrification
- vehicle energy and emissions modeling
- connected and automated vehicles
- intelligent transportation systems, and traffic operations

Hybridization and Full Electrification Potential in Off-Road Applications

Kanok Boriboonsomsin, Fuad Un-Noor, George Scora, Guoyuan Wu
College of Engineering - Center for Environmental Research and Technology
University of California at Riverside

Steven Sokolsky, Jordan Steen
CALSTART

CARB Research Seminar
April 29, 2022

Presentation Outline

- Background and introduction
- State of off-road equipment electrification
- Real-world activity and energy use of off-road equipment
- Technical feasibility of electrifying off-road equipment
- Cost-effectiveness of electrifying off-road equipment
- Conclusions and recommendations

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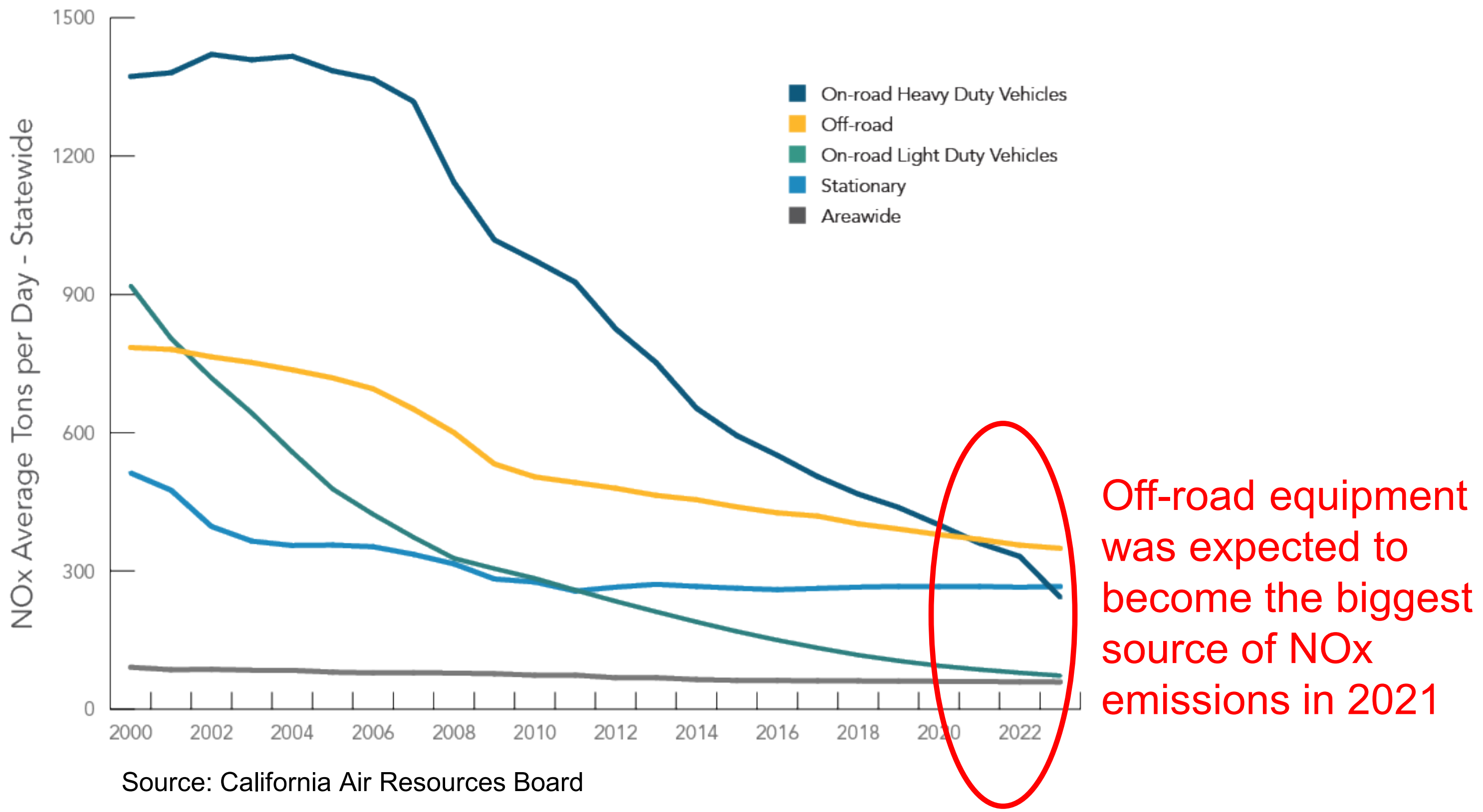
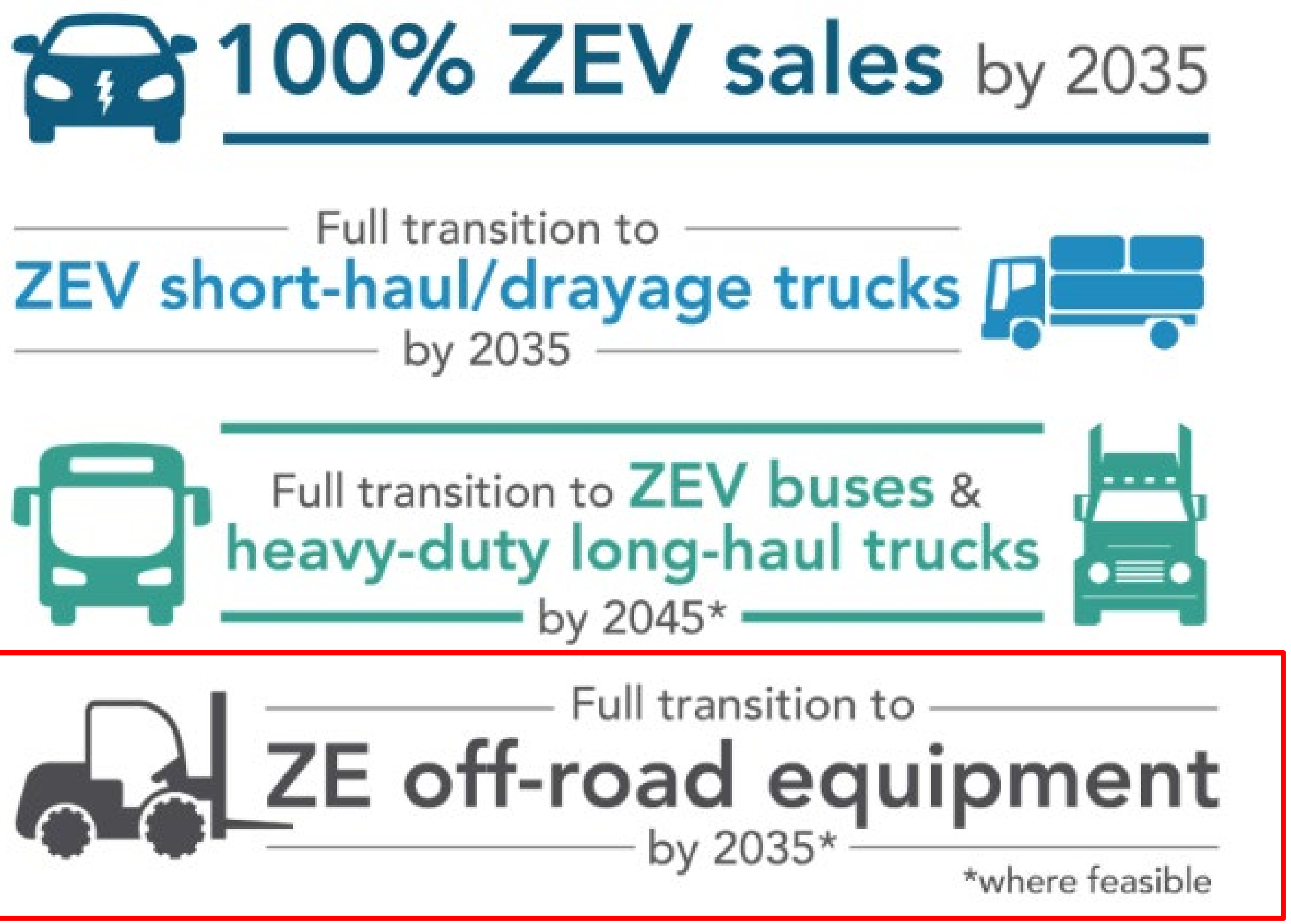
Off-Road Emission Contributions

- Off-road equipment is an important source of GHG and criteria pollutant emissions in California.



Source: California Air Resources Board

California's Executive Order N-79-20



Source: California Air Resources Board

Project Goal and Objectives

- To research pathways for hybridizing or electrifying off-road equipment
  - Maximize climate and air quality benefits
  - Technically and economically viable

- Specific objectives
  - Characterize activities, duty cycles, and energy demands of off-road equipment in different applications
  - Assess the current trends toward hybridization and electrification
  - Determine off-road equipment types that could be partially or fully electrified now and in the near future

Off-Road Equipment

- This study is focused on two off-road equipment categories.
  - Construction and agricultural

- Within category, there are a variety of applications, sizes, and configurations.



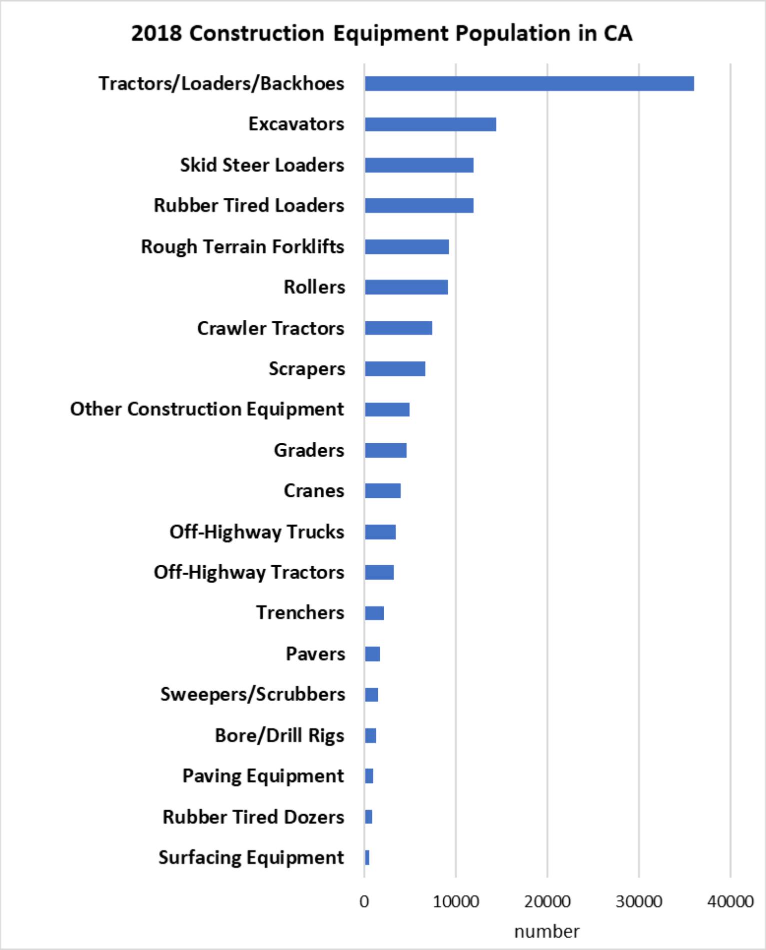




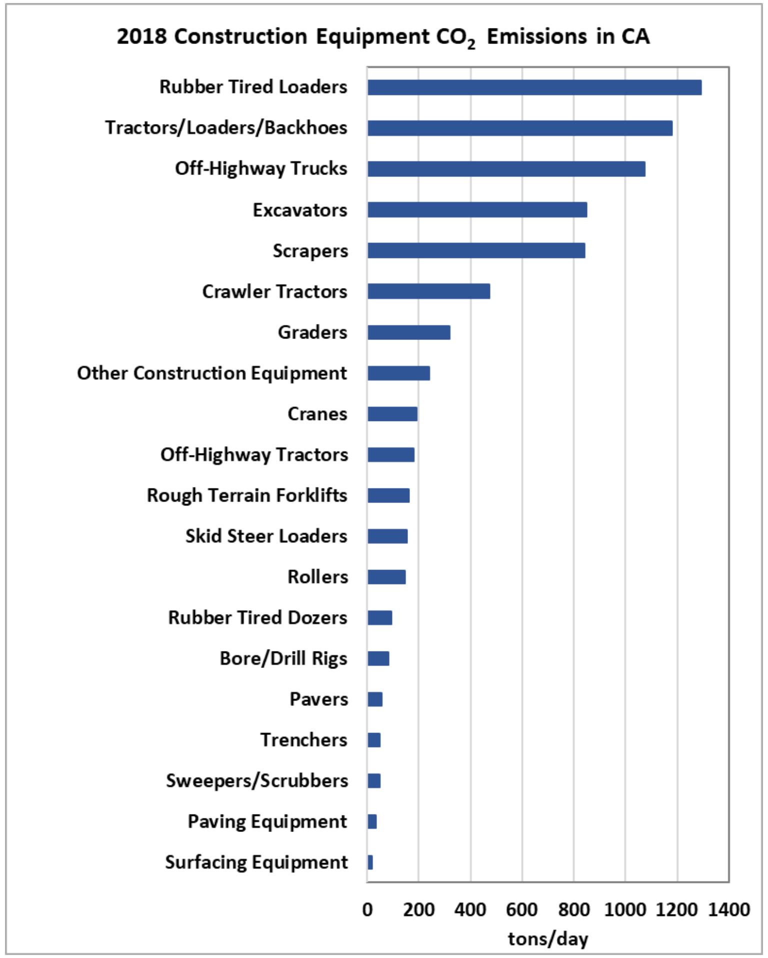

… and many more!

