Hybridization and Full Electrification Potential in Off-Road Applications

(CARB Agreement No. 18RD016)

FINAL REPORT

Prepared for:

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Table of Contents

List of Tables

List of Figures

List of Abbreviations

AQMD	Air Quality Management District
BEV	Battery electric vehicle
Caltrans	California Department of Transportation
CARB	California Air Resources Board
CMAQ	Congestion Mitigation and Air Quality
CO_2	Carbon dioxide
CORE	Clean Off Road Equipment Voucher Incentive Project
CRADA	Cooperative Research and Development Agreement
CRF	Capital Recovery Factor
CSV	comma-separated values file
DC	Direct current
DOORS	Diesel Off-Road Online Reporting System
ECU	Engine control unit
e-CVT	Electronically controlled continuously variable transmission
EIN	Equipment Identification Number
EPA	U.S. Environmental Protection Agency
ESS	Energy storage system
EV	Electric vehicle
FARMER	Funding Agricultural Replacement Measures for Emission Reductions
FCEV	Fuel cell electric vehicle
GHG	Greenhouse gas
gpd	Gallons per day
GPS	Global positioning system
gpy	Gallons per year
HEV	Hybrid electric vehicle
hp-hrs	Horsepower-hours
ICE	Internal combustion engine
ICEV	Internal combustion engine vehicle
L/hr	Liter per hour
lb/h	Pound per hour
$LiFePO_4$	Lithium Iron Phosphate
LiNiMnCo	Lithium Nickel Manganese Cobalt Oxide
$NaNiCl_2$	Sodium-Nickle-Chloride
NH_3	Ammonia
NO_x	Oxides of nitrogen
NRSC	Non-Road Steady Cycle
NRTC	Non-road transient cycle
OEM	Original equipment manufacturer
OHV	Off-highway vehicle
PAMS	Portable activity measurement system
PM	Particulate matter
PM10	Particulate matter with a diameter of 10 microns or less

PM2.5	Particulate matter with a diameter of 2.5 microns or less

List of Abbreviations (continued)

PTO	Power takeoff
PV	Photovoltaic
PWM	Pulse width modulation
QA/QC	Quality assurance/quality control
RES	Renewable energy source
ROG	Reactive organic gases
SC	Supercapacitor
SJVAPCD	San Joaquin Valley Air Pollution Control District
SLB	Second-life battery
SMUD	Sacramento Municipal Utility District
SOC	State of charge
SOON	Surplus Off-Road Opt-In for NOx
SO_x	Sulfur oxides
SUV	Sports utility vehicles
ton/h	Tons per hour
tpd	Tons per day
UCR	University of California at Riverside
US	United States
UTV	Utility terrain vehicles
V2G	Vehicle to grid
VAT	Value-added tax
VRLA	Valve regulated lead acid

Abstract

As the off-road sector accounts for an increasingly larger share of the greenhouse gas and criteria pollutant emission inventories in California, there has been growing interest in partially or fully electrifying this sector. The objective of this research is to assess the potential for electrifying off-road equipment used in construction and agriculture applications. By analyzing their real-world in-use operation and energy demand, it is found that agricultural tractors, excavators, graders, rubber tired loaders, and tractors/loaders/backhoes, which are among the most populous and top emitting equipment types in their respective categories, can be fully electrified with the currently available electric motor and battery technologies. For these equipment types, funding a turnover of equipment smaller than 100 horsepower would generally be more cost-effective, in terms of dollars per ton of emission reduction, than larger ones at this time. Given that diesel equipment with 100 horsepower or lower are responsible for about a quarter of the annual total diesel fuel consumption and greenhouse gas emissions by off-road equipment in California, it is recommended that incentive and regulatory programs be designed to accelerate the development, demonstration, and adoption of electric off-road equipment in these types and sizes as the initial targets.

Executive Summary

Background and Objectives

California has set ambitious goals to reduce greenhouse gas (GHG) emissions across all sectors. These goals will be achieved using a mixture of regulatory strategies and incentives. As a significant source of GHG and criteria pollutant emissions, the off-road sector is an important target for emissions reduction. However, off-road equipment has a wide variety of applications, engine sizes, and configurations making it a challenge to characterize their operations, energy demands, and duty cycles. Additionally, engine and equipment manufacturers vary in their size and market share, and smaller businesses may be significantly impacted by new emission regulations. In order to design incentive programs or regulations that will move this sector toward a cleaner and more sustainable future, a comprehensive study is needed to determine the technological and economic feasibility of partially or fully electrifying off-road equipment. Thus, the objective of this project is to research the potential for hybridization and electrification in off-road equipment that maximize climate and air quality benefits while remaining both technically and economically viable. The focus for this project is on off-road equipment used in construction and agriculture applications.

Methods and Results

To achieve the project objective, four research tasks were performed and the key findings discussed below:

Reviewing the State of Off-Road Equipment Electrification

A thorough literature and market review was conducted on components and powertrain architectures of electric equipment, their advantages and limitations, available and upcoming electric equipment in the market. In addition, industry interviews were conducted to obtain the manufacturers' perspectives on electrifying the off-road sector. The review results reveal that critical electric components (e.g., motor and battery) used in on-road heavy-duty electric vehicles can be transferred to off-road equipment. In fact, a fully electric version of some small equipment such as compact excavators are commercially available, and several electric equipment of larger sizes have been in demonstration or prototype stage (see examples in Figure E-1). While the landscape of electric off-road equipment is fast changing with several new models announced by manufacturers, one key barrier to their market penetration is the higher costs of making these equipment, primarily driven by the battery cost, as compared to the conventional diesel counterpart. In addition, the lack of convenient charging solutions, especially in remote locations, is another important barrier.

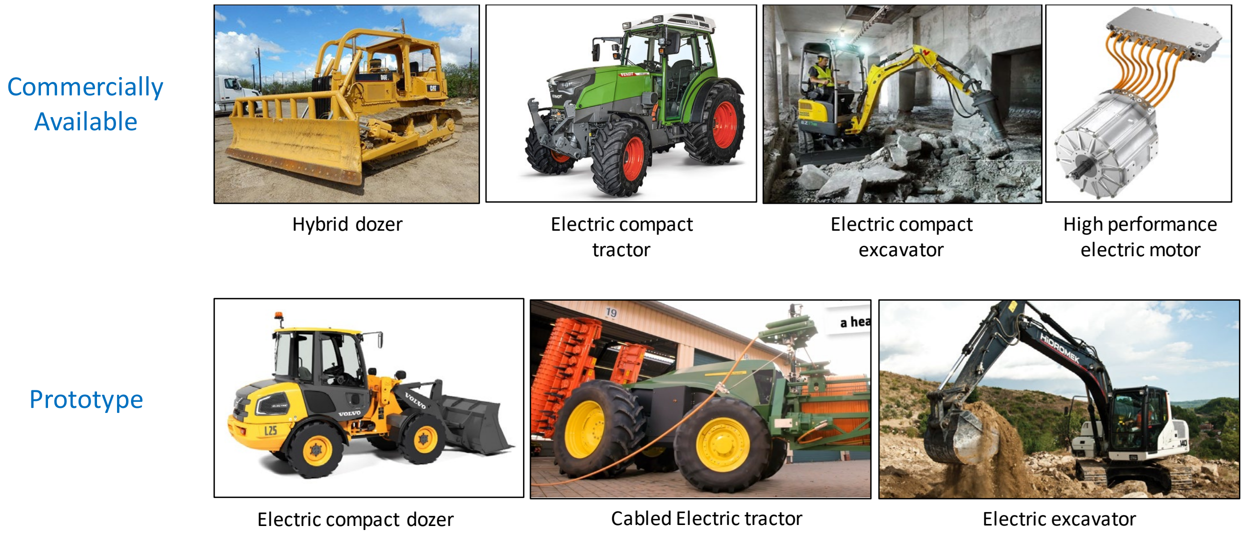


Figure E-1. Examples of commercially available hybrid electric and full electric off-road equipment as well as those in the prototype stage

Analyzing Real-World Energy Consumption of Off-Road Equipment

Detailed analyses of real-world, in-use activity and energy consumption data were performed for 22 pieces of equipment across eight common equipment types: agricultural tractor, crawler tractor, excavator, grader, off-highway tractor, rubber tired loader, scraper, and tractor/loader/backhoe. Activity statistics characterizing number of starts, engine speed, engine torque, fuel consumption, and others were calculated. The results show that these statistics vary within, but more so across equipment types. It was also found that in-use engine speed and torque distributions differ significantly from those of the certification cycles (non-road transient cycle or NRTC, and non-road steady cycle or NRSC) for off-road engines (see Table E-1), suggesting that the certification cycles are not likely to be representative of how the engines of these equipment types operate in the real world. However, it should be noted that certification cycles are composite of duty cycles of multiple equipment types, so the overall differences were expected. In addition, the data reveal that the observed levels of usage for these equipment differs from those estimated by the OFFROAD2017 model by -90% to 456%, although it should be noted that the observed data are from individual pieces of equipment and may not be representative of all the equipment of that type, size, and model year. This finding does not necessarily mean that the OFFROAD2017 model underestimates or overestimates the level of equipment usage and emissions inventory, but rather indicates the high variability in the usage of individual pieces of equipment even of the same type, size, and model year.

Table E-1. Distributions of percent engine torque in real-world in-use engine activity data as compared to those in the certification cycles

	% Torque >		5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	Sum
	% Torque <=	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	
Certification Cycles	NRTC	11	7	5	6	8	7	5	6	5	6	4	4	4	6	11	0	1	1	0	3	100
	NRSC	15	0	10	0	0	0	0	0	0	25	0	0	0	0	25	0	0	0	0	25	100
Agricultural Tractor	JD_413	25	22	14	8	7	5	3	5	4	4	2	1	0	0	0	0	0	0	0	0	100
	JD_414	4	17	13	6	9	10	12	11	7	5	3	1	1	1	0	0	0	0	0	0	100
Excavator	N18029	1	20	15	3	3	3	4	3	4	4	5	5	5	4	6	6	6	2	0	0	100
Grader	N18014	1	1	2	34	32	12	5	5	2	1	0	0	0	0	1	1	0	0	0	0	100
	N18019*	4	30	15	17	14	8	4	3	3	2	1	1	0	0	0	0	0	0	0	0	100
	N18020	3	2	29	21	10	12	7	5	3	2	1	1	1	1	1	0	0	0	0	0	100
	N18022*	17	26	20	17	11	6	2	1	0	0	0	0	0	0	0	0	0	0	0	0	100
	N18023*	2	15	14	12	14	12	10	7	5	4	3	2	1	0	0	0	0	0	0	0	100
Off-Highway Tractor	N18021*	4	25	5	5	6	8	10	9	14	11	3	0	0	0	0	0	0	0	0	0	100
	N18027*	4	32	4	3	3	6	10	11	16	8	3	1	0	0	0	0	0	0	0	0	100
Rubber Tired Loaders	N18015	3	20	20	16	10	8	5	5	4	3	2	2	2	0	0	0	0	0	0	0	100
	N18016	5	24	12	12	8	8	6	6	4	3	2	4	3	1	1	0	0	0	0	0	100
	N18018*	5	46	9	9	8	6	6	3	2	3	2	0	0	0	0	0	0	0	0	0	100
	N18030*	18	34	13	10	7	7	10	1	1	0	0	0	0	0	0	0	0	0	0	0	100
Scraper	N18028*	38	16	14	11	9	5	3	1	1	0	0	0	0	0	0	0	0	0	0	0	100
	N18043*	20	17	14	5	5	4	4	4	3	3	9	9	3	0	0	0	0	0	0	0	100
Tractor/ Loader/ Backhoe	N18011*	2	52	15	10	7	5	3	4	1	0	0	0	0	0	0	0	0	0	0	0	100
	N18012*	2	56	8	13	7	4	3	3	2	1	0	0	0	0	0	0	0	0	0	0	100
	N18013*	15	40	9	10	7	6	5	3	3	1	1	0	0	0	0	0	0	0	0	0	100

** Based on estimated torque*

Evaluating Technical Feasibility of Electrifying Off-Road Equipment

From the 22 equipment pieces mentioned earlier, it was possible to obtain torque and power demands data for 19 of them. The other three had significant amount of missing or invalid data for one or more parameters required to calculate power and torque demands. Using these real-world in-use operating torque and power demands data, the technical feasibility of fully electrifying 19 pieces of equipment in seven different types—two agricultural tractors, one excavator, five graders, two off-highway tractor, four rubber tired loaders, two scrapers, and three tractors/loaders/backhoes—was evaluated. It was found that all the equipment except the two off-highway tractors could operate with a single electric motor as a pre-transmission drop-in replacement for the diesel engine. Use of multiple motors, modification of transmission ratios, or hybridization may be possible options for the off-highway tractors. In addition, battery sizing of these equipment was conducted for a battery electric powertrain employing a commercially available heavy-duty electric motor. For each equipment, the maximum energy consumption per day was taken as the required battery size so that it could serve all the daily energy demands. Also, the charger power rating required was determined by simulating the battery state of charge (SOC) based on the in-use activity profile of each equipment in a time series fashion. The results showed that five equipment types—agricultural tractor, excavator, grader, rubber tired loader, and tractor/loader/backhoe—can be fully electrified with the currently available electric motor and battery components while utilizing a 50 kW charger. (see Figure E-2). These specifications are technologically possible now given the ongoing demonstration of battery electric top handlers with ~1 MWh battery packs at the San Pedro ports. The other two equipment types—off-highway tractor and scraper—would require 2.7 MWh and 1.4 MWh battery packs along with 200 kW and 150 kW chargers, respectively, in order to meet 100% of the energy demands observed. The required battery sizes of these two equipment types may not be realistic at this time, but some form of hybridization may be possible. It is important to note that these conclusions are drawn from studying a fairly small sample of equipment from each type, and considering the largest battery size fitted in an equipment currently as a reference. Further in-depth analyses on a larger equipment population will provide additional information on vocation-specific work and energy demands, charging infrastructure requirements, and equipment costs, which can be used to update the findings and conclusions of this study.