Construction Equipment Inventories

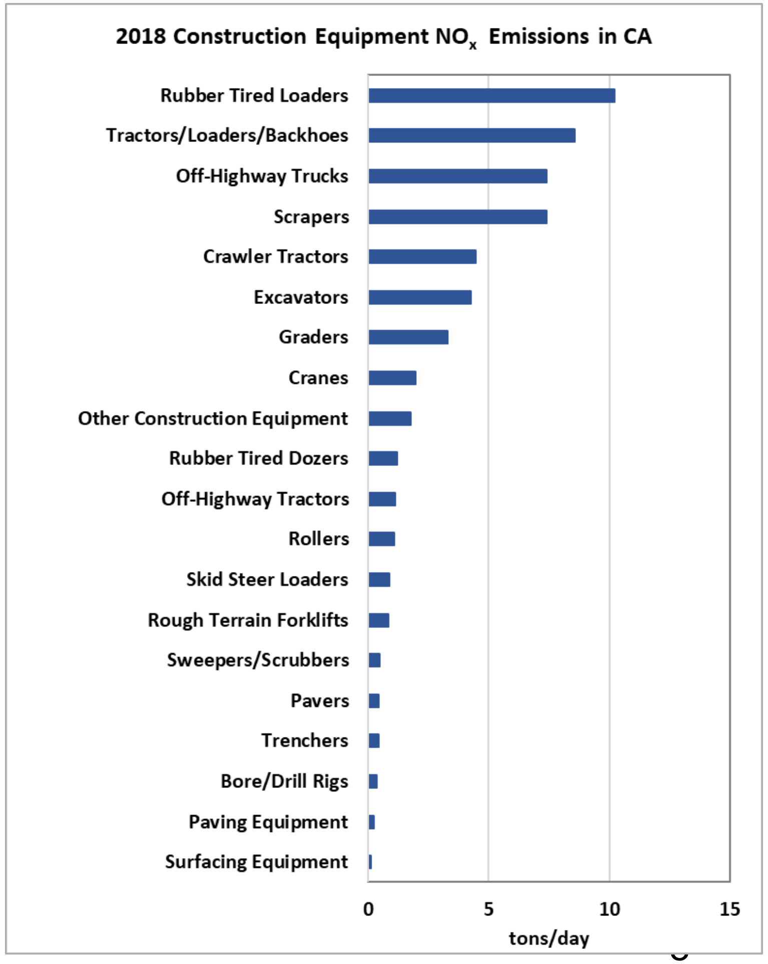
Population



CO2 Emission

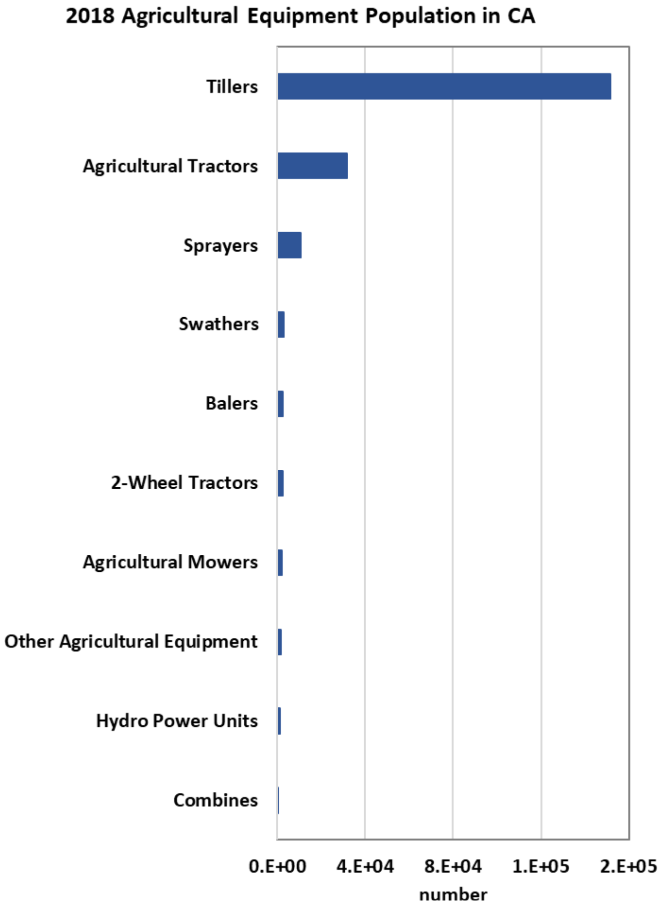


NOx Emission

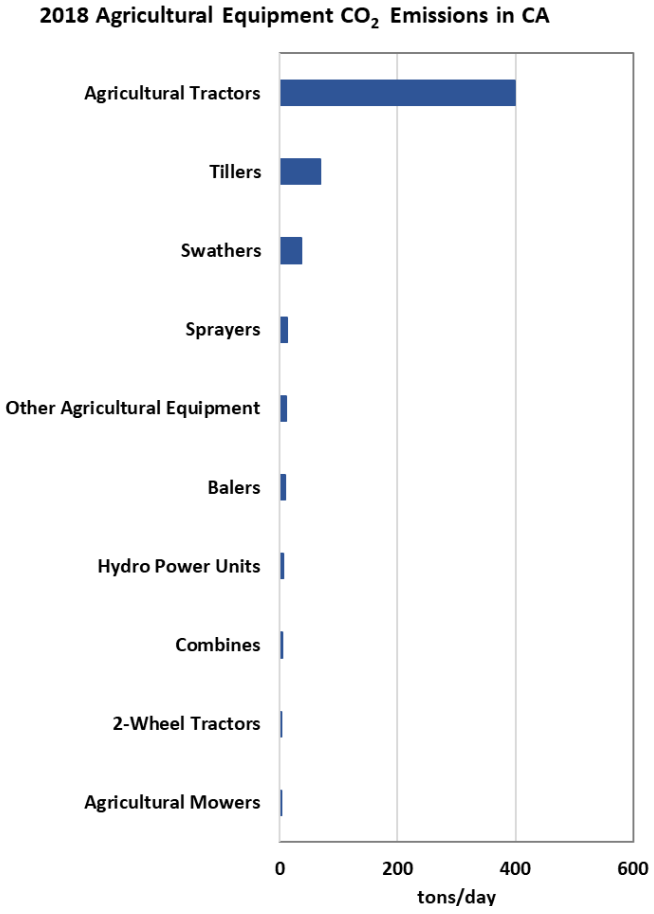


Agricultural Equipment Inventories

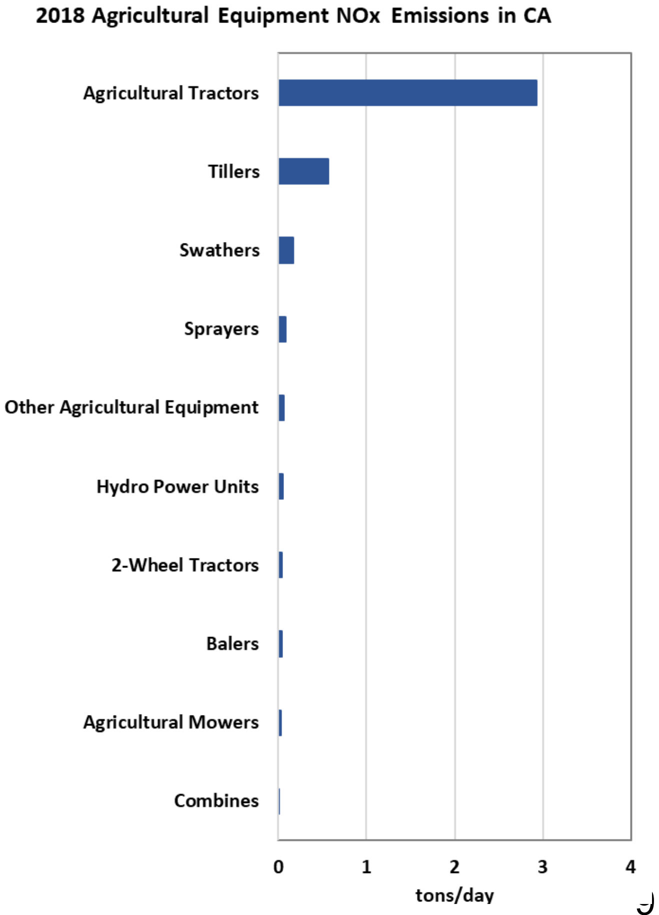
Population



CO2 Emission



NOx Emission



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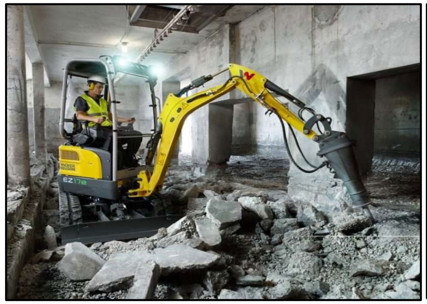
Hybrid and Electric Off-Road Equipment (2019)

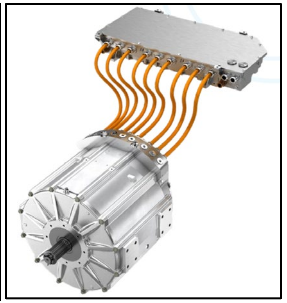
Commercially Available

Hybrid dozer

Electric compact tractor



Electric compact excavator



High performance electric motor

Mobile charging equipment

Prototype

Electric compact dozer

Cabled Electric tractor

Electric excavator

Potential

Electric dozer?

Electric tractor?

Electric else?

Mobile charging trailer?

Full Electrification of Large Off-Road Equipment

Battery electric dump truck

- 700 kWh battery pack
- 100 kW charging station
- 588 kW single synchronous electric motor

Battery electric top handler

- 931 kWh battery pack
- 200 kW charging station
- Demonstrated at Port of Long Beach

Battery electric tractor

- 1,000 kWh battery pack
- 500 to 1,000 kW electric powertrain
- Fully autonomous

Advantages of Electric Off-Road Equipment

Implication / Advantage	Environmental	Operational	Economic
• Less moving parts • Instant bidirectional torque • Higher efficiency • Electric deceleration • No power loss at high altitudes	• Less emission	• Ease of operation • Simpler drivetrain • Less wear • Less maintenance	• Less operating cost • Less downtime • Increased work efficiency and productivity
• Less fuel consumption	• Less emission • Improved workplace environment	• Less dependency on fuel supply	• Less operating cost
• Reduced noise	• Reduced noise pollution	• More flexibility in choosing operating hours and areas	• Increased productivity • Reduced downtime
• Flexible design	N/A	• More utility	• Potential reduction of manufacturing cost

Barriers and Potential Solutions

	Barriers	Solutions
Technical issues	• Short range	• Better ESS • Better energy recuperation techniques
	• Long charging time	• High voltage charging
	• Dynamic high-power requirement	• Use of transmission • Improved ESS
Logistics issues	• Lack of research	• Increased funding • Regulations • Incentives
	• Inadequate charging infrastructure	• Development of necessary charging infrastructure while developing any commercial off-road equipment.
	• Charging station placement	• Proper planning • Mobile charging facilities
Market issues	• Cost	• Increased production • Lease • Incentive
	• Competition	• Regulations • Incentives • Proving superior performance

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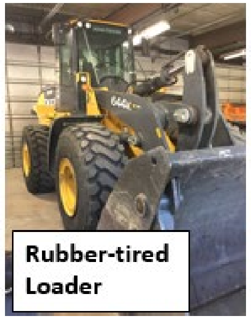
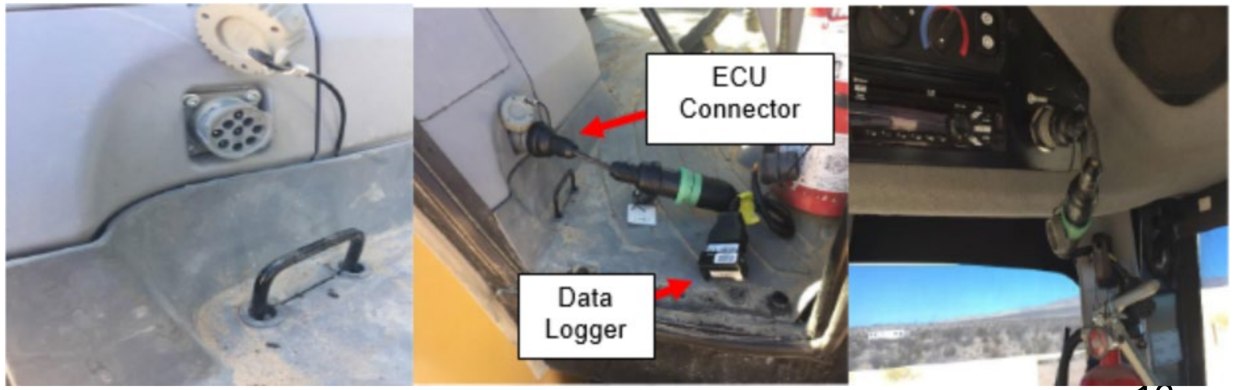
Real-World Activity and Energy Use Data Collection





Engine Starts and Idle Statistics

Equipment Type	Equip-ment ID	Engine Size (L)	Total (hrs)	Idle (hrs)	Non-Idle (hrs)	Idle (%)	Non-Idle (%)	No. of Starts per Weekday in Range	No. of Starts per Weekday Operating	No. of Cold Starts per Weekday in Range	No. of Cold Starts per Weekday Operating
Agricultural Tractor	JD_413	4.5	81.5	24.6	56.9	30.2	69.8	4.66	6.37	0.73	1.00
	JD_414	4.5	34.2	8.9	25.3	26.0	74.0	3.36	7.12	0.47	1.00
Crawler Tractor	N18024	18.1	256.4	33.3	223.0	13.0	87.0	2.64	2.64	0.45	0.45
	N18025	18.1	104.7	14.3	90.4	13.6	86.4	4.29	4.29	0.29	0.29
Excavator	N18029	4.4	256.1	56.8	199.3	22.2	77.8	1.06	2.76	0.37	0.98
Grader	N18014	9	13.3	6.2	7.1	46.4	53.6	1.33	3.27	0.41	1.00
	N18019	9.3	263.0	67.6	195.4	25.7	74.3	1.10	1.69	0.65	1.00
	N18020	9	62.4	13.1	49.3	21.0	79.0	2.30	4.60	0.50	1.00
	N18022	9.3	72.9	16.7	56.2	22.9	77.1	5.75	6.05	0.95	1.00
	N18023	9.3	67.4	12.0	55.4	17.8	82.2	4.00	4.00	0.94	0.94
Off-Highway Tractor	N18021	18.1	223.7	38.7	184.9	17.3	82.7	2.59	2.71	0.86	0.90
	N18027	18.1	253.7	68.6	185.0	27.1	72.9	2.05	2.05	1.00	1.00
Rubber Tired Loader	N18015	9	38.6	5.5	33.1	14.3	85.7	1.41	2.60	0.52	0.96
	N18016	6.6	149.5	18.6	130.9	12.4	87.6	2.85	3.56	0.70	0.88
	N18018	7.01	111.3	29.1	82.2	26.2	73.8	3.14	4.91	0.61	0.96
	N18026	7.755	112.6	22.6	90.0	20.0	80.0	4.84	5.50	0.88	1.00
	N18030	9.3	222.0	27.5	194.5	12.4	87.6	1.76	3.65	0.48	1.00
Scraper	N18028	9.3	54.6	7.3	47.3	13.3	86.7	11.73	15.18	0.77	1.00
	N18043	N/A	449.5	62.9	386.6	14.0	86.0	1.04	1.37	0.69	0.90
Tractor/ Loaders/ Backhoe	N18011	6.8	66.3	39.5	26.7	59.7	40.3	8.62	10.06	0.62	0.72
	N18012	4.5	79.9	44.8	35.1	56.0	44.0	8.57	9.38	0.70	0.76
	N18013	6.8	59.9	28.4	31.5	47.4	52.6	3.72	7.00	0.50	0.94

Power, Work, and Fuel Use Statistics

Equipment Type	Equip-ment ID	Engine Size (L)	Median Power (hp)	Mean Power (hp)	Median Fuel Rate (gal/hr)	Mean Fuel Rate (gal/hr)	Max Daily Work (hp-hr/day)	Median Daily Work (hp-hr/day)	Mean Daily Work (hp-hr/day)	Max Daily Fuel Use (gal/day)	Median Daily Fuel Use (gal/day)	Mean Daily Fuel Use (gal/day)
Agricultural Tractor	JD_413	4.5	8.7	16.7	0.95	1.28	176.7	30.5	45.4	12.30	2.75	3.47
	JD_414	4.5	20.5	23.8	1.33	1.54	190.9	43.1	50.7	12.27	2.79	3.29
Crawler Tractor	N18024	18.1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	N18025	18.1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Excavator	N18029	4.4	40.2	41.5	3.61	3.63	478.2	217.3	231.3	40.83	19.41	20.21
Grader	N18014	9	19.1	26.0	1.47	2.00	66.5	8.1	12.8	5.19	0.62	0.98
	N18019	9.3	30.9*	41.3*	2.69	3.52	509.2*	323.7*	278.5*	42.67	27.81	24.33
	N18020	9	38.2	52.6	2.25	3.09	465.1	361.8	327.8	27.56	21.16	19.26
	N18022	9.3	42.1*	50.0*	3.66	4.24	396.2*	124.5*	158.5*	33.26	10.58	13.44
	N18023	9.3	47.2*	53.0*	4.07	4.49	336.1*	165.8*	162.4*	28.44	13.90	13.75
Off-Highway Tractor	N18021	18.1	226.1*	192.1*	18.03	15.32	2,526.5*	1,981.8*	1,718.6*	201.34	158.28	137.04
	N18027	18.1	223.7*	182.2*	17.84	14.52	2,221.8*	1,960.4*	1,777.7*	176.77	156.06	141.64
Rubber Tired Loader	N18015	9	18.8	34.7	1.68	2.69	235.8	20.4	51.5	17.47	1.71	3.99
	N18016	6.6	18.9	35.5	1.82	3.12	673.1	333.2	312.4	58.63	29.02	27.41
	N18018	7.01	17.3*	32.7*	1.65	2.83	435.0*	189.3*	165.2*	36.82	16.41	14.33
	N18026	7.755	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	N18030	9.3	27.3*	54.0*	2.40	4.50	550.7*	201.1*	226.1*	45.64	16.84	18.83
Scraper	N18028	9.3	49.1*	70.8*	4.20	5.81	509.0*	247.1*	241.5*	41.62	20.37	19.83
	N18043	N/A	62.3*	114.0*	5.23	9.17	1,540.8*	1,182.3*	1,090.1*	123.86	95.16	87.73
Tractor/ Loaders/ Backhoe	N18011	6.8	11.7*	30.5*	0.89	2.06	202.3*	101.1*	101.0*	13.59	6.90	6.83
	N18012	4.5	8.0*	23.2*	0.67	1.65	269.0*	84.5*	88.1*	19.34	6.03	6.29
	N18013	6.8	10.7*	31.9*	0.83	2.15	231.3*	87.8*	95.5*	15.14	5.88	6.44

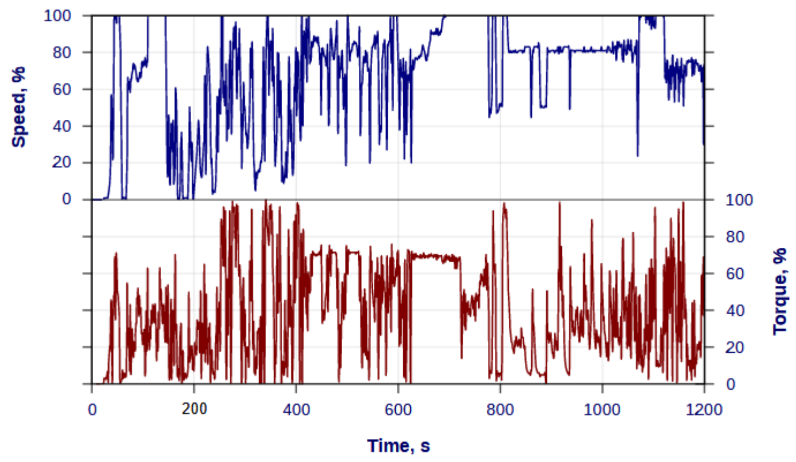
**Based on estimated engine brake power*

Comparison with Engine Certification Cycles

Non-Road Steady Cycle (NRSC)

Mode Number	Engine Speed	Torque (%)	Weighting Factor
1	Rated	100	0.15
2	Rated	75	0.15
3	Rated	50	0.15
4	Rated	10	0.10
5	Intermediate	100	0.10
6	Intermediate	75	0.10
7	Intermediate	50	0.10
8	Idle	N/A	0.15

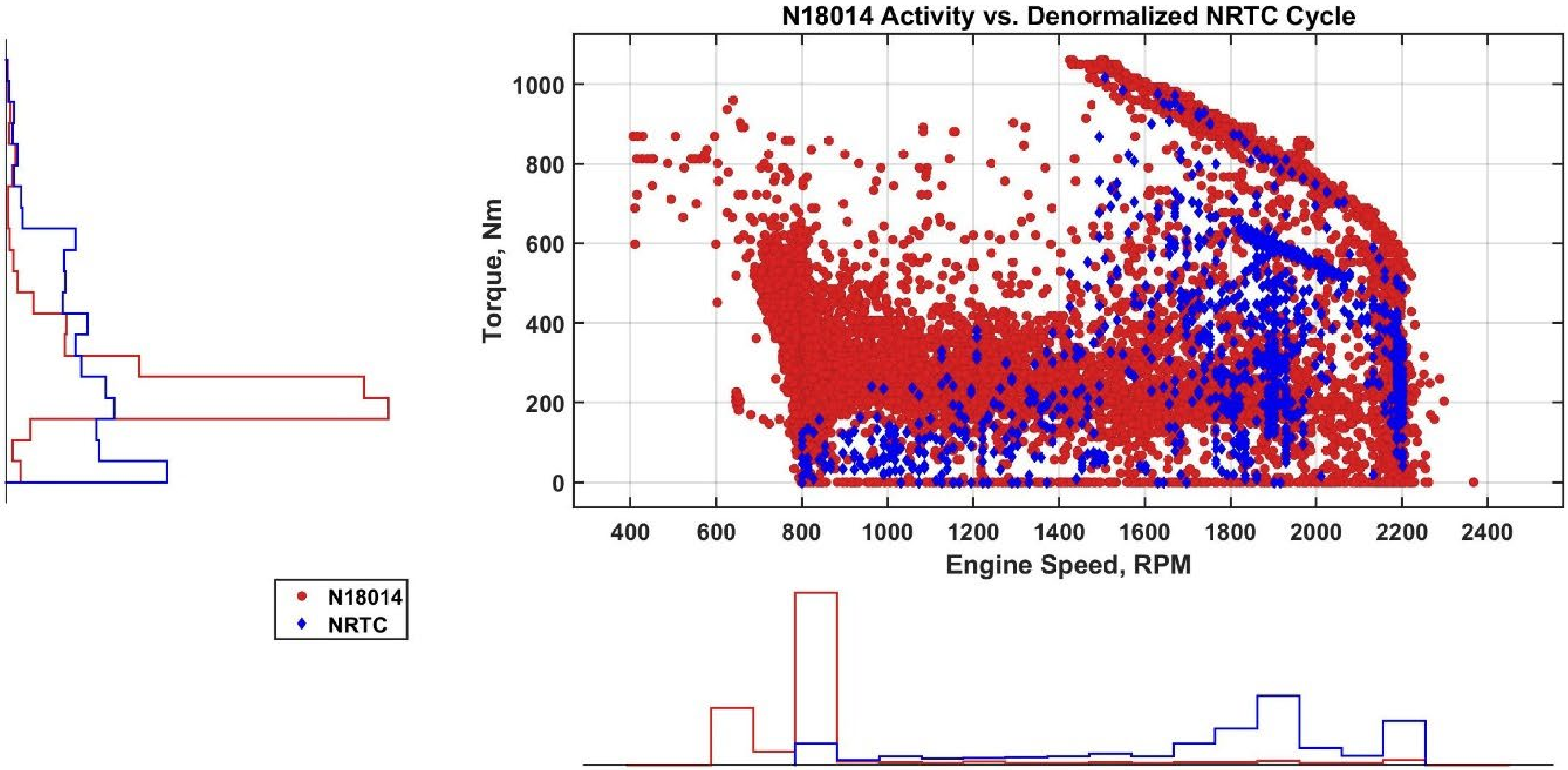
Non-Road Transient Cycle (NRTC)