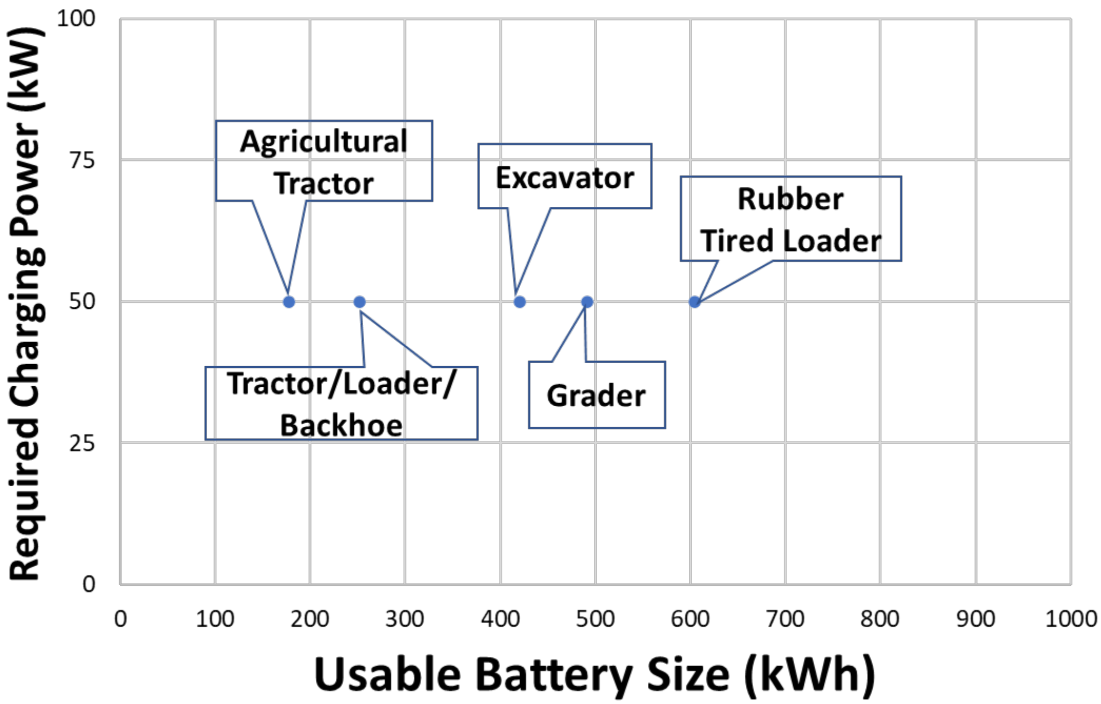


Figure E-2. Battery size and charging power required for equipment types suitable for battery electrification, as determined by real-world in-use activity data

Estimating Cost-Effectiveness of Funding a Purchase of Electric Off-Road Equipment

To estimate the cost-effectiveness of funding a turnover of existing off-road diesel equipment to electric equipment, a methodology was developed that utilizes available data from the OFFROAD2017 model to determine the sizes of electric motor and battery for each equipment type and size, which were then used to estimate the base cost of the corresponding electric equipment. After that, the estimated base cost was used to determine the funding cost-effectiveness in terms of dollars per ton of emission reduction. The methodology was applied to 78 equipment types in the OFFROAD2017 model, which include the five equipment types deemed feasible to be fully electrified in the previous task. This resulted in a database of funding cost-effectiveness for each equipment type and size, which can be compared across different equipment types and sizes. For example, among the five equipment types that can be fully electrified, it is most cost-effective to fund a turnover of equipment in the 51-75 horsepower range, especially for tractors/loaders/backhoes. This is illustrated in Figure E-3, which shows the average funding cost-effectiveness per equipment for certain equipment types and sizes over a 10-year lifetime.

It should be pointed out that recent data released after the cost-effectiveness analysis has been completed show that the real battery price in 2020 was only 60% of the projected battery price used in the analysis. Since the battery cost accounts for approximately 80% of the total electric vehicle component cost in the analysis, the actual incentive funding required and the dollars per ton of emission reduction would be about half of the results presented in Figure E-3 and in this report.

Conclusions and Recommendations

As the off-road sector accounts for an increasingly larger share of the GHG and criteria pollutant emission inventories in California, there has been growing interest in partially or fully electrifying this sector. This research has shown that agricultural tractors, excavators, graders, rubber tired loaders, and tractors/loaders/backhoes, which are among the most populous and top emitting equipment types in their respective categories, can be electrified with the currently available electric motor and battery components. For these equipment types, funding a turnover of equipment smaller than 100 horsepower would generally be more cost-effective, in terms of dollars per ton of emission reduction, than larger ones at this time. Data from the OFFROAD2017 model show that diesel equipment with 100 horsepower or lower are responsible for about 24% of the annual total diesel fuel consumption and 78% of the total population of off-road equipment in California. Therefore, it is recommended that incentive and regulatory programs be designed to accelerate the development, demonstration, and adoption of electric off-road equipment in these types and sizes as the initial targets.

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

Figure E-3. Average funding cost-effectiveness for selected equipment types and sizes

1 Introduction

1.1 Background

California has set ambitious goals to reduce greenhouse gas (GHG) emissions as defined in Assembly Bill 32 [1]. These goals will be achieved using a mixture of regulatory strategies and incentives. As a significant source of GHG and criteria pollutant emissions, the off-road sector is an important target for emissions reduction [2]. However, off-road equipment has a wide variety of applications, engine sizes, and configurations making it a challenge to characterize their operations, energy demands, and duty cycles. Additionally, engine and equipment manufacturers vary in their size and market share and smaller businesses may be significantly impacted by new emission regulations. In order to design incentive programs or regulations that will move this sector toward a cleaner and more sustainable future, an assessment needed to determine both the technological and economic feasibility of hybridizing or fully electrifying off-road equipment.

1.1.1 Inventories of Off-Road Equipment

We have performed an extensive search for information about off-road equipment inventory, especially one specific to California. We have found that there is very limited information available publicly that can be used to construct the inventory of off-road construction and agricultural equipment in California. The best source of this information is the California Air Resources Board (CARB)'s OFFROAD2017 database [3] from where population and emission estimates of off-road construction (including mining) and agricultural equipment in various applications can be obtained. Thus, the analysis results in this section are based on data from OFFROAD2017.

1.1.1.1 Construction Equipment Inventory

There are 20 types of construction equipment in the OFFROAD2017 database. Figure 1-1 shows the population of each equipment type in California in calendar year 2018. The tractors/loaders/backhoes category is the primary one, accounting for 26% of the total construction equipment population. When combined with rubber tired loaders (9%) and skid steer loaders (9%), the loaders in general are the most common type of construction equipment in California. Excavators also contribute significantly to the off-road construction equipment inventory in California, having the second largest population in the state (11%). Together the top 10 categories account for about 85% of the total population.

Estimates of emissions from each type of construction equipment are also available from the OFFROAD2017 database. Estimates for carbon dioxide (CO_2), oxides of nitrogen (NO_x), and particulate matter (PM) emissions were obtained for calendar year 2018. Figure 1-2 shows CO_2 emission from each type of construction equipment, where rubber tired loaders along with tractors/loaders/backhoes, off-highway trucks, excavators, and scrapers are the top five CO_2 emitters. Off-highway trucks, scrapers, rubber tired loaders, and even excavators have significantly smaller population than tractors/loaders/backhoes. But in terms of CO_2 emission, these categories are comparable with tractors/loaders/backhoes. Therefore, targeting these four off-road equipment categories for electrification/hybridization can lead to significant reduction in CO_2 emission with comparatively less investment in fleet turnover than the tractors/loaders/backhoes category.

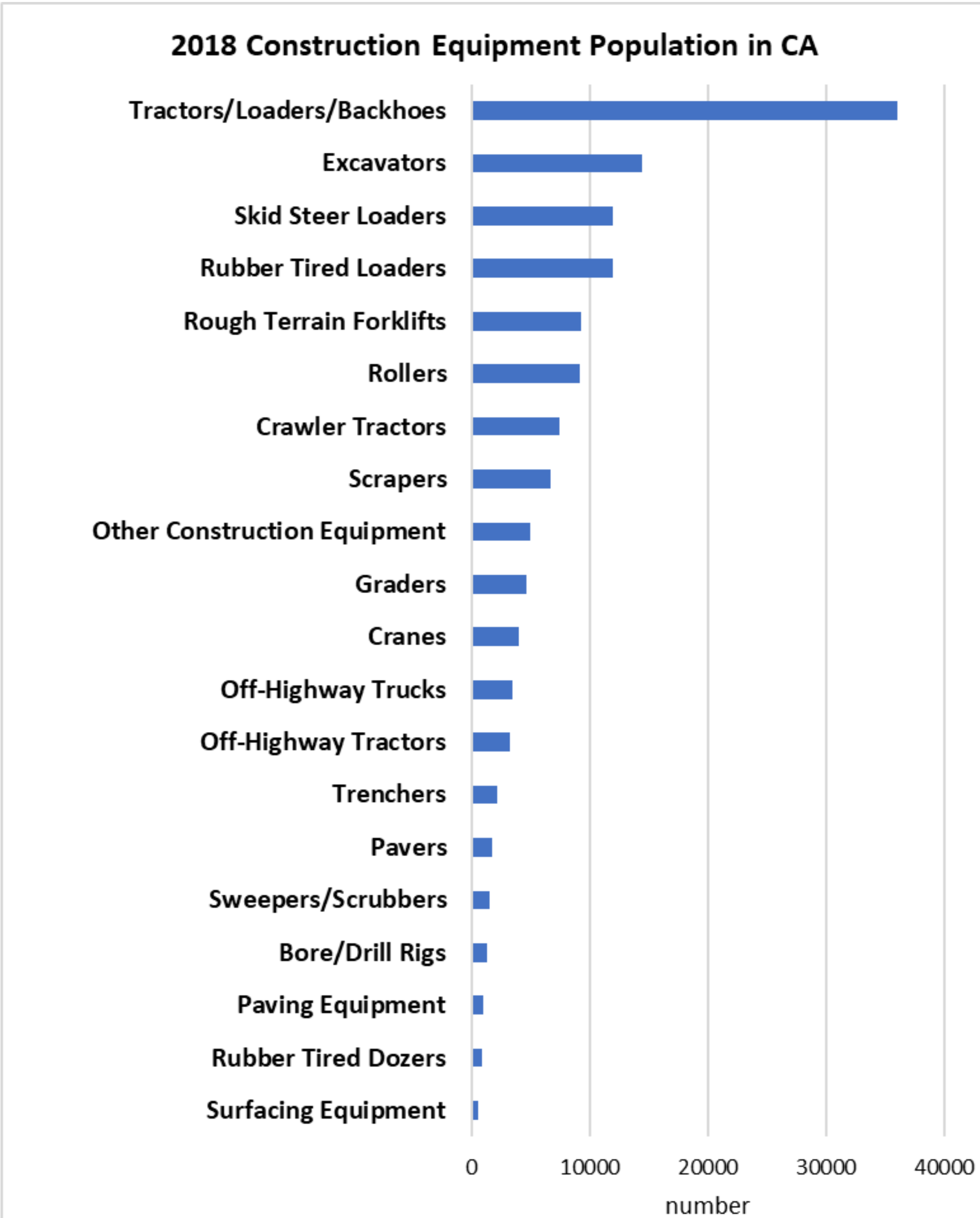


Figure 1-1. Construction equipment population in California in 2018 (adapted from [3])