	% Torque >		5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95
	% Torque <=	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
Certification Cycles	NRTC	10.7	7.3	4.7	5.7	7.7	7.0	5.4	5.9	5.2	6.0	4.1	4.0	4.3	6.1	10.7	0.5	1.1	0.7	0.5	2.8
	NRSC	15.0	0.0	10.0	0.0	0.0	0.0	0.0	0.0	0.0	25.0	0.0	0.0	0.0	0.0	25.0	0.0	0.0	0.0	0.0	25.0
Ag Tractor	JD_413	25.3	21.7	13.6	8.1	7.0	5.3	3.2	4.6	3.8	3.7	2.2	0.8	0.3	0.1	0.2	0.1	0.0	0.0	0.0	0.0
	JD_414	4.2	17.1	12.9	6.4	8.6	10.0	11.7	10.9	7.0	5.1	2.5	1.1	0.7	0.5	0.4	0.3	0.2	0.2	0.1	0.1
Excavator	N18029	0.7	20.0	15.4	3.0	2.9	2.7	3.9	3.4	4.3	3.7	5.1	5.3	4.5	4.4	6.1	5.5	6.5	2.2	0.4	0.0
Grader	N18014	1.3	0.6	2.2	34.2	32.0	11.9	5.3	5.4	2.5	1.2	0.5	0.4	0.2	0.2	0.6	0.8	0.2	0.4	0.2	0.2
	N18019*	3.6	29.6	15.0	17.1	13.6	7.8	4.4	2.9	2.9	1.5	0.8	0.6	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	N18020	2.5	2.2	29.1	21.0	10.4	12.3	7.3	4.5	2.7	2.0	1.2	1.3	1.2	0.9	0.5	0.3	0.2	0.2	0.1	0.0
	N18022*	16.8	26.5	20.2	17.2	10.6	6.0	1.9	0.7	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	N18023*	2.1	15.1	13.9	11.7	14.4	12.5	10.0	6.5	4.7	3.7	2.7	1.5	0.6	0.3	0.2	0.1	0.0	0.0	0.0	0.0
Off-Highway Tractor	N18021*	4.2	24.8	4.9	5.2	5.7	8.3	9.6	9.3	14.0	10.6	2.8	0.5	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	N18027*	3.7	32.1	3.9	2.7	3.2	6.1	10.0	10.8	16.2	7.9	2.7	0.7	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Rubber Tired Loaders	N18015	3.1	19.7	19.8	15.5	9.8	8.2	5.3	5.1	3.6	2.6	1.7	2.1	1.8	0.5	0.5	0.3	0.2	0.3	0.0	0.0
	N18016	5.5	24.1	11.6	12.3	8.2	7.7	5.5	6.0	4.4	3.1	2.3	4.1	3.1	0.7	0.5	0.3	0.3	0.4	0.0	0.0
	N18018*	4.8	45.6	9.3	9.2	7.9	6.5	5.5	3.4	2.4	3.4	1.9	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	N18030*	17.6	33.6	13.3	9.9	7.1	6.7	9.8	1.3	0.6	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Scraper	N18028*	37.9	15.9	14.4	10.9	9.4	5.1	3.3	1.2	0.9	0.4	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.1	0.0
	N18043*	20.0	17.1	13.6	5.4	4.8	4.2	3.9	3.8	3.3	3.4	8.8	8.7	2.8	0.2	0.0	0.0	0.0	0.0	0.0	0.0
Tractor/ Loader/ Backhoe	N18011*	1.8	52.2	15.4	9.8	7.0	4.8	3.5	3.6	1.2	0.3	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	N18012*	2.3	56.4	8.1	13.2	7.1	4.3	2.9	3.4	1.6	0.6	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	N18013*	15.1	39.7	9.5	9.6	7.2	5.8	4.6	3.3	2.8	1.1	1.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

* Based on estimated torque

Engine Operations of a Grader vs. NRTC Cycle



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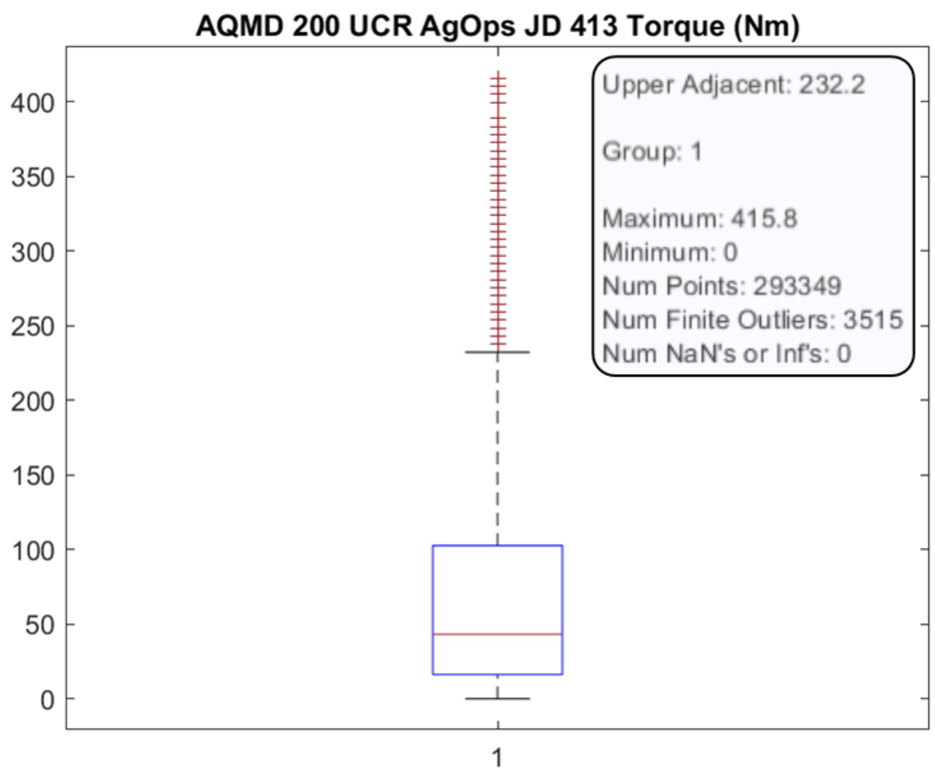
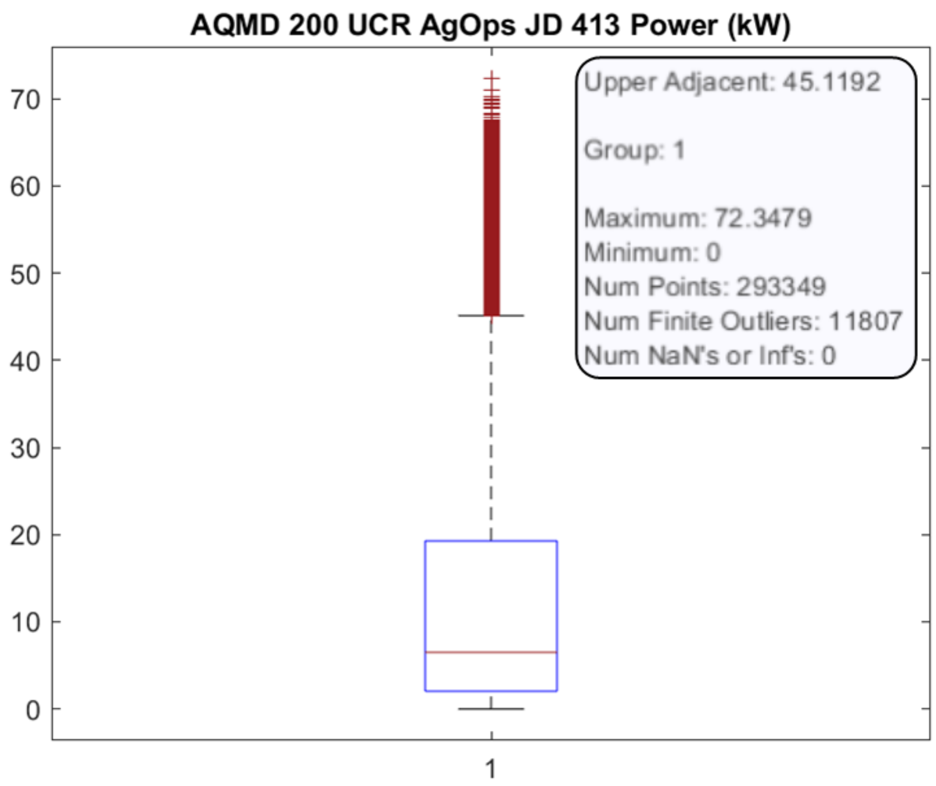
Real-World Torque and Power Requirements

- Equipment-specific torque and power distributions





Motor Sizing Analysis

Peak and Continuous Ratings Required

Equipment Type	Equipment ID	Torque Demand (Nm)		Power Demand (kW)	
		Maximum	Upper Adjacent	Maximum	Upper Adjacent
Agricultural Tractor	JD_413	416	232	72	45
	JD_414	420	317	78	62
Excavator	N18029	439	439	74	74
Grader	N18014	799	298	133	32
	N18019	1,151	563	125*	94*
	N18020	1,270	622	203	106
	N18022	1,139	588	127*	127*
	N18023	1,151	613	124*	124*
Off-Highway Tractor	N18021	2,692	2,692	282*	282*
	N18027	2,723	2,723	281*	281*
Rubber Tired Loader	N18015	820	479	142	76
	N18016	704	521	124	88
	N18018	1,051	1,051	87*	87*
	N18030	1,332	521	141*	141*
Scraper	N18028	1,101	375	200*	200*
	N18043	1,139	1,139	242*	242*
Tractor/ Loaders/ Backhoe	N18011	966*	317*	93*	82*
	N18012	722*	252*	76*	67*
	N18013	941*	401*	92*	92*

Ratings of Commercially Available Motors

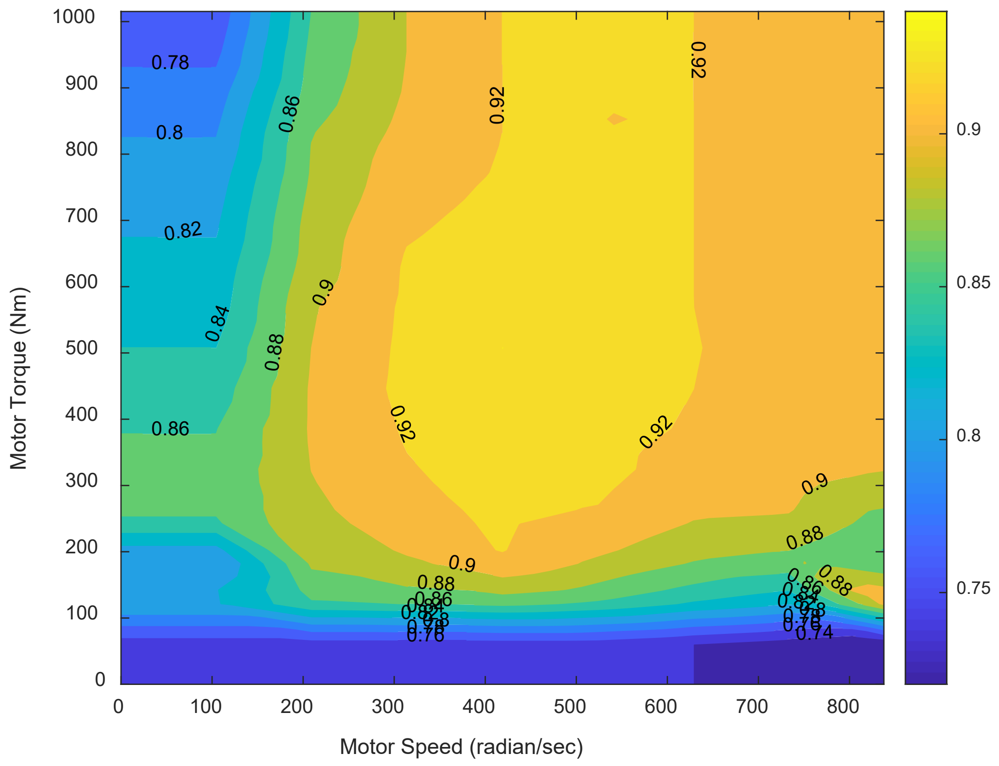
Series	Model	Torque Ratings (Nm)		Power Ratings (kW)	
		Peak	Continuous	Peak	Continuous
UQM 200 series	PowerPhase HD 220	700	350	220	120
	PowerPhase HD 250	900	360	250	150
	PowerPhase HD 950T	950	400	145	100
TM4 SUMO	HV2700-9P	2700	2060	250	195
	HV3400-9P	3400	2060	250	195
	HV3500-9P	3445	1970	370	260
Borg Warner HVH410-150	-	~2000	1400	160	120
EVO Axial Flux Electric Motor	1	600	260	220	94
	2	700	290	280	128
	3	1200	520	440	188
	4	350	145	140	64

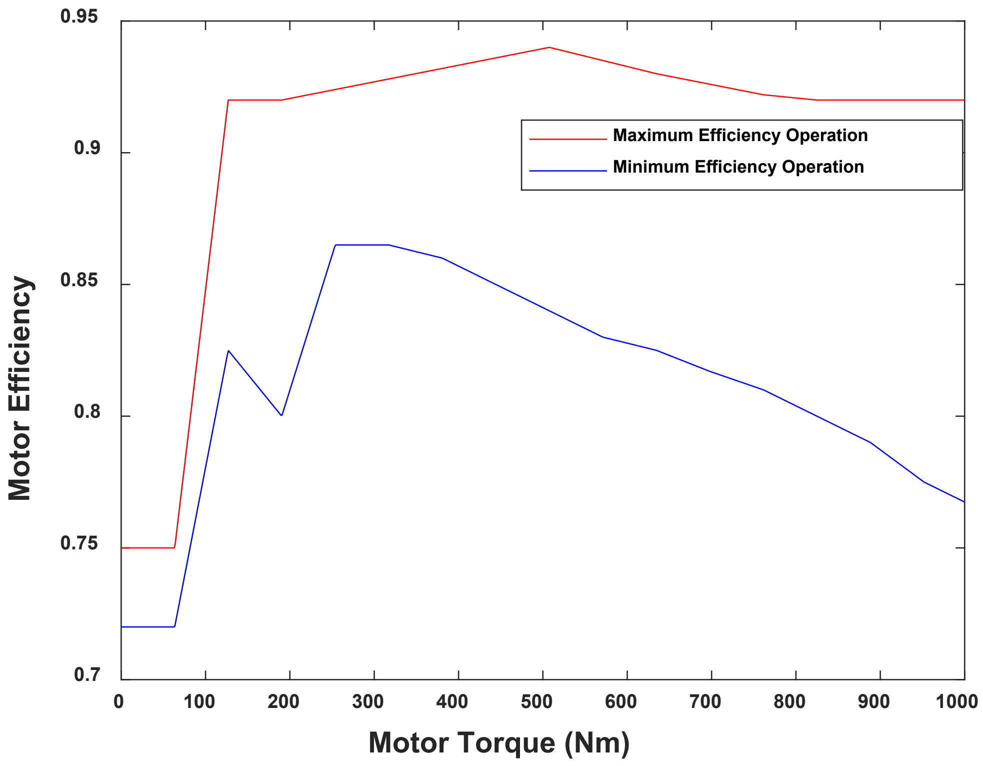
Motor Sizing Results

Equipment Type	Equip-ment ID	Available Motors										
		UQM Power-Phase HD 220	UQM Power-Phase HD 250	UQM Power-Phase HD 950T	TM4 SUMO HV2700-9P	TM4 SUMO HV3400-9P	TM4 SUMO HV3500-9P	Borg Warner HVH410-150	EVO Axial Flux Electric Motor 1	EVO Axial Flux Electric Motor 2	EVO Axial Flux Electric Motor 3	EVO Axial Flux Electric Motor 4
Excavator	N18029				X	X	X	X			X	
Grader	N18014		X	X	X	X	X	X			X	
Grader	N18019				x	x	x	x				
Grader	N18020				X	X	X					
Grader	N18022				x	x	x					
Grader	N18023				x	x	x				x	
Off-Highway Tractors	N18021											
Off-Highway Tractors	N18027											
Rubber-tired Loaders	N18015				X	X	X	X			X	
Rubber-tired Loaders	N18016				X	X	X	X				
Rubber-tired Loaders	N18018				x	x	x	x				
Rubber-tired Loaders	N18030				x	x	x					
Scraper	N18028						x					
Scraper	N18043						x					
Tractor/Loaders/Backhoes	N18011				x	x	x	x			x	
Tractor/Loaders/Backhoes	N18012		x	x	x	x	x	x			x	
Tractor/Loaders/Backhoes	N18013				x	x	x	x			x	

Battery Sizing Analysis

- Utilize efficiency map of a commercial heavy-duty electric motor
  - Assume minimum efficiency operation





Battery Sizing Analysis (continued)

- $Instataneous\ Energy\ Consumption\ (kW) = \frac{Motor\ Power\ Demand\ (kW)}{Minimum\ Motor\ Efficiency}$

- $Daily\ Energy\ Consumption\ (kWh) = \frac{\sum_{i=1}^{n}(Instantaneous\ Energy\ Consumption\ (kW))_i}{3600}$

- *Usable Battery Size* = max(*Daily Energy Consumption*)

- *Equipped Battery Size* = *Usable Battery Size* * 1.3

Battery Sizing Results

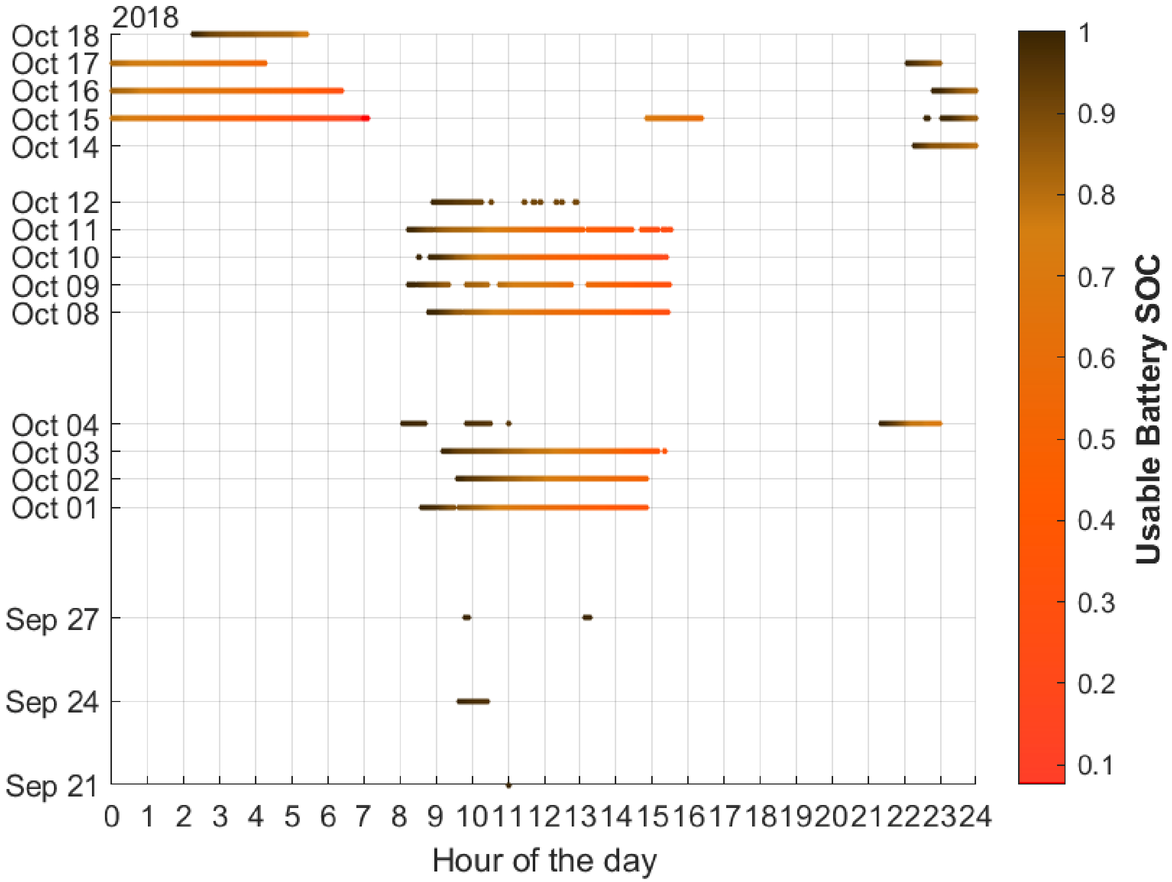
Equipment Type	Equipment ID	Individual Battery Size (kWh)	Standard Battery Size (kWh)		
			Usable Battery Size	Equipped Battery Size	Rounded Equipped Battery Size
Agricultural Tractor	JD_413	166	177	230	240
	JD_414	176			
Excavator	N18029	420	420	546	550
Grader	N18014	60	491	638	640
	N18019	490*			
	N18020	414			
	N18022	380*			
	N18023	323*			
Off-Highway Tractor	N18021	2,711*	2,712	3,526	3,530
	N18027	2,409*			
Rubber Tired Loader	N18015	210	604	785	790
	N18016	603			
	N18018	421*			
	N18030	534*			
Scraper	N18028	502*	1,423	1,850	1,850
	N18043	1,422*			
Tractor/ Loader/ Backhoe	N18011	184*	252	328	330
	N18012	251*			
	N18013	206*			

*Based on estimated power

Activity and Energy Flow Simulation

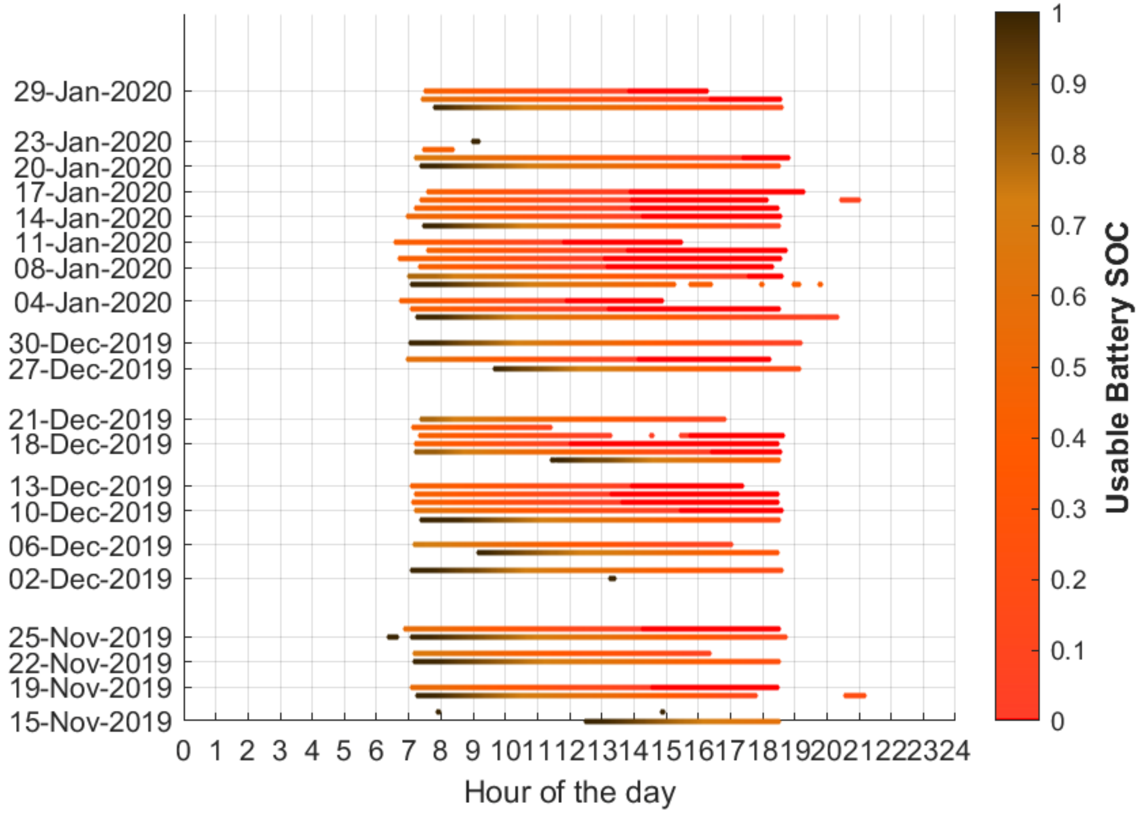
- Simulate electric equipment performing the same work as diesel equipment
- Consider various charging scenarios
  - End-of-shift charging
  - Opportunity charging during long breaks (> 2 hours)
  - Different charging power levels (50, 150, 200, 350 kW)

Simulated Electric Rubber-Tired Loader; 50 kW Charger

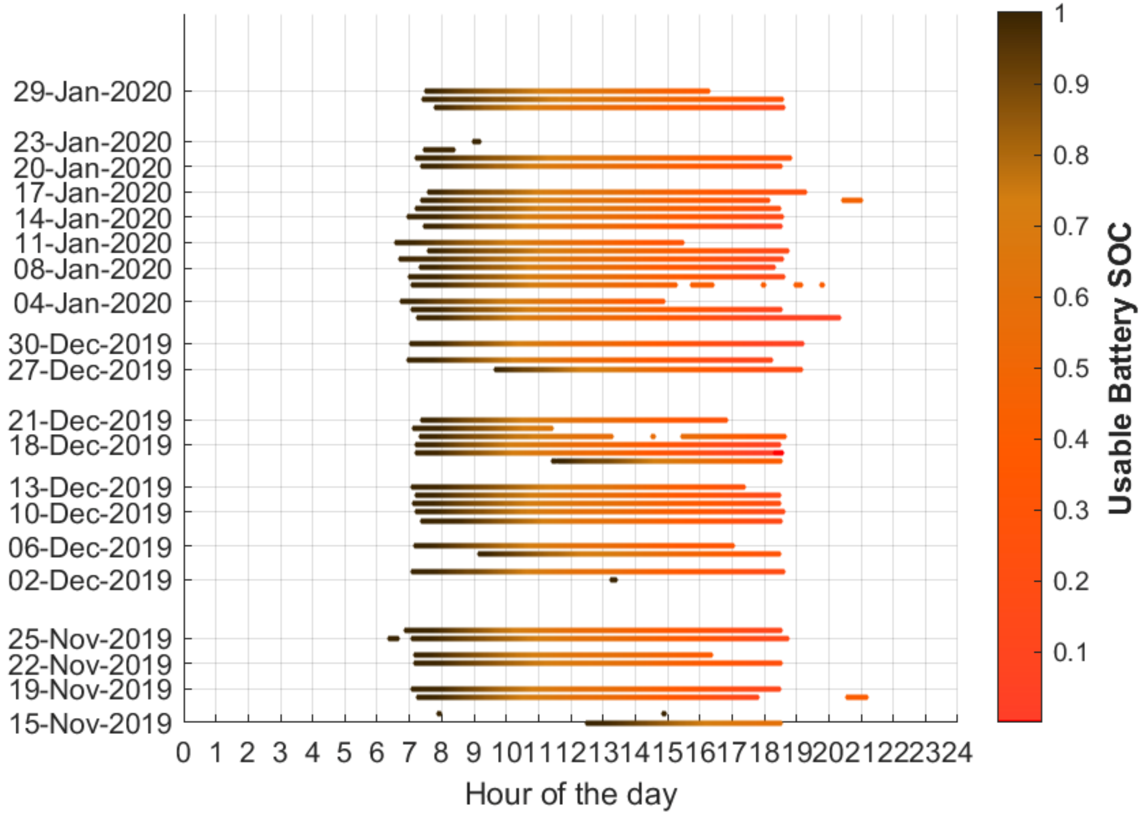


Effect of Charging Power Level

Simulated Electric Scraper; 50 kW Charger



Simulated Electric Scraper; 150 kW Charger



Summary of Simulation Results

Equipment Type	Usable Battery Size (kWh)	Equipment ID	Charging Power (kW)	Active Events (seconds)	Fulfilled Active Events (seconds)	% Active Events Fulfilled	Total Opera-ting Days	Opera-ting Days Fully Served	% Opera-ting Days Fully Served
Ag Tractor	177	JD 413	50	293,349	293,349	100	31	31	100
		JD 414	50	122,959	122,959	100	17	17	100
Excavator	420	N18029	50	921,961	921,961	100	46	46	100
Grader	491	N18014	50	47,705	47,705	100	27	27	100
		N18019	50	946,960	946,960	100	39	39	100
		N18020	50	224,505	224,505	100	10	10	100
		N18022	50	262,575	262,575	100	23	23	100
		N18023	50	242,771	242,771	100	22	22	100
Off-Highway Tractor	2712	N18021	50	805,247	441,578	55	25	8	32
			150	805,247	746,148	93	25	17	68
			200	805,247	805,247	100	25	25	100
		N18027	50	913,232	486,430	53	26	5	19
			150	913,232	902,398	99	26	23	88
			200	913,232	913,232	100	26	26	100
Rubber Tired Loader	604	N18015	50	138,858	138,858	100	26	26	100
		N18016	50	538,320	538,320	100	17	17	100
		N18018	50	400,560	400,560	100	23	23	100
		N18030	50	799,262	799,262	100	53	53	100
Scraper	1423	N18028	50	196,410	196,410	100	18	18	100
		N18043	50	1,618,271	1,289,937	80	47	23	49
			150	1,618,271	1,618,271	100	47	47	100
Tractor/ Loader/ Backhoe	252	N18011	50	238,583	238,583	100	20	20	100
		N18012	50	287,583	287,583	100	22	22	100
		N18013	50	215,585	215,585	100	20	20	100