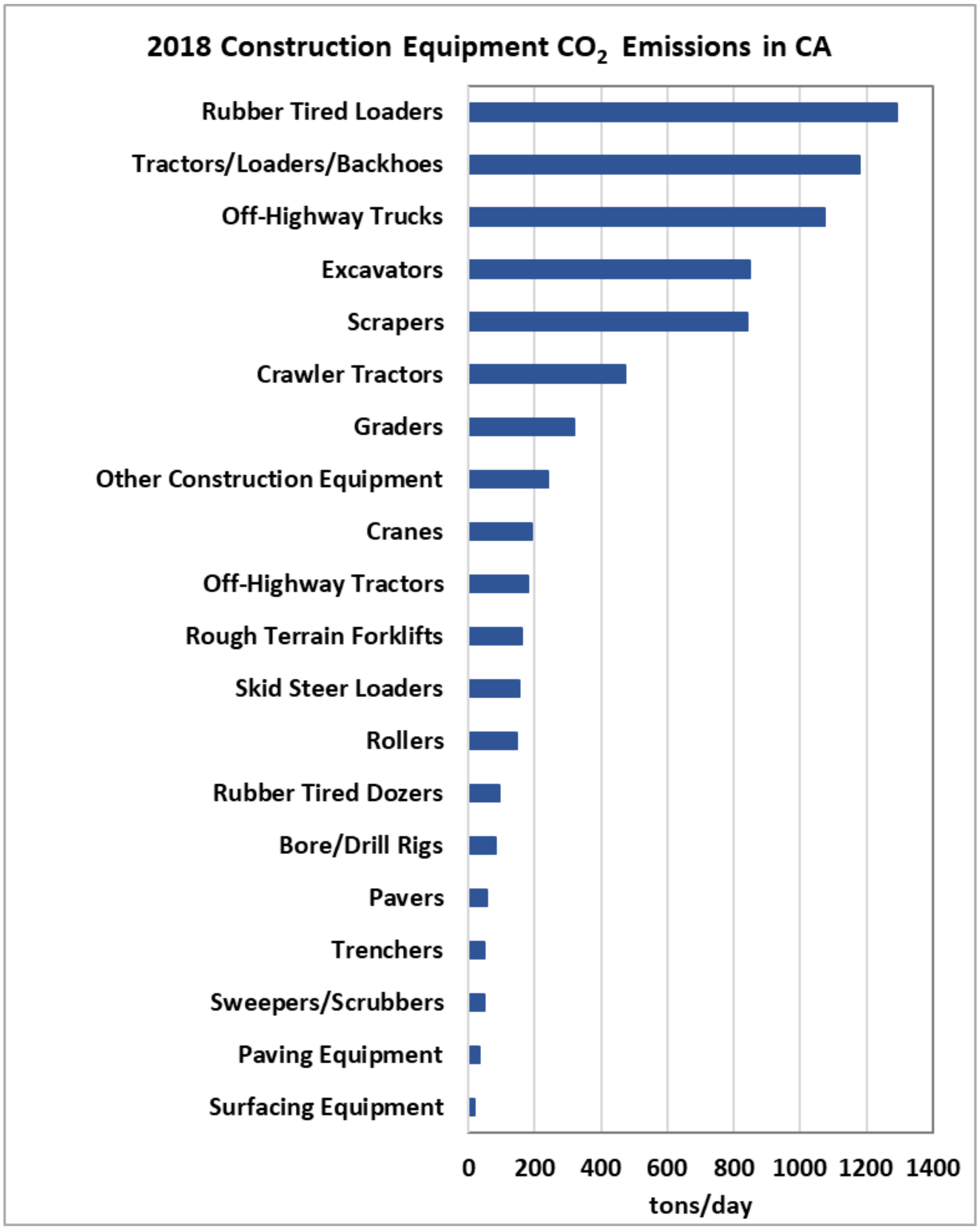


Figure 1-2. CO_2 emission from construction equipment in California in 2018 (adapted from [3])

The scenario is not much different as far as NO_x emission is concerned, as shown in Figure 1-3. The top three categories in terms of NO_x emission are the same ones for CO_2 emission. In order from high to low, they are rubber tired loaders, tractors/loaders/backhoes, and off-highway trucks, respectively. There are differences in how excavators, scrapers, and crawler tractors are placed in the NO_x ranking as compared to the CO_2 ranking. Nevertheless, they are in the top six categories in both emission category rankings.

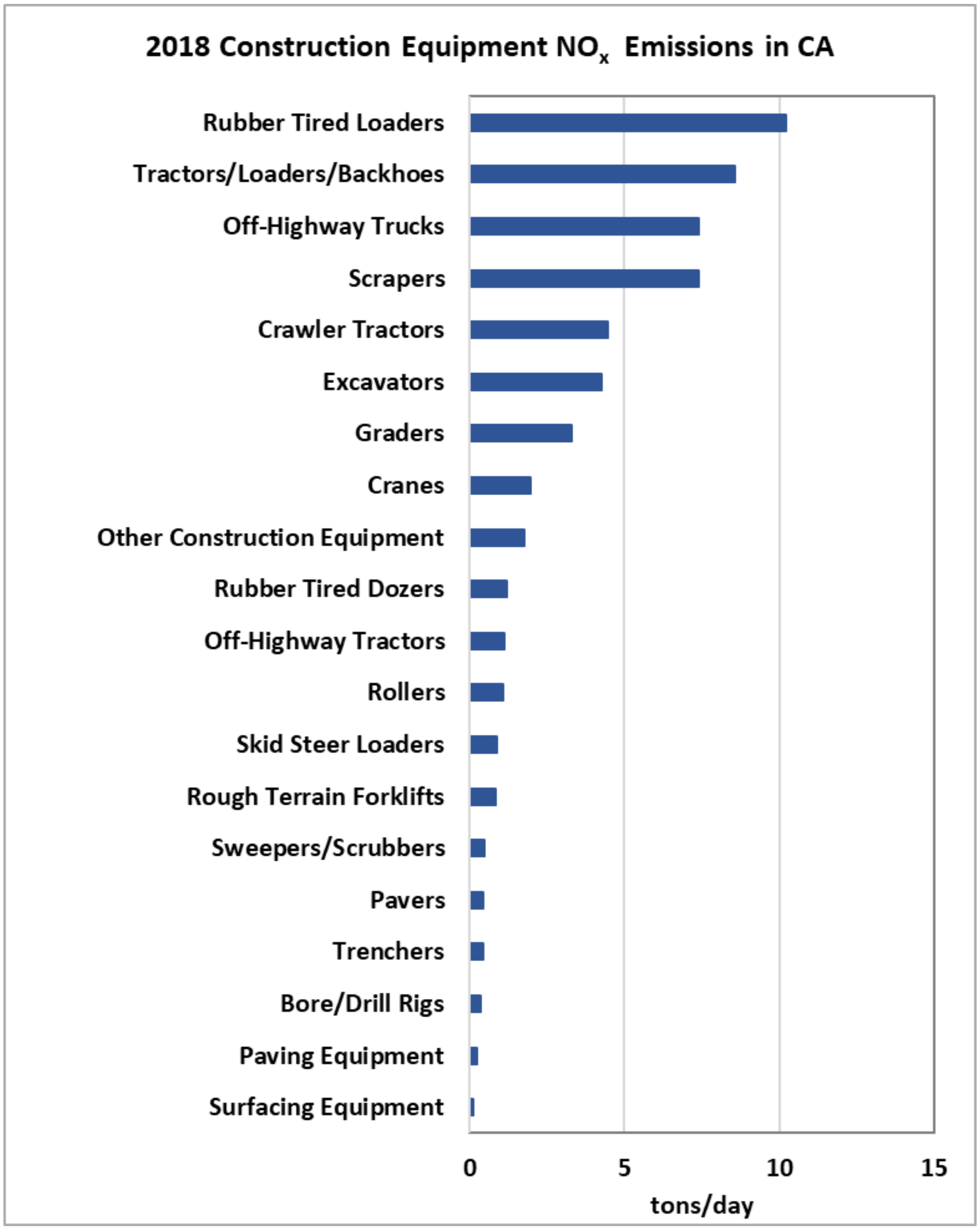


Figure 1-3. NO_x emission from construction equipment in California in 2018 (adapted from [3])

The ranking of top construction equipment categories for PM emission is quite different from those for CO_2 and NO_x emissions. As shown in Figure 1-4, tractors/loaders/backhoes are the top category, followed by rubber tired loaders, scrapers, off-highway trucks, crawler tractors, and excavators, respectively. Nevertheless, these categories are the same as those in the top six categories for CO_2 and NO_x emissions. Thus, they should be the primary targets for electrification/hybridization in the construction equipment sector.

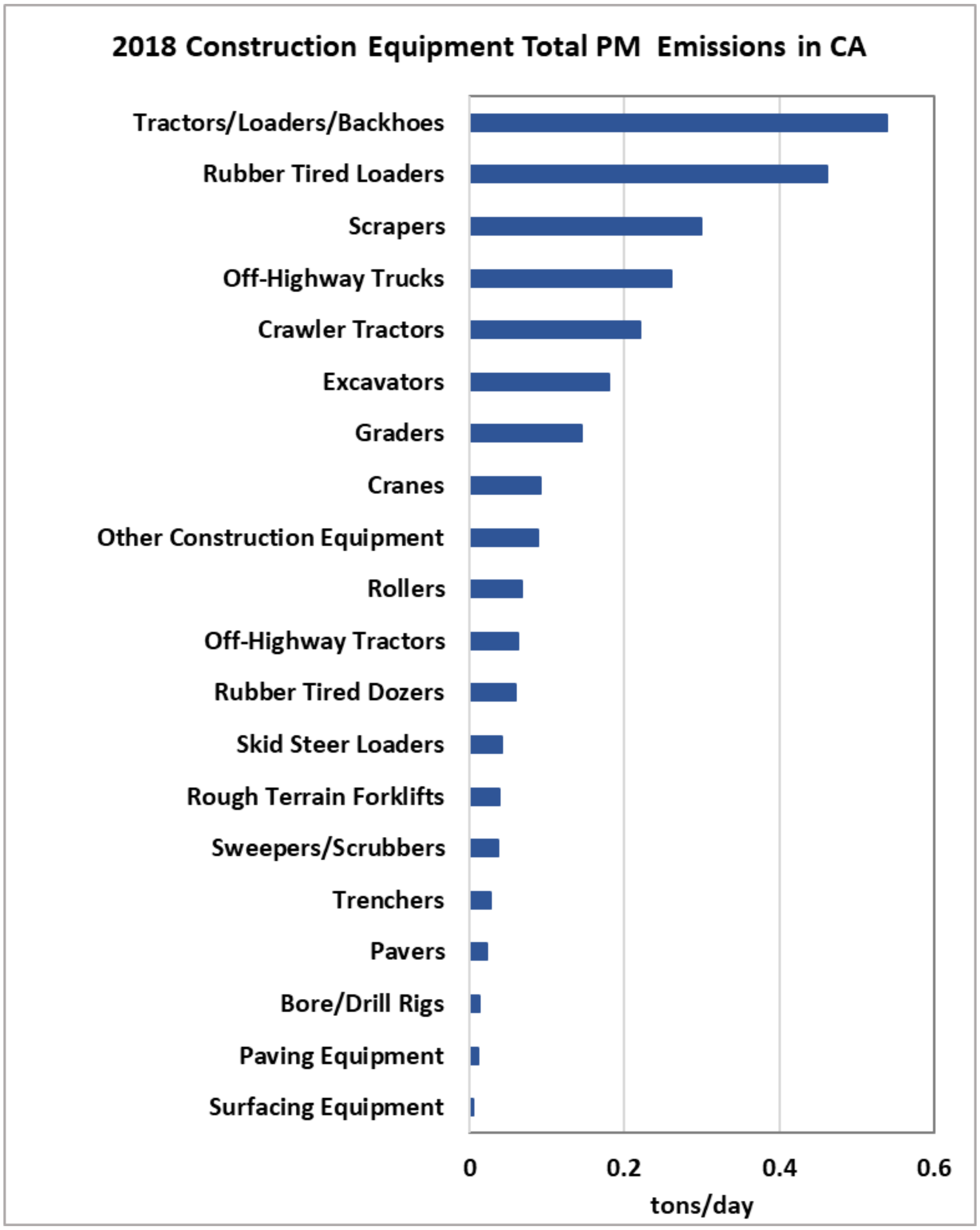


Figure 1-4. PM emission from construction equipment in California in 2018 (adapted from [3])

1.1.1.2Agricultural Equipment Inventory

For agricultural equipment, in terms of population, tillers are the leading category by a large margin, as can be seen from Figure 1-5. Their population in California in 2018 was more than four times the population of the following category, which is agricultural tractors. However, despite the small population of agricultural tractors, they are the most significant contributors to CO_2, NO_x, and PM emission inventories for agricultural equipment, as shown in Figure 1-6, Figure 1-7, and Figure 1-8, respectively. The reasons for this are the extensive use of agricultural tractors to drive a variety of attachments (e.g., tiller, sprayer) for different purposes as well as the relatively large engine sizes of these tractors. For instance, even though tillers are the dominant category in terms of population, most stand-alone tillers are small equipment used in small-scale applications. For large-scale tilling applications, tractors are often used in conjunction with the necessary attachment. Given that tractors are the top emitters of CO_2, NO_x, and PM emissions in the agricultural sector, they should be the primary target for electrification/hybridization.