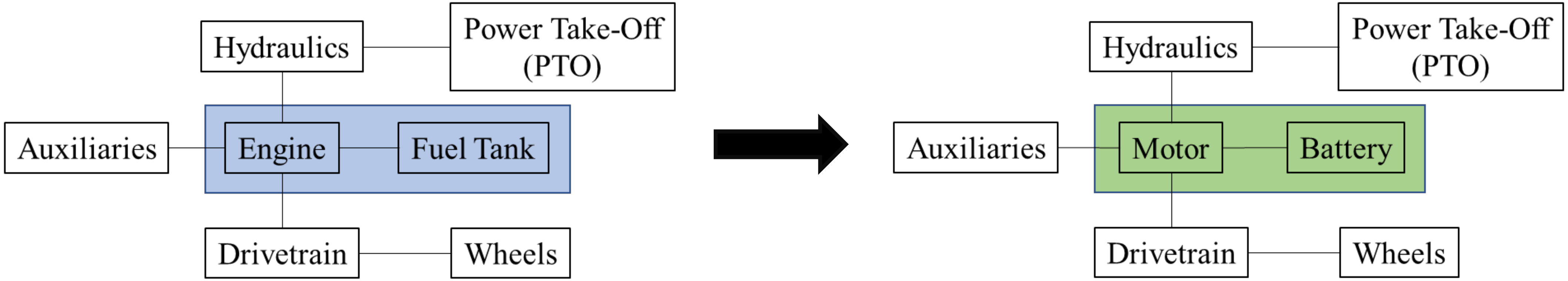
Presentation Outline

- Background and introduction
- State of off-road equipment electrification
- Real-world activity and energy use of off-road equipment
- Technical feasibility of electrifying off-road equipment
- Cost-effectiveness of electrifying off-road equipment
- Conclusions and recommendations

Analysis Overview

- Use equipment population, activity, fuel consumption, and emission data from OFFROAD2017

- Assume a drop-in replacement of ICE components by EV components



- Assume that new electric equipment will be used at the activity level reported in OFFROAD2017 for the calendar year it is purchased

Component Sizing based on OFFROAD2017 Data

- Battery
  - *fuel_gpd_per_equipment* = max(*fuel_gpd_per_equipment*)
  - *energy of consumed fuel* (kWh) $=$ *fuel_gpd_per_equipment* $\times 40.7$
  - *battery size* (kWh) = (*energy of consumed fuel* (kWh) × *engine efficiency*) ÷ *motor efficiency*

- Motor
  - *motor rating* (kW) = HP bin/*1.341*

- ICE
  - *ICE rating* (kW) = HP bin/*1.341*

Cost Calculation

- EV component costs
  - *battery cost* (\$) = *battery size* (kWh) × *per−unit battery cost* (\$/kWh)
  - *motor cost* (\$) = *motor fixed cost* (\$) + (*motor rating* (kW) × *per−unit motor cost* (\$/kW)
  - *additional EV system cost* (\$) = *motor rating* (kW) × *per−unit additional system cost* (\$/kW)
  - *advanced engineering cost* = η_{eng} × (*battery cost* + *motor cost* + *additional system cost*)

- ICE component costs
  - *ICE cost* (\$) = *ICE rating* (kW) × *per−unit ICE cost* (\$/kW)
  - *fuel tank cost* (\$) = *\$482*

Cost-Effectiveness Calculation

- Required funding amount
  - *funding per equipment* (\$) = *EV component costs* − *ICEV component costs*

- Emission reduction
  - *emission reduction* (tons per year) = *emission produced* (tons per day) × 186

- Cost-effectiveness of incentive funding
  - $cost\ effectiveness\ of\ funding\ dollars\ = \frac{Capital\ Recovery\ Factor\ \times funding\ amount}{emission\ reduction\ (tons\ per\ year)}$
  - $Capital\ Recovery\ Factor\ (CRF) = \frac{(1+discount\ rate)^{project\ duration} \times (discount\ rate)}{(1+discount\ rate)^{project\ duration}-1}$

Base Case Assumptions

- Diesel engine efficiency (used to size battery) is 35%.
- Electric motor efficiency (used to size battery) is 72%.
- Required motor power is the same as the HP bin.
- EV advanced engineering cost adds an additional 10%.
- Fuel tank cost is $482.
- Discount rate of US dollar is 1%.
- Per-unit component costs are taken from literature.

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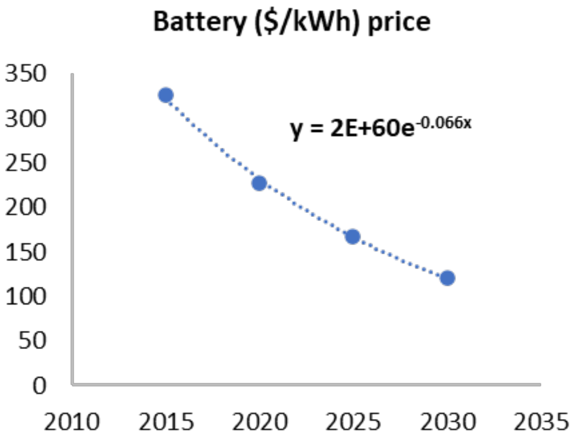
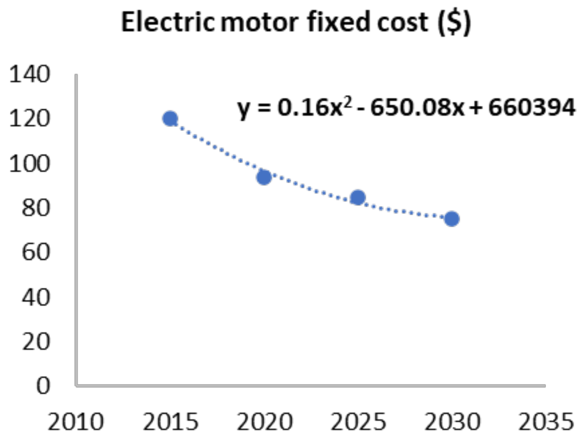
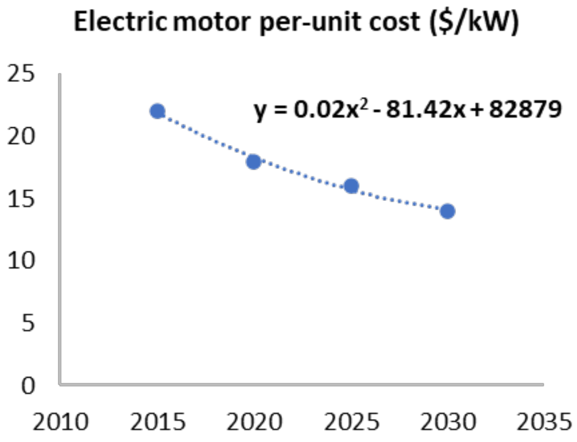
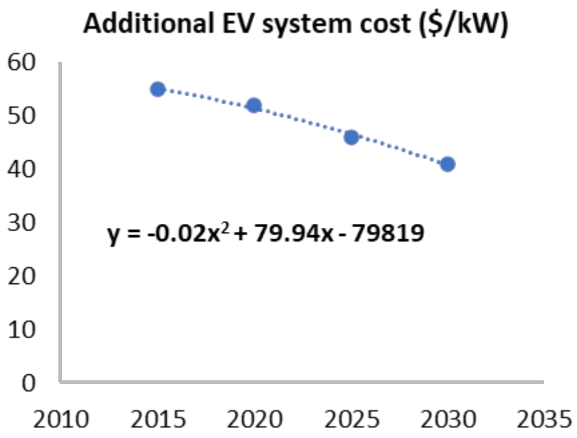
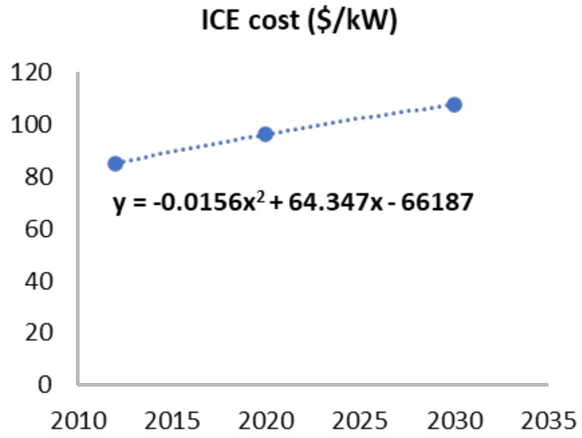
Per-Unit Component Costs







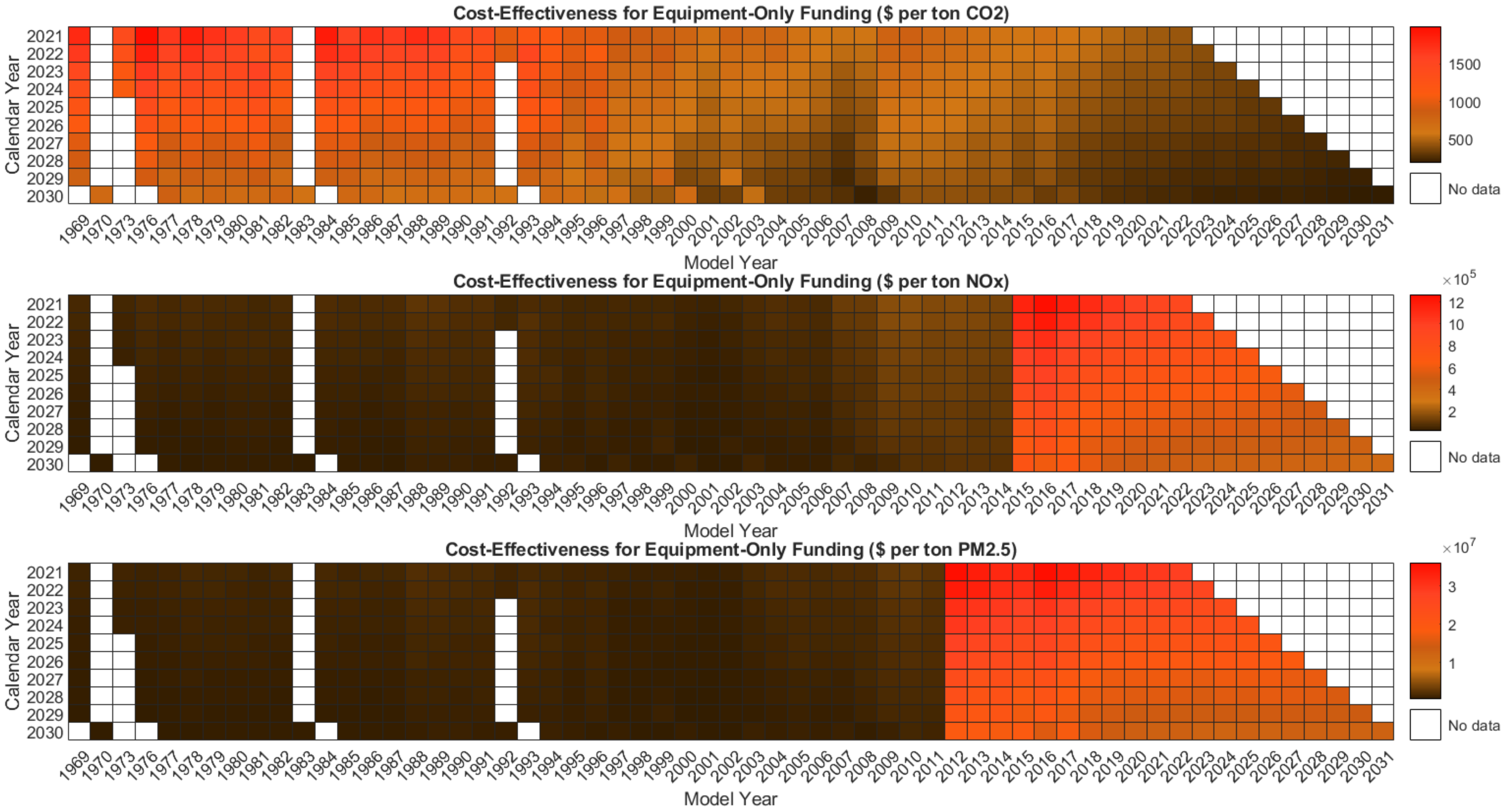




Sources:
den Boer, E., Aarnink, S., Kleiner, F., & Pagenkopf, J. (2013, July). Zero emission trucks. An overview of state-of-the-art technologies and their potential. CE Delft.
Moultak, Marissa, Nic Lutsey, and Dale Hall. "Transitioning to zero-emission heavy-duty freight vehicles." Int. Counc. Clean Transp (2017).