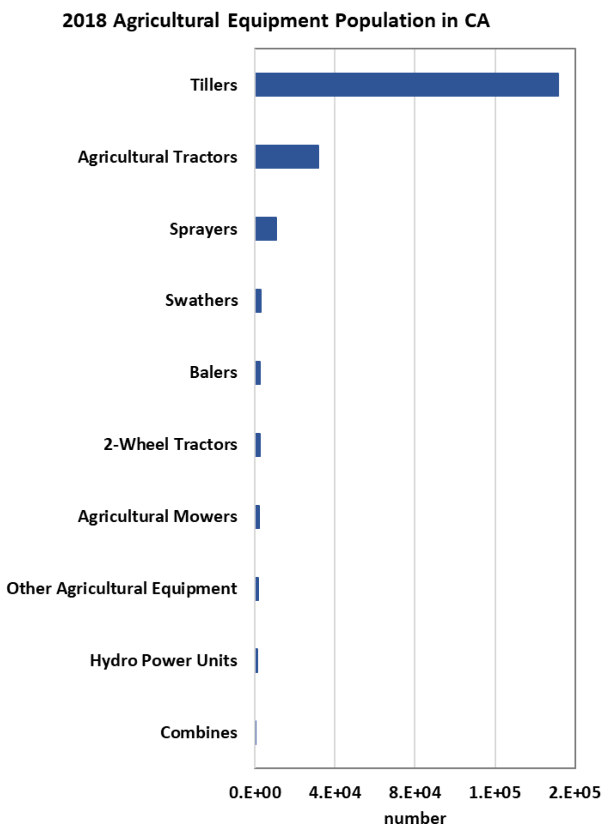


Figure 1-5. Agricultural equipment population in California in 2018 (adapted from [3])

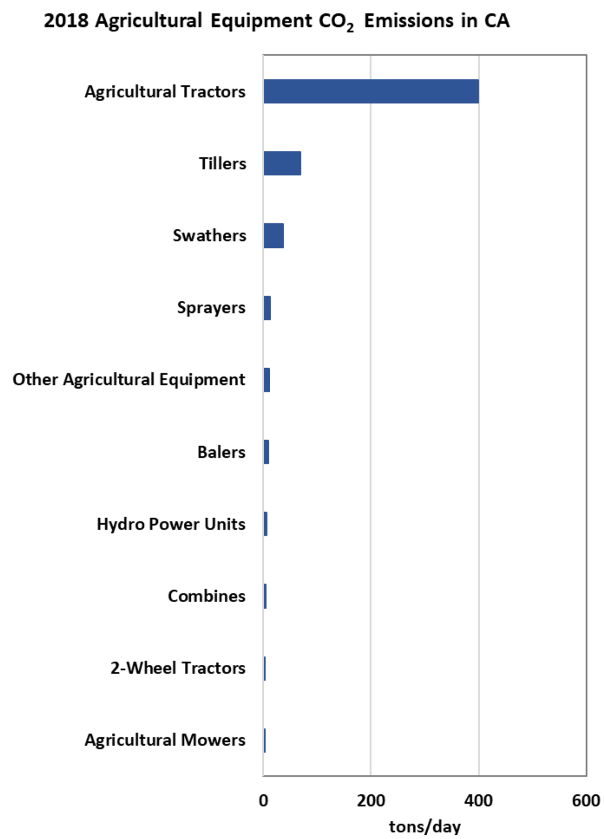


Figure 1-6. CO_2 emission from agricultural equipment in California in 2018 (adapted from [3])

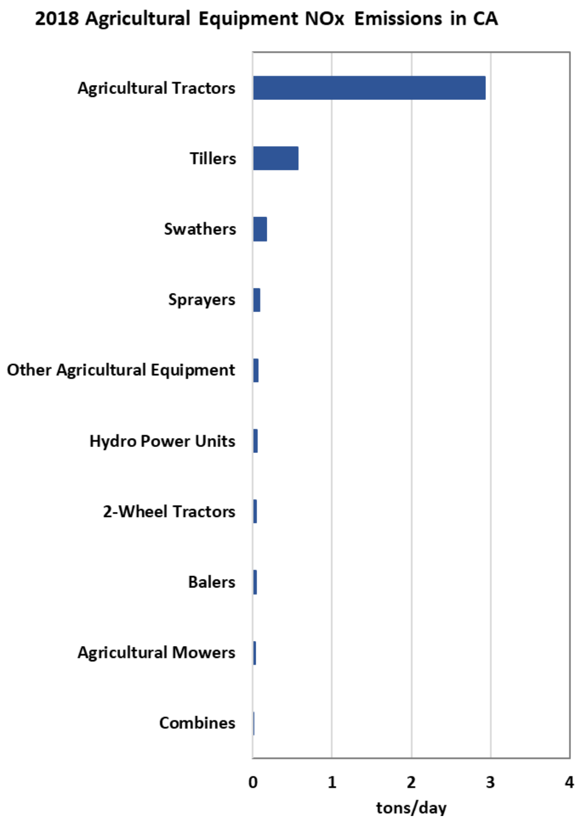


Figure 1-7. NO_x emission from agricultural equipment in California in 2018 (adapted from [3])

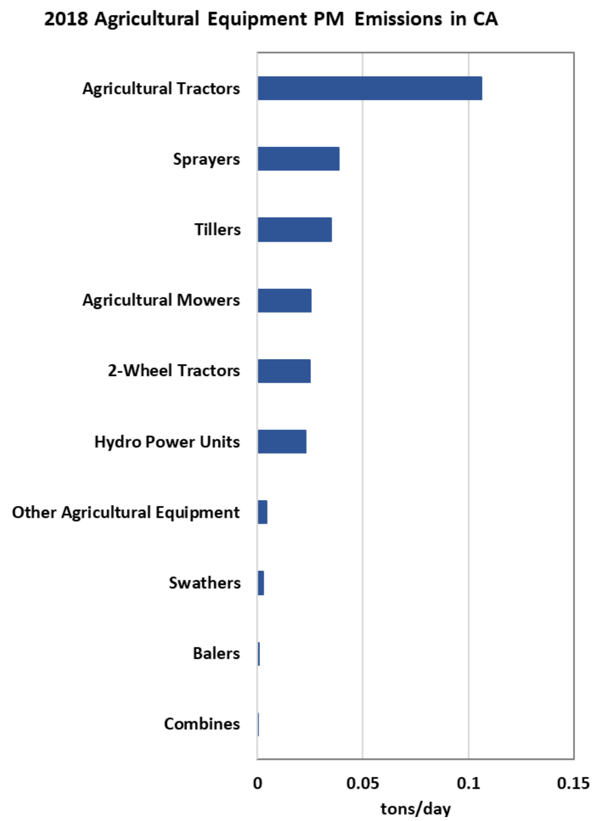


Figure 1-8. PM emission from agricultural equipment in California in 2018 (adapted from [3])

Table 1-1 summarizes the target categories for electrification/hybridization in both construction and agricultural sectors, based on the review of their existing population and contribution to emissions inventories in California. In the figures that follow, we examine the distributions of population and emissions of these equipment categories by horsepower group and model year group to determine which group(s) should be targeted for turnover to fully electric or hybrid electric versions.

Table 1-1. Heavy-duty electric/hybrid equipment of interest

Sector	Equipment of interest
Construction	Rubber tired loaders
	Tractors/loaders/backhoes
	Off-highway trucks
	Excavators
	Scrapers
	Crawler tractors
Agriculture	Tractors

Figure 1-9 shows the distributions of population as well as total CO_2, NO_x, and PM emissions of diesel engine rubber tired loaders in California in 2018 by horsepower group and model year group. It is observed that the majority of their population are less than 20 years old with most being model years 2005-2009. While model years 2015-2019 contribute significantly to the CO_2 emission inventory, their contribution to the NO_x and PM emission inventories is minimal. The majority of all types of emissions are from model years 2000-2009. In terms of engine size, the diesel engines used in rubber tired loaders can range anywhere from 75 to 600 hp with most of them being in the 175-300 hp range. However, the biggest rubber tired loaders with 300-600 hp contribute the most to all types of emissions.

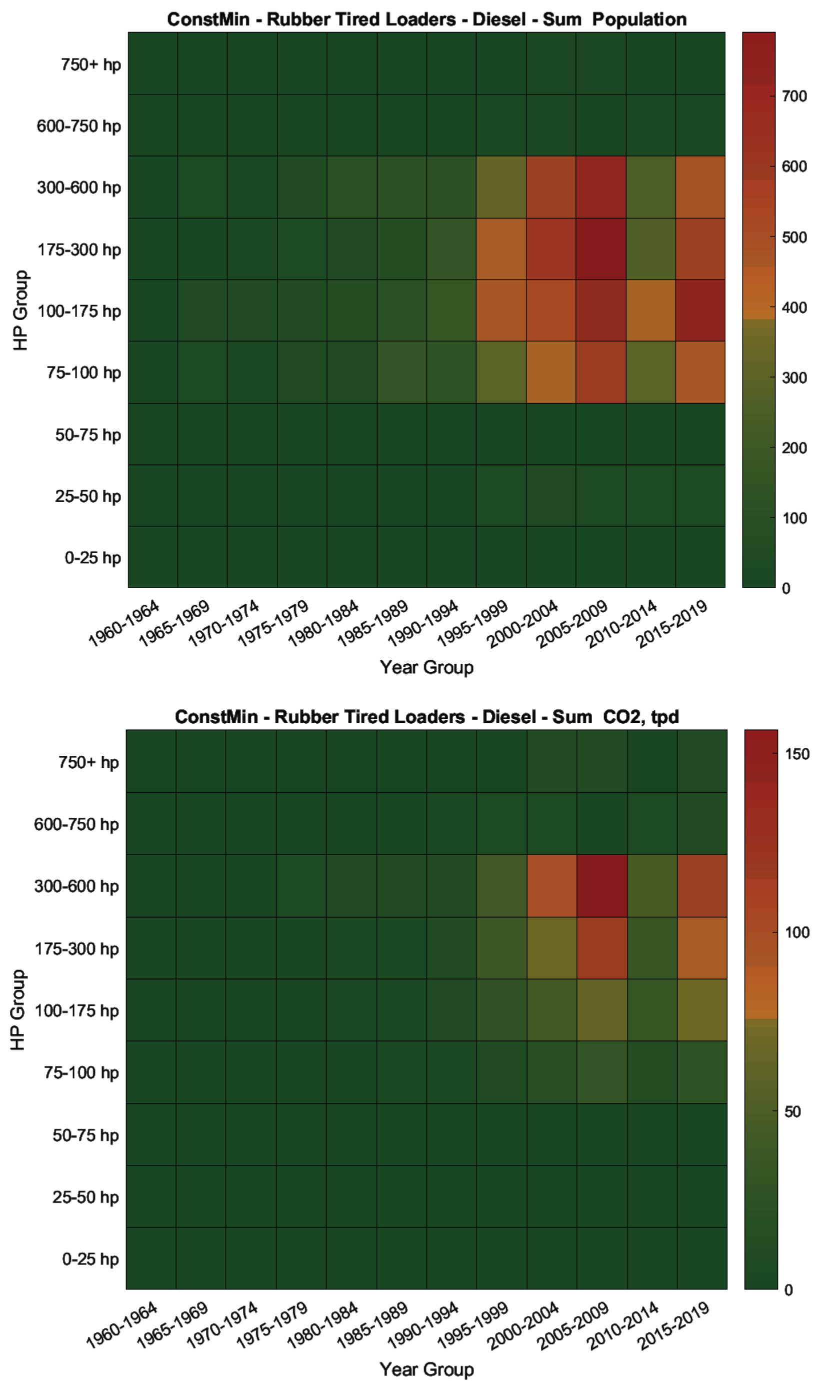
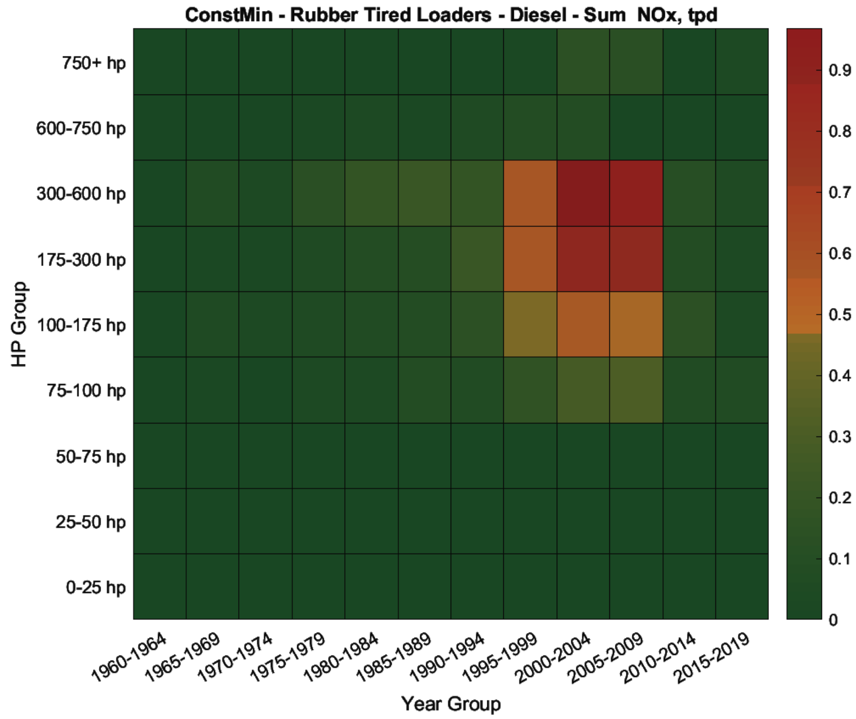


Figure 1-9. Population and emissions of diesel engine rubber tired loaders in CA in 2018



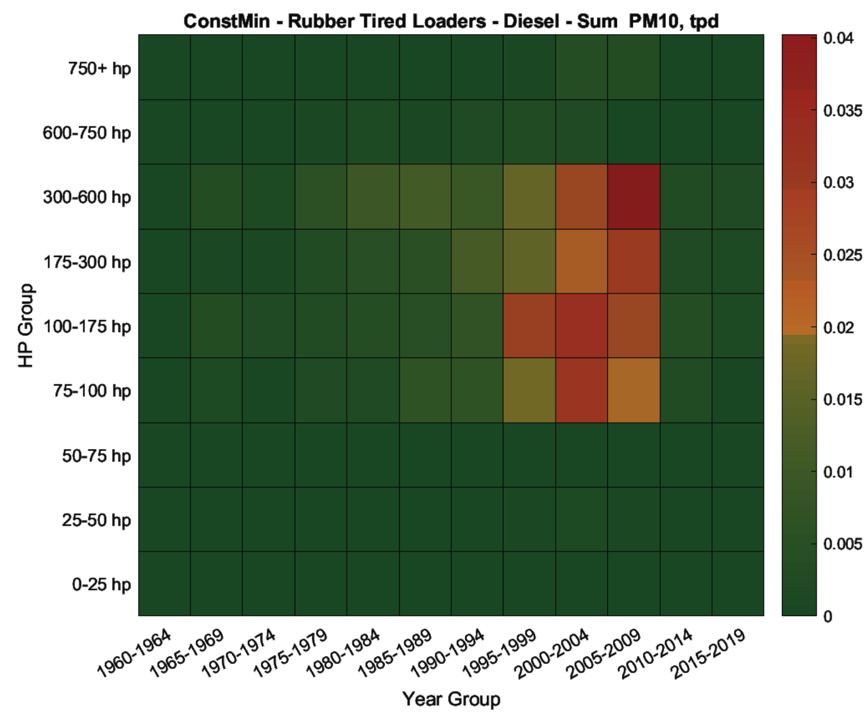
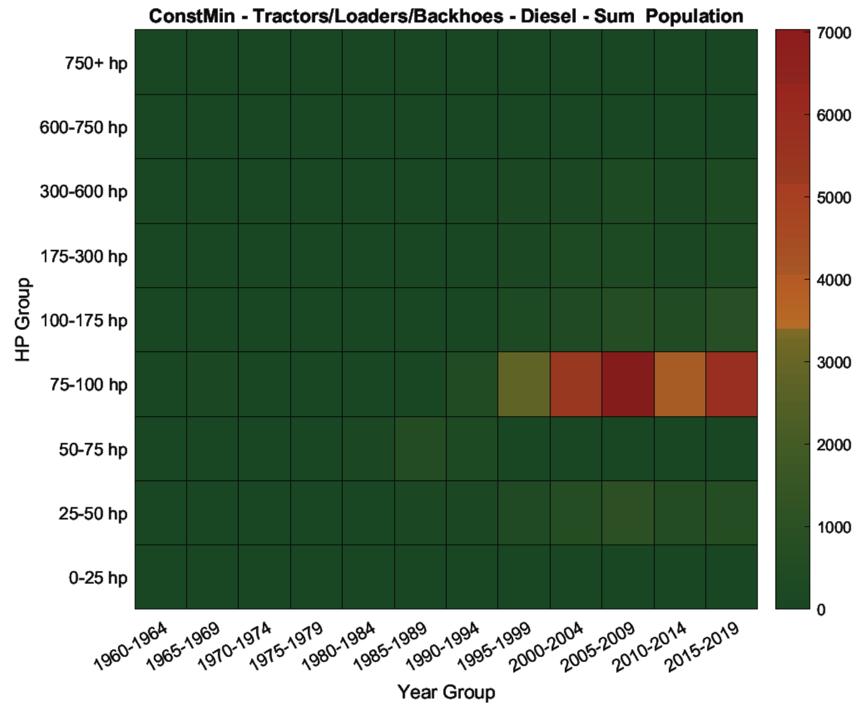


Figure 1-9 (continued). Population and emissions of diesel engine rubber tired loaders in CA in 2018

Figure 1-10 shows the distributions of population as well as CO_2, NO_x, and PM emissions of diesel engine tractors/loaders/backhoes in California in 2018 by horsepower group and model year group. It is observed that the majority of their population are less than 20 years old with most being model years 2005-2009. While model years 2015-2019 contribute the most to the CO_2 emission inventory, the majority of NO_x emissions are from model years 2005-2009 while the majority of PM emissions are from model years 2000-2004. In terms of engine size, the diesel engines used in tractors/loaders/backhoes are predominantly small, in the range of 75-100 hp.



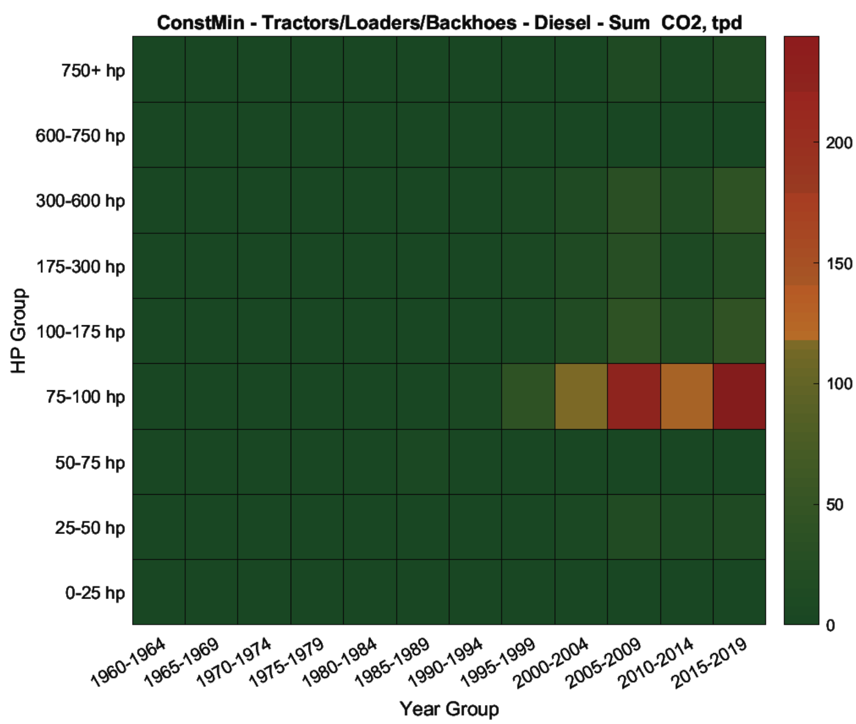


Figure 1-10. Population and emissions of diesel engine tractors/loaders/backhoes in CA in 2018

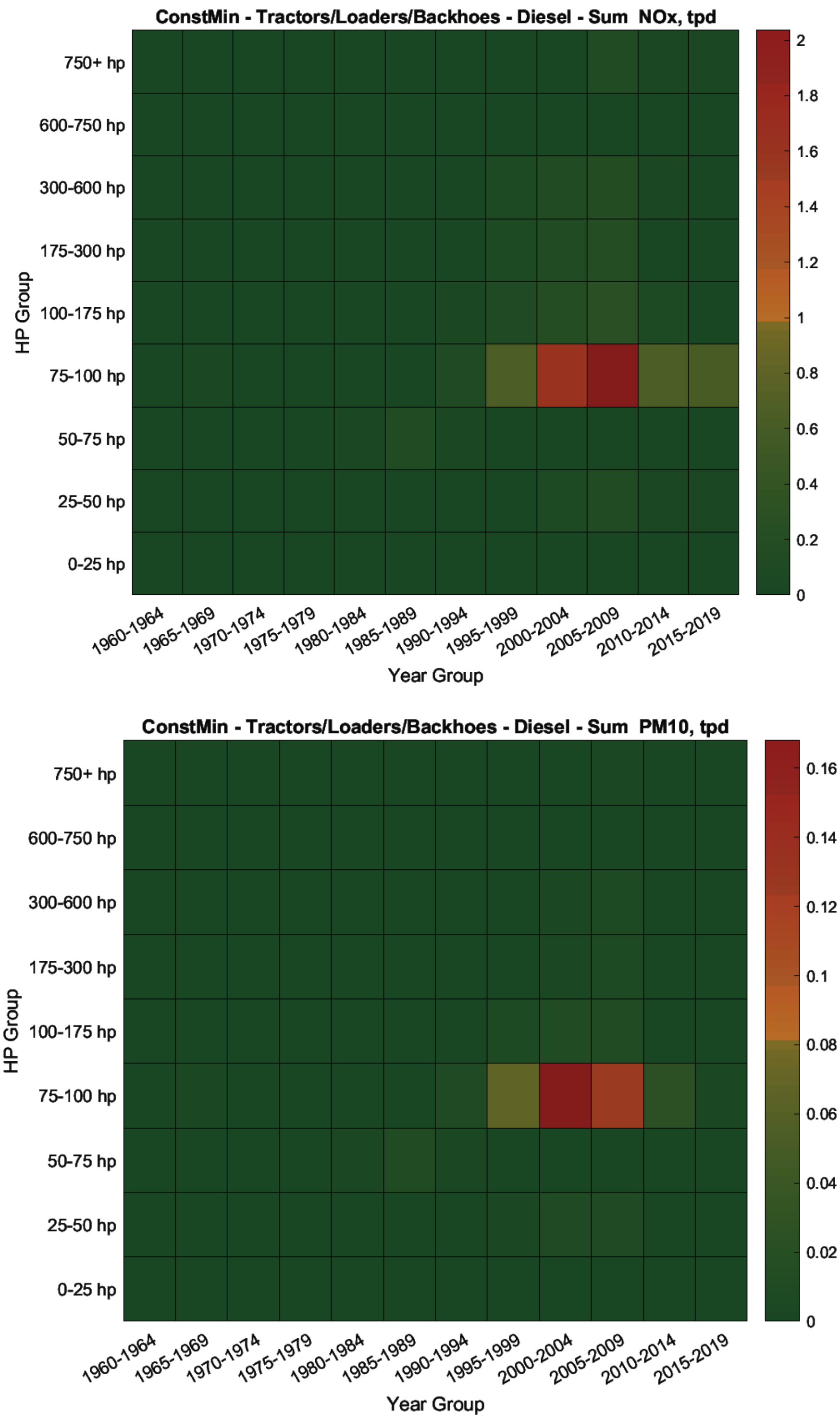
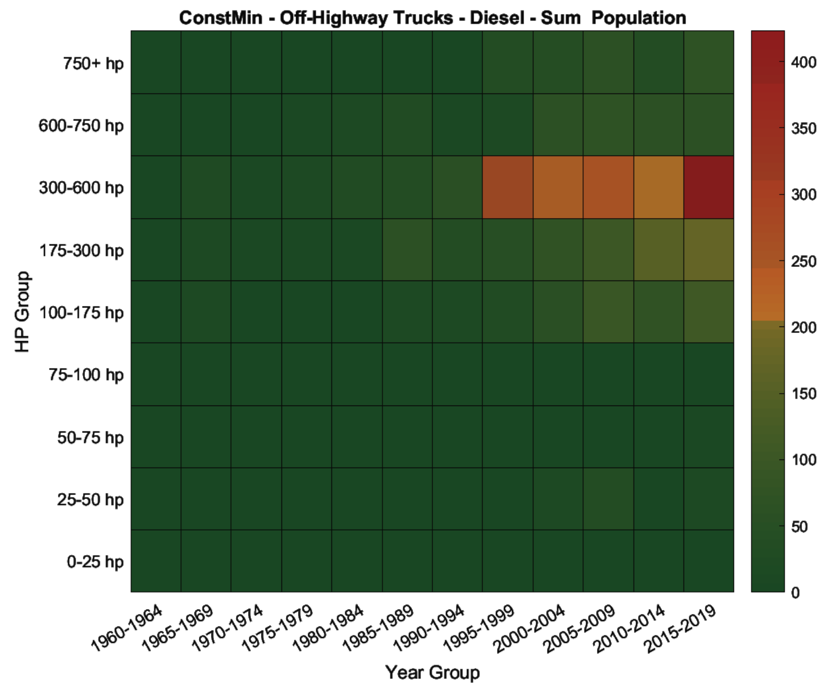


Figure 1-10 (continued). Population and emissions of diesel engine tractors/loaders/backhoes in CA in 2018

Figure 1-11 shows the distributions of population as well as CO_2, NO_x, and PM emissions of diesel engine off-highway trucks in California in 2018 by horsepower group and model year group. It is observed that a large portion of their population is fairly new with most being model years 2015 or newer. While model years 2015-2019 contribute significantly to the CO_2 emission inventory, the majority of NO_x and PM emissions are from model years 1995-2009. In terms of engine size, the diesel engines used in off-highway trucks are predominantly in the 300-600 horsepower group, which also contributes the most to CO_2, NO_x, and PM emissions. However, there is notable contribution to all types of emissions from the largest off-highway trucks whose engine size is larger than 750 hp.