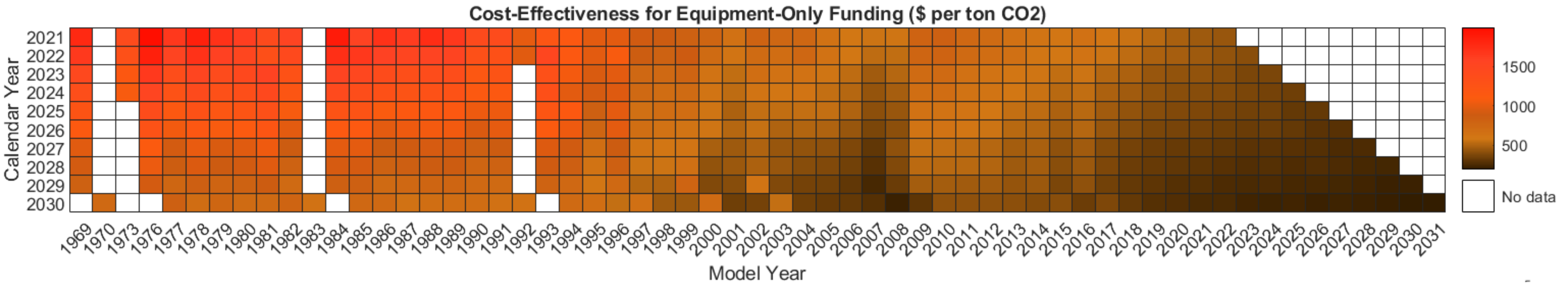
Cost Effectiveness Results

Excavator;
175 HP Bin

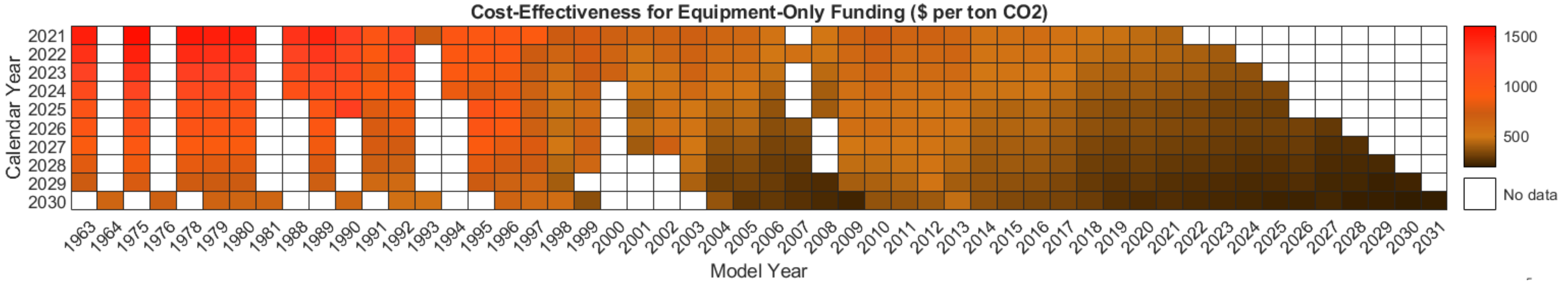


Cost Effectiveness Comparisons

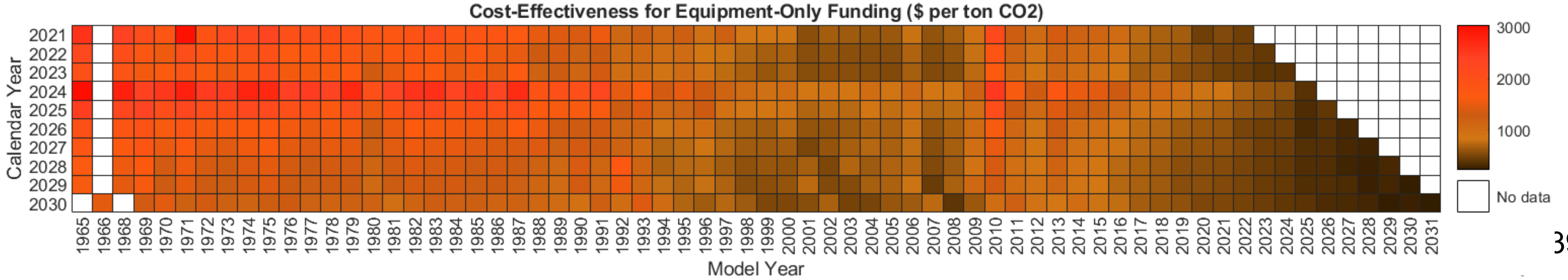
Excavator; 175 HP Bin



Excavator; 100 HP Bin



Graders; 175 HP Bin



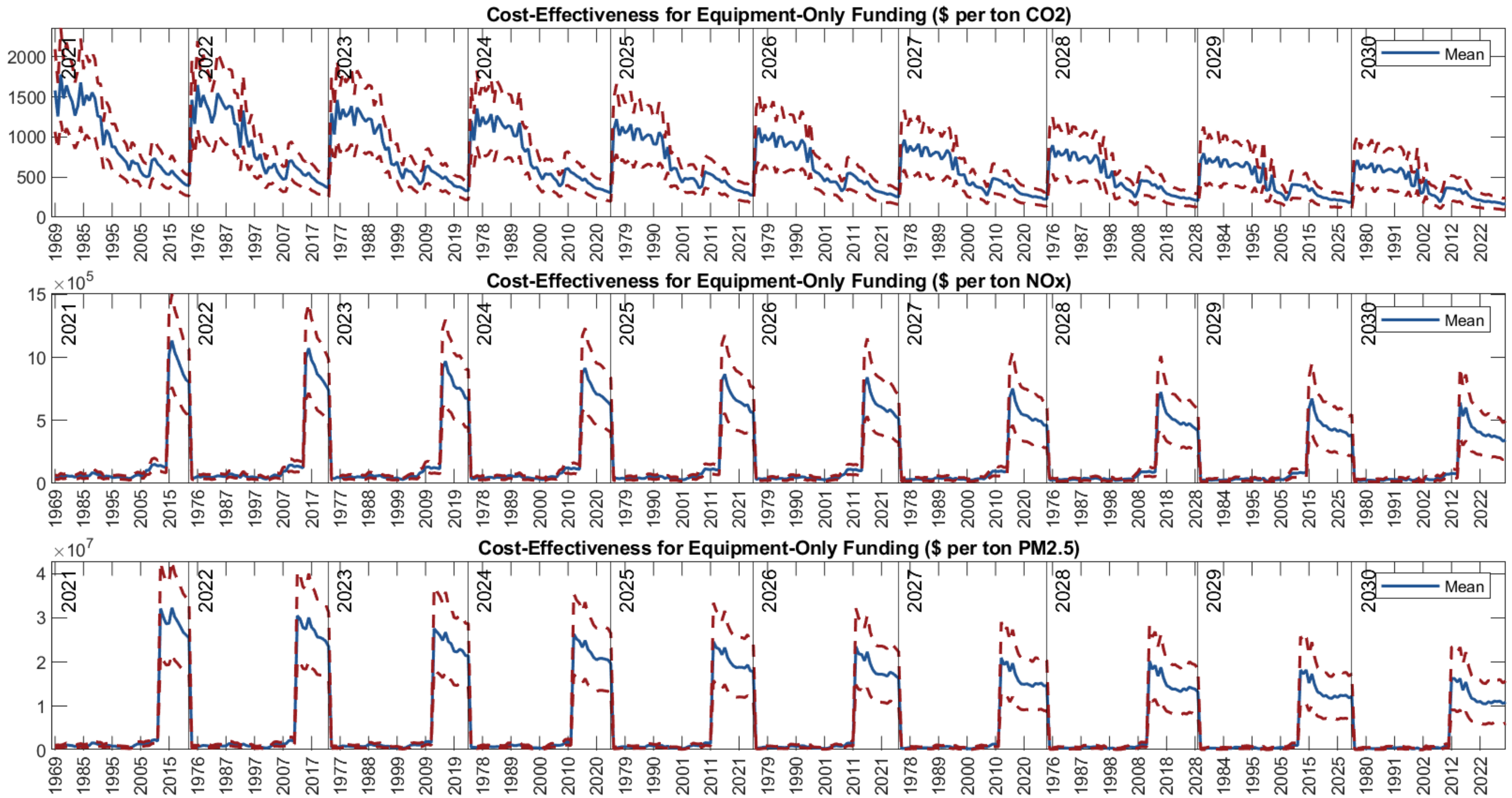
Sensitivity Analysis

- To evaluate the effects of parameter changes from the base case
  - Simulation of 59,049 scenarios

Parameter	Base Value	Values for Sensitivity Analysis
Diesel engine efficiency	0.35	0.25, 0.35, 0.45
Electric motor efficiency	0.72	0.72, 0.88, 0.94
%HP	1 (equal to the HP Bin size)	0.80, 0.90, 1
Battery per-unit cost ($/kWh)	$y = 2 \times 10^6 \times e^{-0.066x}$	y-10%, y, y+10%
Motor fixed cost ($)	$y = 0.16x^2 - 650.08x + 660394$	y-10%, y, y+10%
Motor per-unit cost ($/kW)	$y = 0.02x^2 - 81.42x + 82879$	y-10%, y, y+10%
Additional EV system per-unit cost ($/kW)	$y = -0.02x^2 + 79.94x - 79819$	y-10%, y, y+10%
Advanced engineering cost for EV	0.10	0.10, 0.15, 0.20
ICE cost ($/kW)	$y = -0.0156x^2 + 64.347x - 66187$	y-10%, y, y+10%
Fuel tank cost ($)	$y = 481.701$	y-10%, y, y+10%

Sensitivity Analysis Results

Excavator; 175 HP Bin



Cost Effectiveness by Equipment Type and Size

- It is most cost-effective to fund a turnover of equipment in the 51-75 horsepower range.
- Tractors/Loaders/ Backhoes are the most cost-effective type to be electrified.

Cost-Effectiveness for Equipment-Only Funding ($ per ton CO2)

HP Bin	50	75	100	175	300	600
Agricultural Tractors	$1660	$1792	$2171	$2059	$2205	$2288
Excavators	$467	$436	$503	$595	$580	$496
Graders	$796	$430	$896	$911	$721	$442
Rubber Tired Loaders	$742	$477	$735	$764	$722	$1012
Tractors/Loaders/Backhoes	$725	$140	$681	$765	$750	$881

Cost-Effectiveness for Equipment-Only Funding ($ per ton NOx)

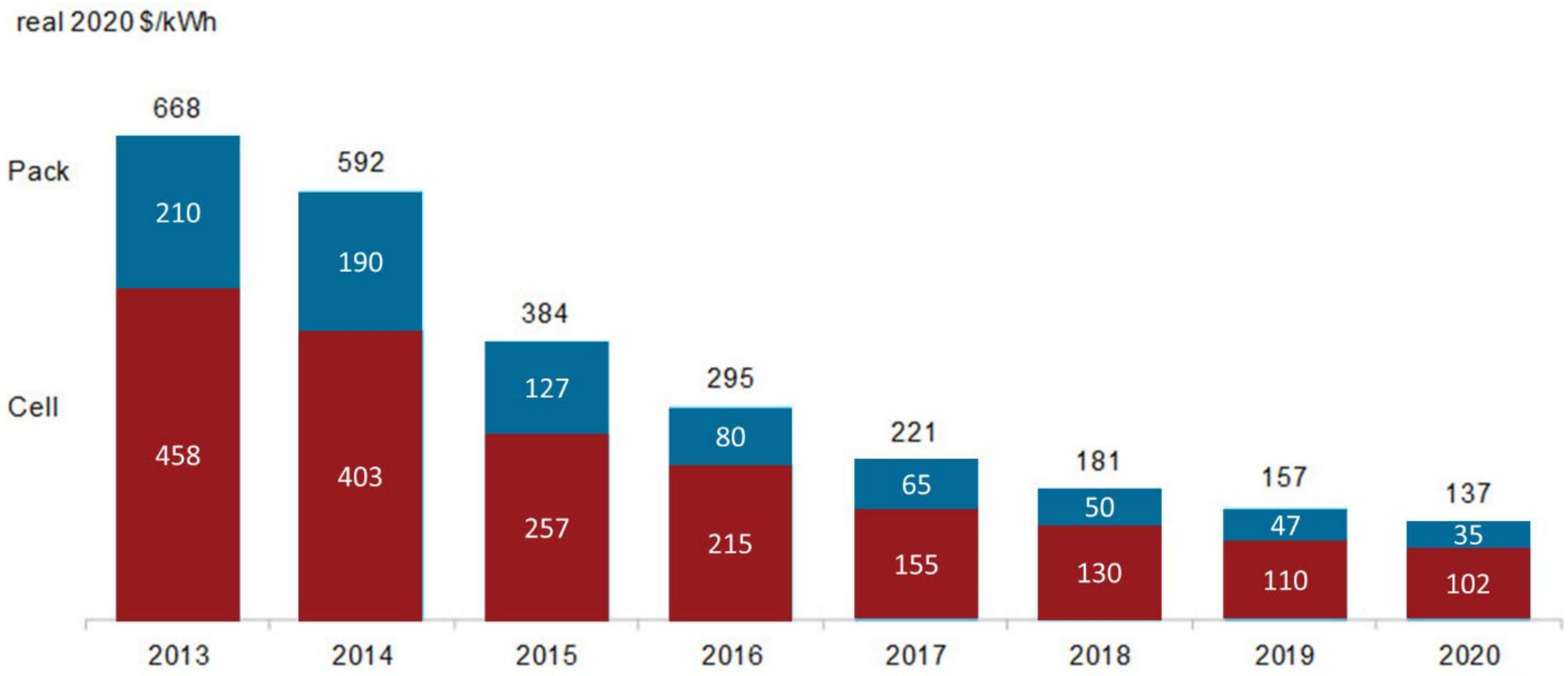
HP Bin	50	75	100	175	300	600
Agricultural Tractors	$24907	$21681	$52300	$36455	$45959	$99105
Excavators	$59466	$34087	$56107	$66863	$66288	$74049
Graders	$90646	$21053	$70047	$83337	$82923	$74803
Rubber Tired Loaders	$86869	$24250	$68039	$78864	$79129	$131349
Tractors/Loaders/Backhoes	$81308	$5468	$82291	$76316	$80208	$132903

Cost-Effectiveness for Equipment-Only Funding ($ per ton PM2.5)

HP Bin	50	75	100	175	300	600
Agricultural Tractors	$313639	$306780	$676315	$671842	$1167380	$2337584
Excavators	$874570	$383389	$805523	$1274696	$1653753	$1921092
Graders	$1042437	$283170	$913600	$1588636	$2077499	$2545574
Rubber Tired Loaders	$1115641	$278351	$951583	$1512206	$1952307	$3291922
Tractors/Loaders/Backhoes	$938036	$76281	$1264163	$1496643	$1923059	$3312555

Battery Prices Have Dropped

- Average prices of battery pack (dark blue) and battery cell (dark red)
  - 2020 real price is only 60% of the projected price



Source: BloombergNEF

Presentation Outline

- Background and introduction
- State of off-road equipment electrification
- Real-world activity and energy use of off-road equipment
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State of Off-Road Equipment Electrification

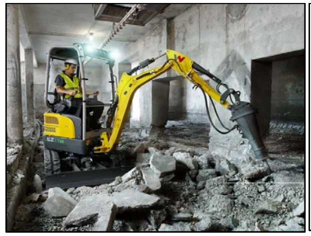
- Several construction & agricultural equipment can be, and have been, electrified.

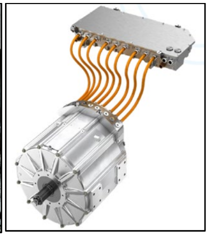
- Many barriers exist, but so do potential solutions.

Commercially Available


Hybrid dozer


Electric compact tractor


Electric compact excavator


High performance electric motor

Prototype


Electric compact dozer


Cabled Electric tractor


Electric excavator

Real-World Activity and Energy Use

- Activity and energy use patterns of the studied equipment vary widely.
  - Vary within each equipment type, but more so across equipment types
- Real-world engine operating patterns differ significantly from those of the certification cycles.

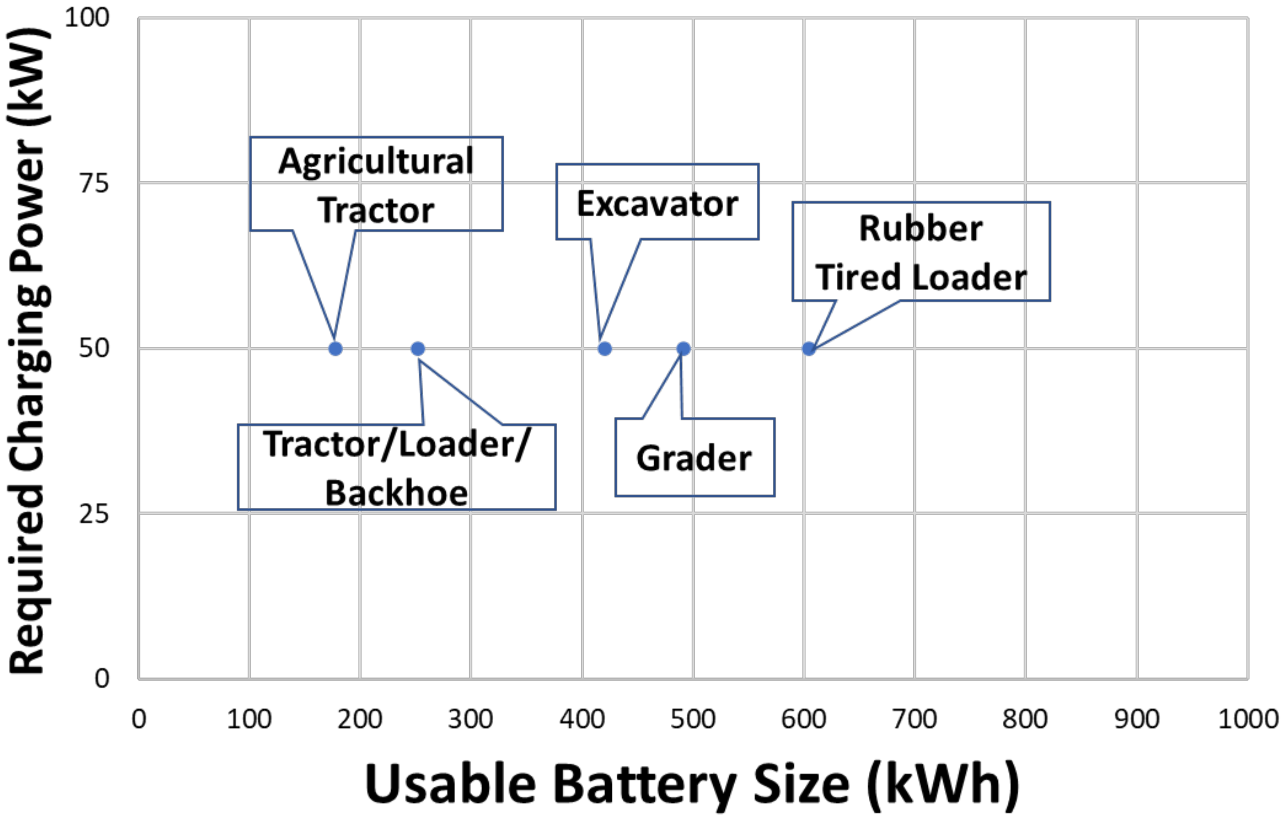
	% Torque >		5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95
	% Torque <=	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
Certification Cycles	NRTC	10.7	7.3	4.7	5.7	7.7	7.0	5.4	5.9	5.2	6.0	4.1	4.0	4.3	6.1	10.7	0.5	1.1	0.7	0.5	2.8
	NRSC	15.0	0.0	10.0	0.0	0.0	0.0	0.0	0.0	0.0	25.0	0.0	0.0	0.0	0.0	25.0	0.0	0.0	0.0	0.0	25.0
Ag Tractor	JD_413	25.3	21.7	13.6	8.1	7.0	5.3	3.2	4.6	3.8	3.7	2.2	0.8	0.3	0.1	0.2	0.1	0.0	0.0	0.0	0.0
	JD_414	4.2	17.1	12.9	6.4	8.6	10.0	11.7	10.9	7.0	5.1	2.5	1.1	0.7	0.5	0.4	0.3	0.2	0.2	0.1	0.1
Excavator	N18029	0.7	20.0	15.4	3.0	2.9	2.7	3.9	3.4	4.3	3.7	5.1	5.3	4.5	4.4	6.1	5.5	6.5	2.2	0.4	0.0
Grader	N18014	1.3	0.6	2.2	34.2	32.0	11.9	5.3	5.4	2.5	1.2	0.5	0.4	0.2	0.2	0.6	0.8	0.2	0.4	0.2	0.2
	N18019*	3.6	29.6	15.0	17.1	13.6	7.8	4.4	2.9	2.9	1.5	0.8	0.6	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	N18020	2.5	2.2	29.1	21.0	10.4	12.3	7.3	4.5	2.7	2.0	1.2	1.3	1.2	0.9	0.5	0.3	0.2	0.2	0.1	0.0
	N18022*	16.8	26.5	20.2	17.2	10.6	6.0	1.9	0.7	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	N18023*	2.1	15.1	13.9	11.7	14.4	12.5	10.0	6.5	4.7	3.7	2.7	1.5	0.6	0.3	0.2	0.1	0.0	0.0	0.0	0.0
Off-Highway Tractor	N18021*	4.2	24.8	4.9	5.2	5.7	8.3	9.6	9.3	14.0	10.6	2.8	0.5	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	N18027*	3.7	32.1	3.9	2.7	3.2	6.1	10.0	10.8	16.2	7.9	2.7	0.7	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Rubber Tired Loaders	N18015	3.1	19.7	19.8	15.5	9.8	8.2	5.3	5.1	3.6	2.6	1.7	2.1	1.8	0.5	0.5	0.3	0.2	0.3	0.0	0.0
	N18016	5.5	24.1	11.6	12.3	8.2	7.7	5.5	6.0	4.4	3.1	2.3	4.1	3.1	0.7	0.5	0.3	0.3	0.4	0.0	0.0
	N18018*	4.8	45.6	9.3	9.2	7.9	6.5	5.5	3.4	2.4	3.4	1.9	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	N18030*	17.6	33.6	13.3	9.9	7.1	6.7	9.8	1.3	0.6	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Scraper	N18028*	37.9	15.9	14.4	10.9	9.4	5.1	3.3	1.2	0.9	0.4	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.1	0.0
	N18043*	20.0	17.1	13.6	5.4	4.8	4.2	3.9	3.8	3.3	3.4	8.8	8.7	2.8	0.2	0.0	0.0	0.0	0.0	0.0	0.0
Tractor/ Loader/ Backhoe	N18011*	1.8	52.2	15.4	9.8	7.0	4.8	3.5	3.6	1.2	0.3	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	N18012*	2.3	56.4	8.1	13.2	7.1	4.3	2.9	3.4	1.6	0.6	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	N18013*	15.1	39.7	9.5	9.6	7.2	5.8	4.6	3.3	2.8	1.1	1.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

* Based on estimated torque

Technical Feasibility of Electric Off-Road Equipment

- Six of the seven equipment types studied could operate with a single electric motor.

- Five equipment types can be fully electrified with currently available electric motor and battery technologies, coupled with 50 kW charger.



Cost Effectiveness of Electric Off-Road Equipment

- It is generally more cost-effective to electrify equipment smaller than 100 horsepower.

- Dollars per ton of emissions reduction today would be about half of the results shown as battery prices have dropped.

Cost-Effectiveness for Equipment-Only Funding ($ per ton CO2)

HP Bin	50	75	100	175	300	600
Agricultural Tractors	$1660	$1792	$2171	$2059	$2205	$2288
Excavators	$467	$436	$503	$595	$580	$496
Graders	$796	$430	$896	$911	$721	$442
Rubber Tired Loaders	$742	$477	$735	$764	$722	$1012
Tractors/Loaders/Backhoes	$725	$140	$681	$765	$750	$881

Cost-Effectiveness for Equipment-Only Funding ($ per ton NOx)

HP Bin	50	75	100	175	300	600
Agricultural Tractors	$24907	$21681	$52300	$36455	$45959	$99105
Excavators	$59466	$34087	$56107	$66863	$66288	$74049
Graders	$90646	$21053	$70047	$83337	$82923	$74803
Rubber Tired Loaders	$86869	$24250	$68039	$78864	$79129	$131349
Tractors/Loaders/Backhoes	$81308	$5468	$82291	$76316	$80208	$132903

Cost-Effectiveness for Equipment-Only Funding ($ per ton PM2.5)

HP Bin	50	75	100	175	300	600
Agricultural Tractors	$313639	$306780	$676315	$671842	$1167380	$2337584
Excavators	$874570	$383389	$805523	$1274696	$1653753	$1921092
Graders	$1042437	$283170	$913600	$1588636	$2077499	$2545574
Rubber Tired Loaders	$1115641	$278351	$951583	$1512206	$1952307	$3291922
Tractors/Loaders/Backhoes	$938036	$76281	$1264163	$1496643	$1923059	$3312555

Recommendations

- Initially focused on the most populous and top emitting equipment types
  - Agricultural tractors
  - Excavators
  - Graders
  - Rubber tired loaders
  - Tractors/loaders/backhoes

- Initially focused on equipment with 100 horsepower or lower
  - 78% of the total population of off-road equipment in California
  - 24% of the annual total diesel fuel consumption
  - Relatively more cost-effective than electrifying larger equipment

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Thank You

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