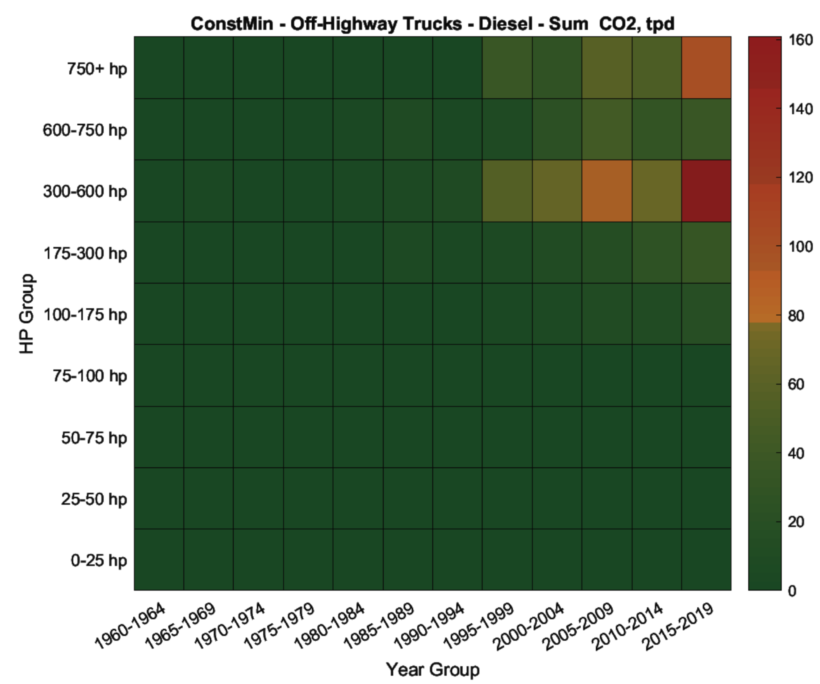


Figure 1-11. Population and emissions of diesel engine off-highway trucks in CA in 2018

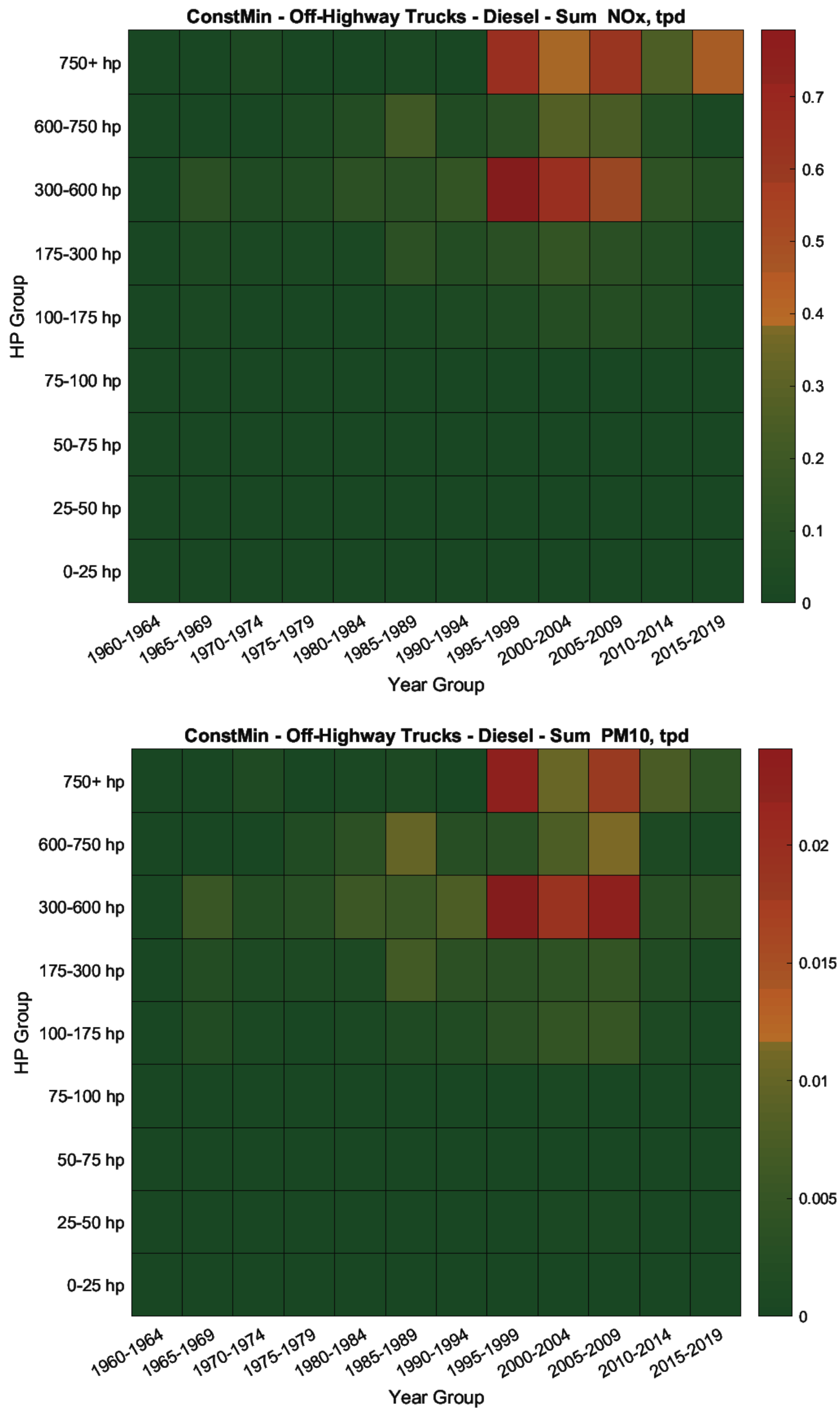


Figure 1-11 (continued). Population and emissions of diesel engine off-highway trucks in CA in 2018

Figure 1-12 shows the distributions of population as well as CO_2, NO_x, and PM emissions of diesel engine excavators in California in 2018 by horsepower group and model year group. It is observed that the majority of their population are less than 20 years old with most being model years 2015 or newer. While model years 2015-2019 contribute significantly to the CO_2 emission inventory, the majority of NO_x and PM emissions are from model years 2000-2009. In terms of engine size, there is a wide range of diesel engines used in excavators ranging from 25 to 600 hp. There is a distinct group of small excavators with engine size of 25-50 hp, which contributes significantly to the PM emission inventory. However, the biggest excavators with 300-600 hp contribute the most to all types of emissions.

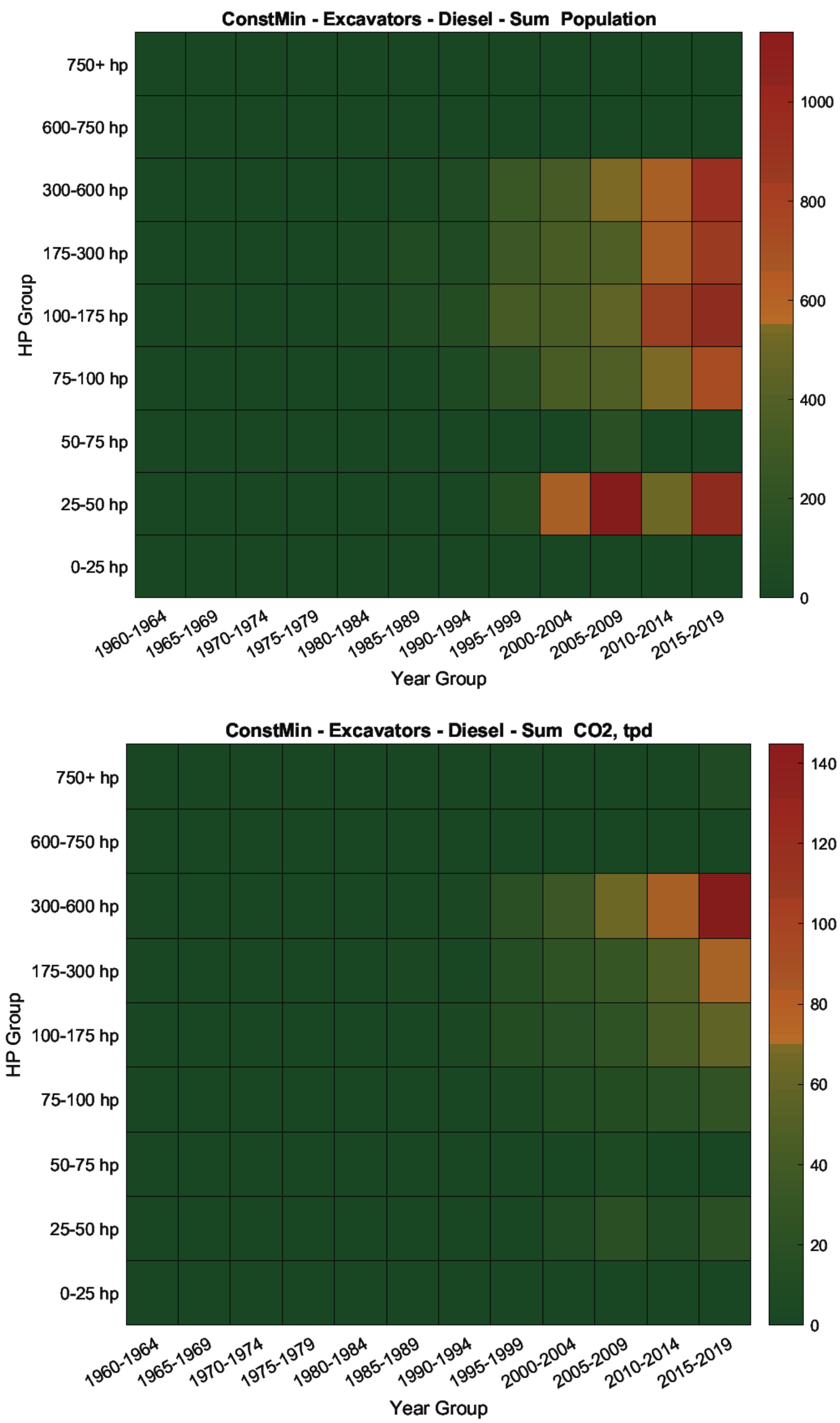
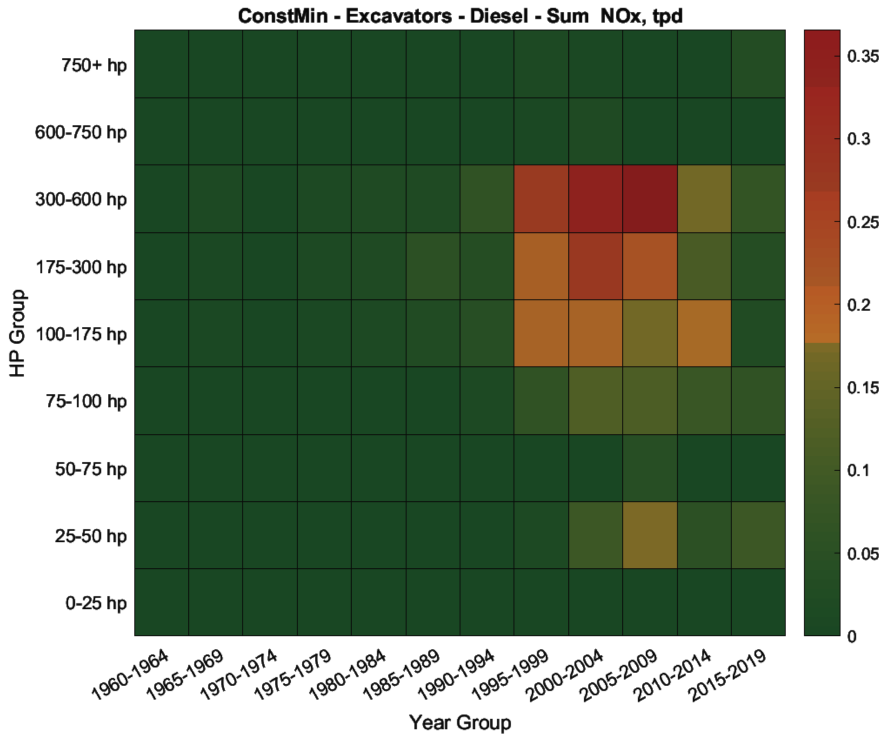


Figure 1-12. Population and emissions of diesel engine excavators in CA in 2018



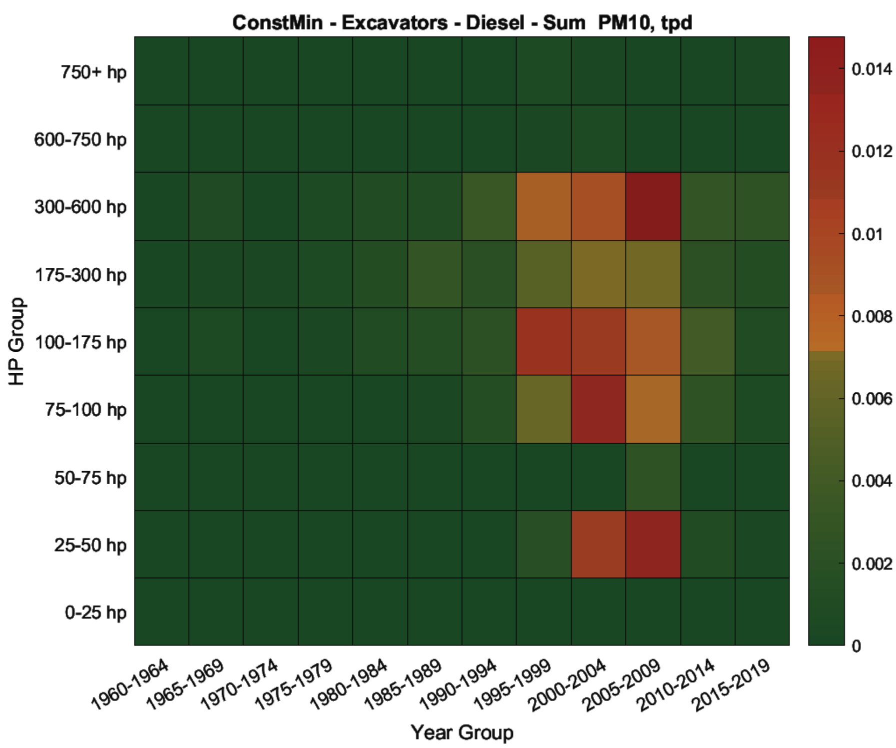
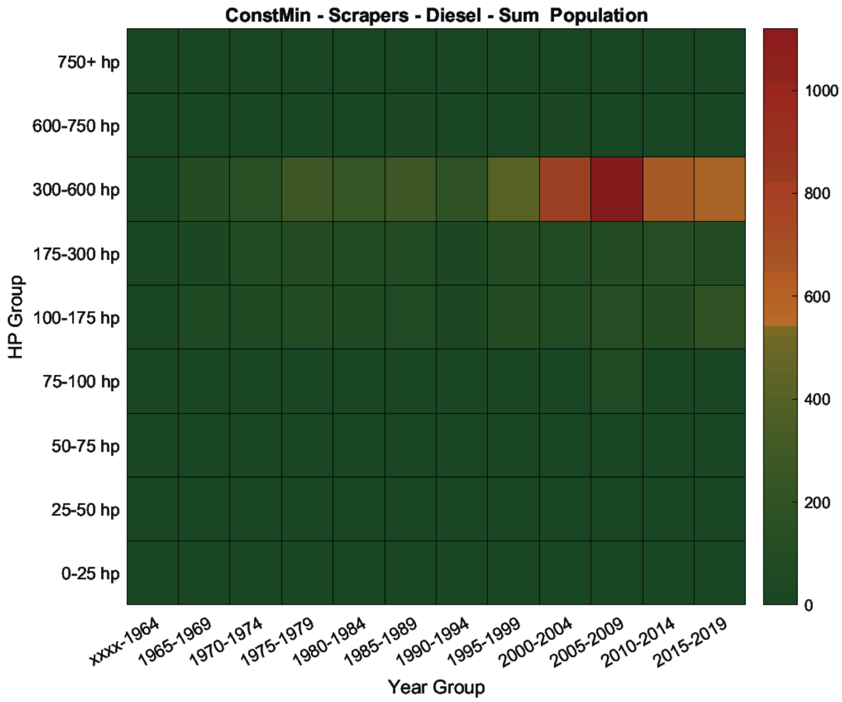


Figure 1-12 (continued). Population and emissions of diesel engine excavators in CA in 2018

Figure 1-13 shows the distributions of population as well as CO_2, NO_x, and PM emissions of diesel engine scrapers in California in 2018 by horsepower group and model year group. It is observed that the majority of their population are less than 20 years old with most being model years 2000-2009. These model years also contribute the most to the CO_2, NO_x, and PM emission inventories. In terms of engine size, the diesel engines used in tractors/loaders/backhoes are predominantly large, in the range of 300-600 hp.



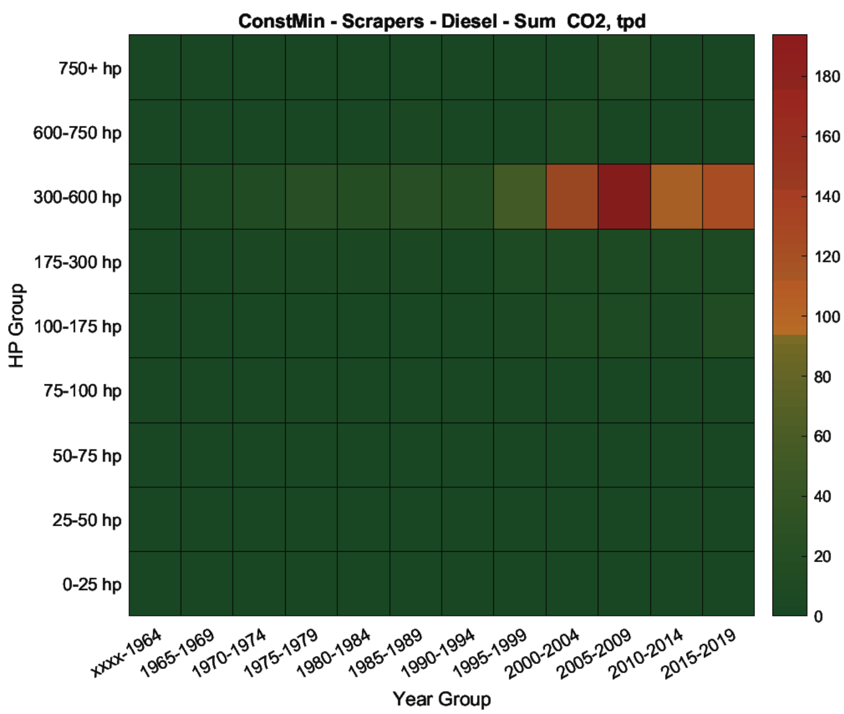


Figure 1-13. Population and emissions of diesel engine scrapers in CA in 2018

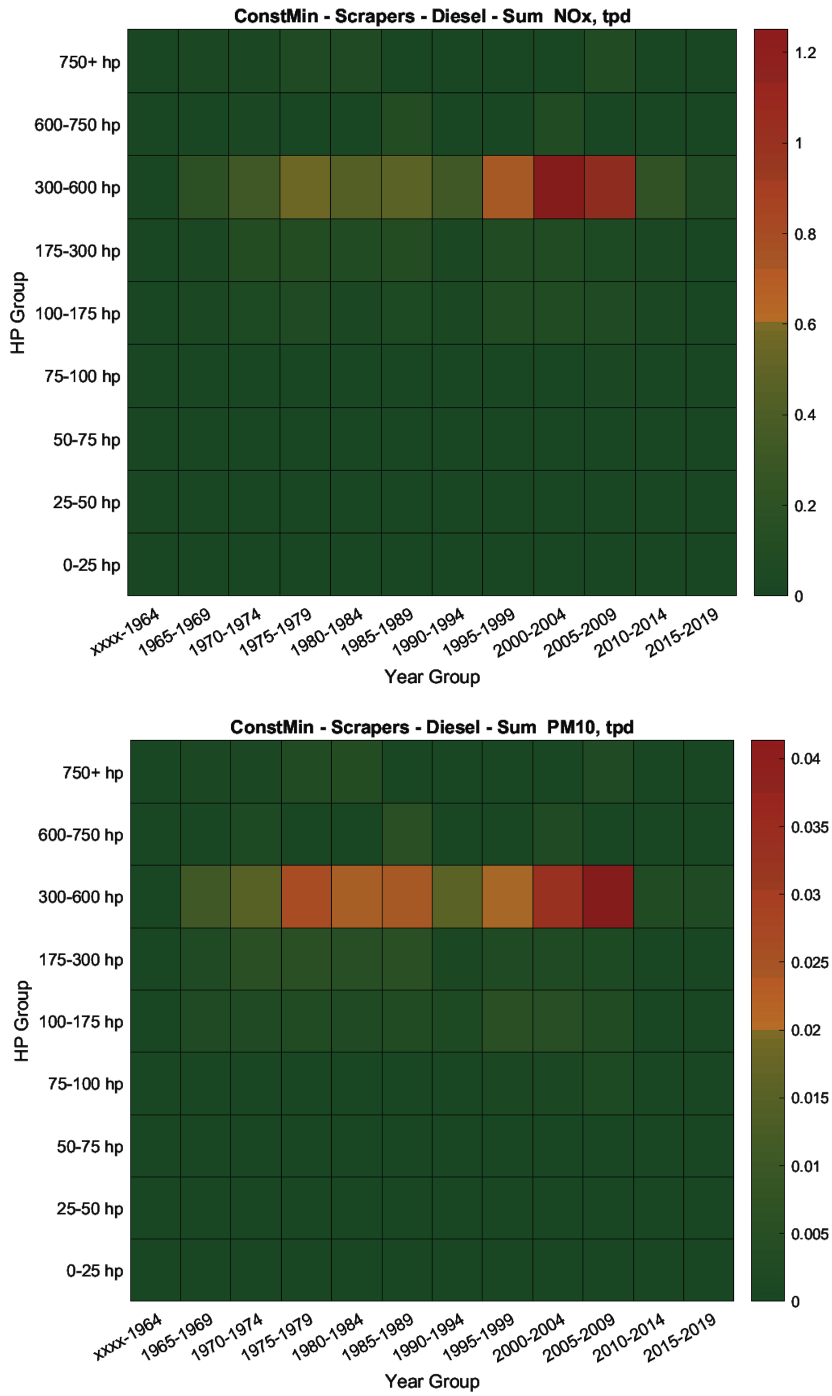
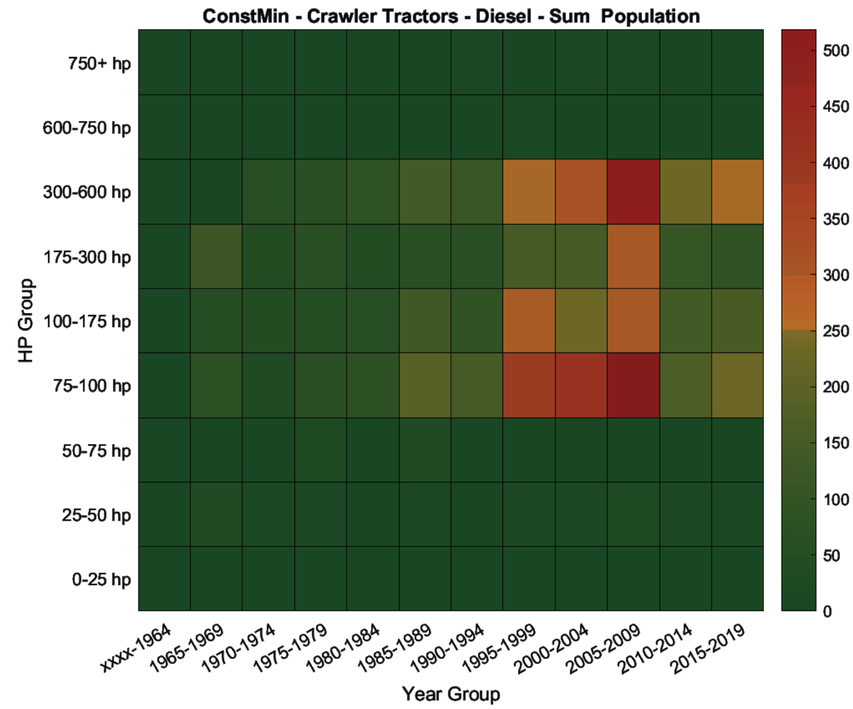


Figure 1-13 (continued). Population and emissions of diesel engine scrapers in CA in 2018

Figure 1-14 shows the distributions of population as well as CO_2, NO_x, and PM emissions of diesel engine crawler tractors in California in 2018 by horsepower group and model year group. It is observed that the majority of their population are 10 years old or older. The model year group with the largest population is 2005-2009, which also contributes the most to the CO_2 emission inventory. However, a wider range of model years, from 1995 to 2009, contributes to the majority of the NO_x and PM emission inventories. In terms of engine size, the diesel engines used in crawler tractors range from 75 to 600 hp. There is a distinct group of small crawler tractors with engine size of 75-100 hp, which contributes the most to the PM emission inventory. There is another distinct group of large crawler tractors with 300-600 hp that contributes the most to the CO_2 and NO_x emission inventories.



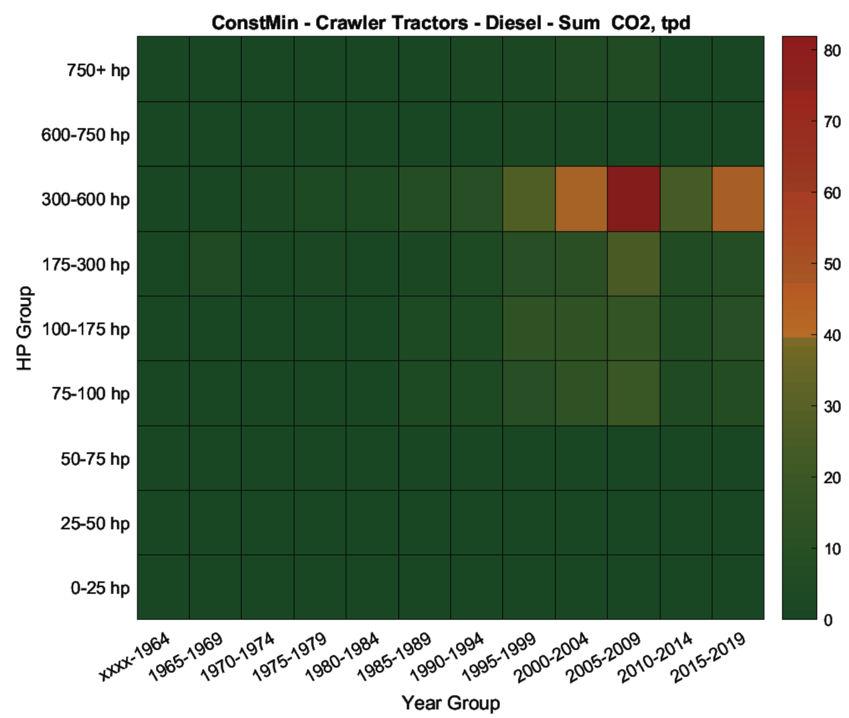
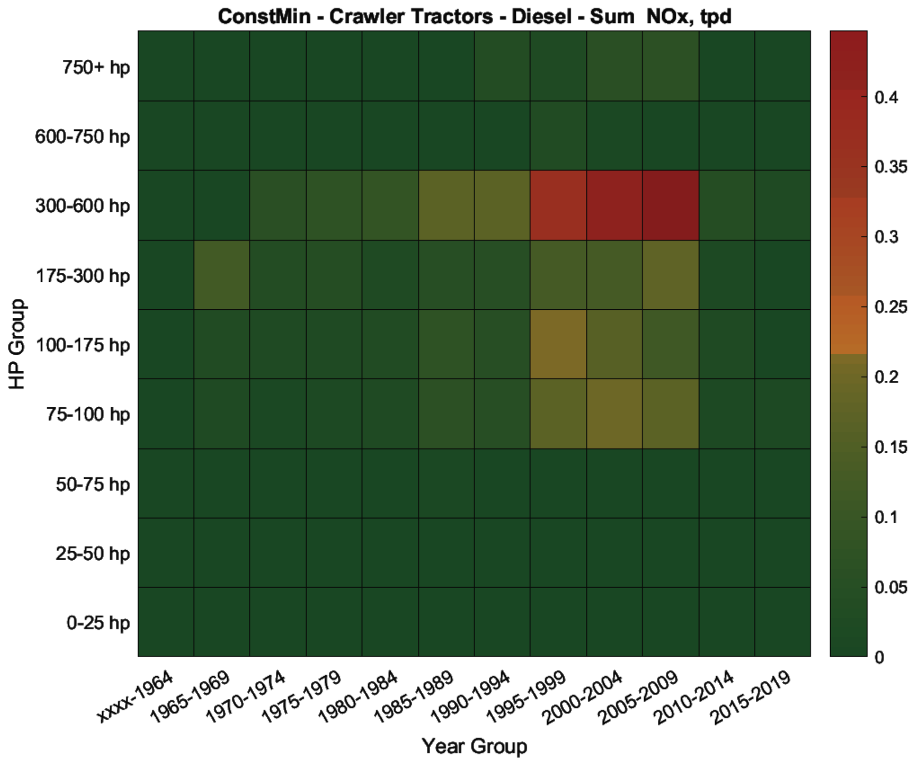


Figure 1-14. Population and emissions of diesel engine crawler tractors in CA in 2018



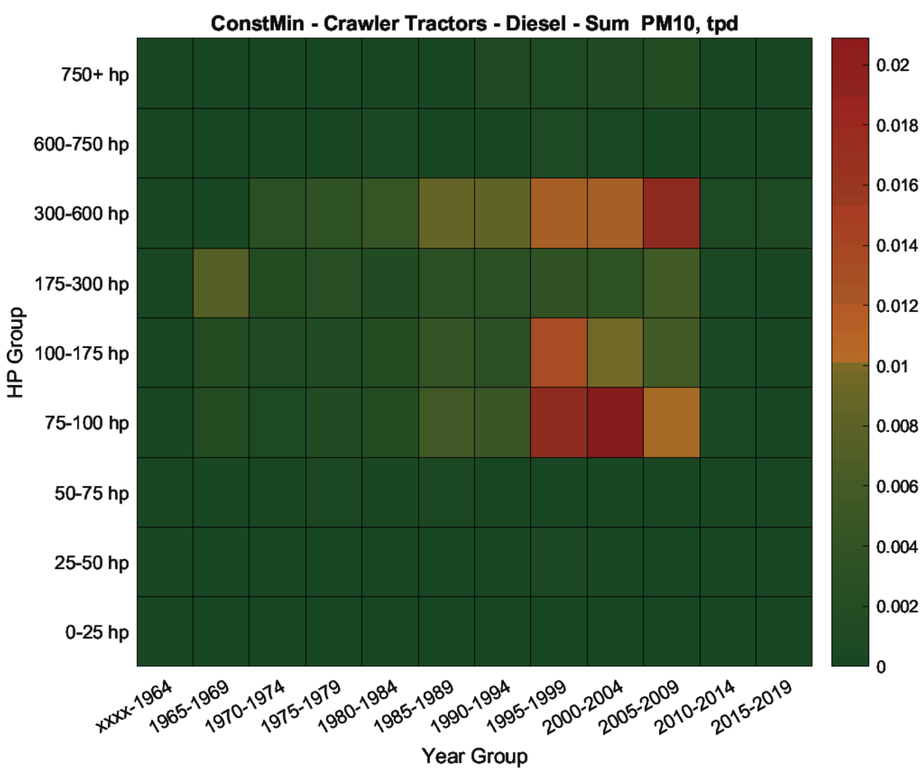


Figure 1-14 (continued). Population and emissions of diesel engine crawler tractors in CA in 2018

1.1.1.3 Other Sources of Off-Road Equipment Inventory Data

While the OFFROAD2017 database contains a wide range of data regarding off-road equipment inventory in California, these data are only as recent as the last time the model was updated. In terms of population data by equipment type, publicly available data sources are virtually non-existent. There are a few market reports for sale, but these reports only break down the data to the country or regional level. For example, they provide data for the U.S. market as a whole, but not for California specifically. In addition, these market analysis reports only cover major off-road equipment categories (e.g., excavators, loaders, etc.) and provide data in terms of sales (in U.S. dollars) rather than population count.

In addition to the OFFROAD2017 database, CARB also maintains the Diesel Off-Road Online Reporting System (DOORS) [4]. All vehicles in California subject to the in-use off-road diesel-fueled fleets regulation should be labeled with Equipment Identification Numbers (EINs) and reported to CARB through DOORS. This makes the DOORS database the most pertinent source for off-road equipment operating in California. Figure 1-15 shows a screenshot of DOORS for reporting vehicle and engine information including equipment type, make, model, and engine specifications.

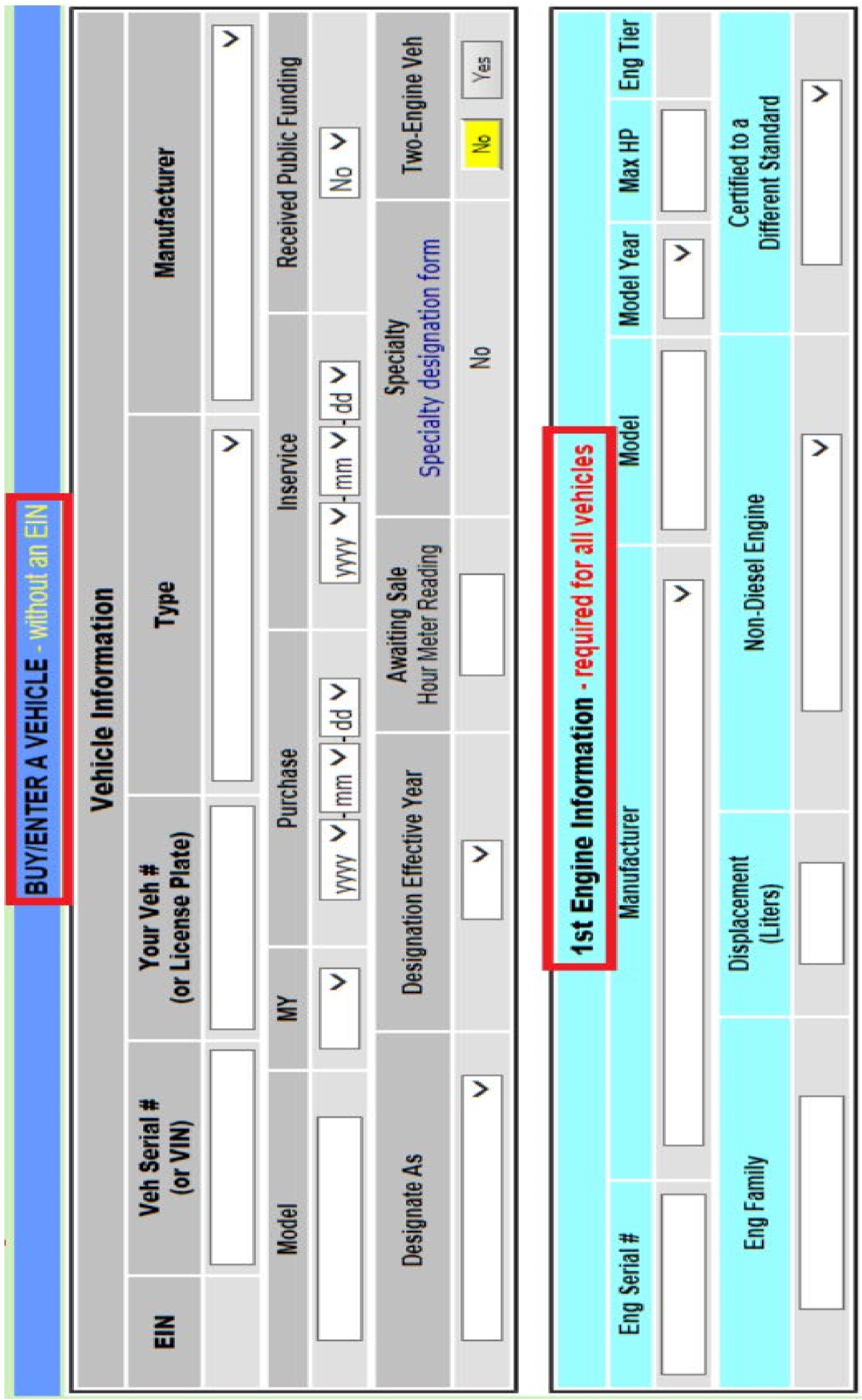


Figure 1-15. Online tool for submitting vehicle and engine information of off-road equipment to DOORS database

One benefit of the DOORS database is that the data in it are more up to date so analyses for recent calendar years can be done with actual data rather than estimated data. Figure 1-16 shows an example of an analysis done on the data available in the DOORS database in 2017.

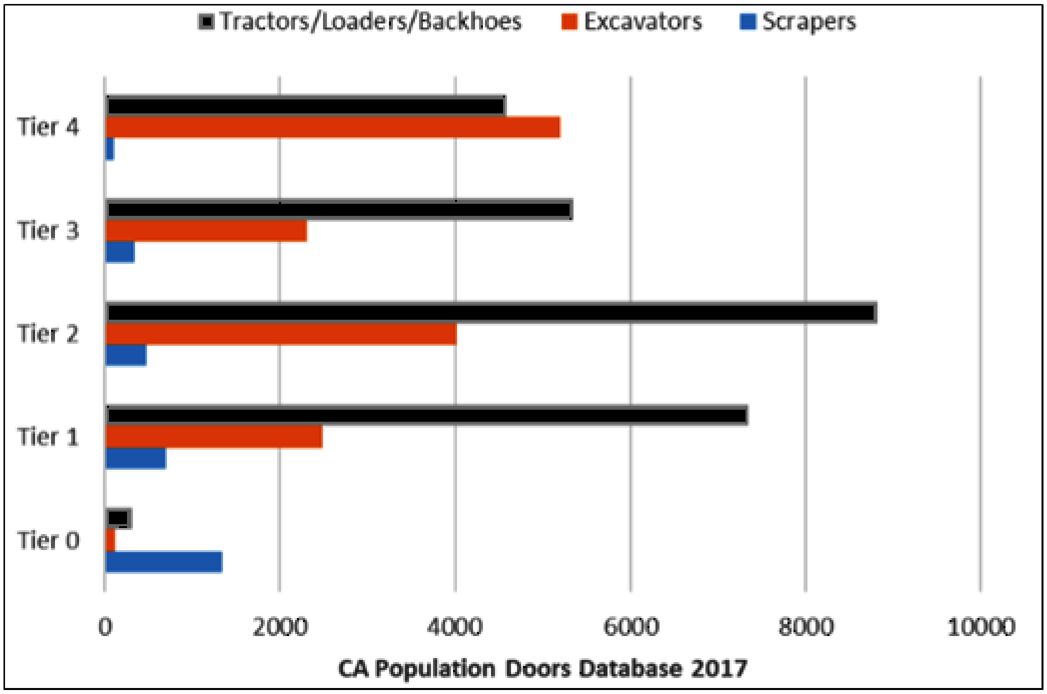


Figure 1-16. Example of analysis done on the DOORS database in a previous study [5]

1.1.2 Market Share and Market Trend Data

Similar to the inventory data, market share and trend data for off-road equipment are hardly available in the public domain. There are a few market reports for sale, but these reports only break down the data to the country or regional level. For example, they provide data for the U.S. market as a whole, but not for California specifically. Moreover, the few sample graphs that are available often do not show numbers necessary for interpreting those graphs effectively. Nonetheless, data can be estimated from the available graphs visually.

The top plots in Figure 1-17, Figure 1-18, and Figure 1-19 show the trends of global market size from 2000 to 2020 for loaders, excavators, and off-highway trucks and tractors, respectively [6]. All the plots show the steady trends of increasing global market size for these types of construction equipment over the 20-year time span. In Figure 1-17, Figure 1-18, and Figure 1-19, we plot the population of the corresponding type of equipment in California during the same time span in order to investigate any correlation with the trend of global market size. The population data are from the OFFROAD2017 database. For all three equipment types, the trends of population in California from 2000 to 2020 are similar where the population increased from 2000 to 2005, then had a significant drop in 2010, before increasing again afterward.

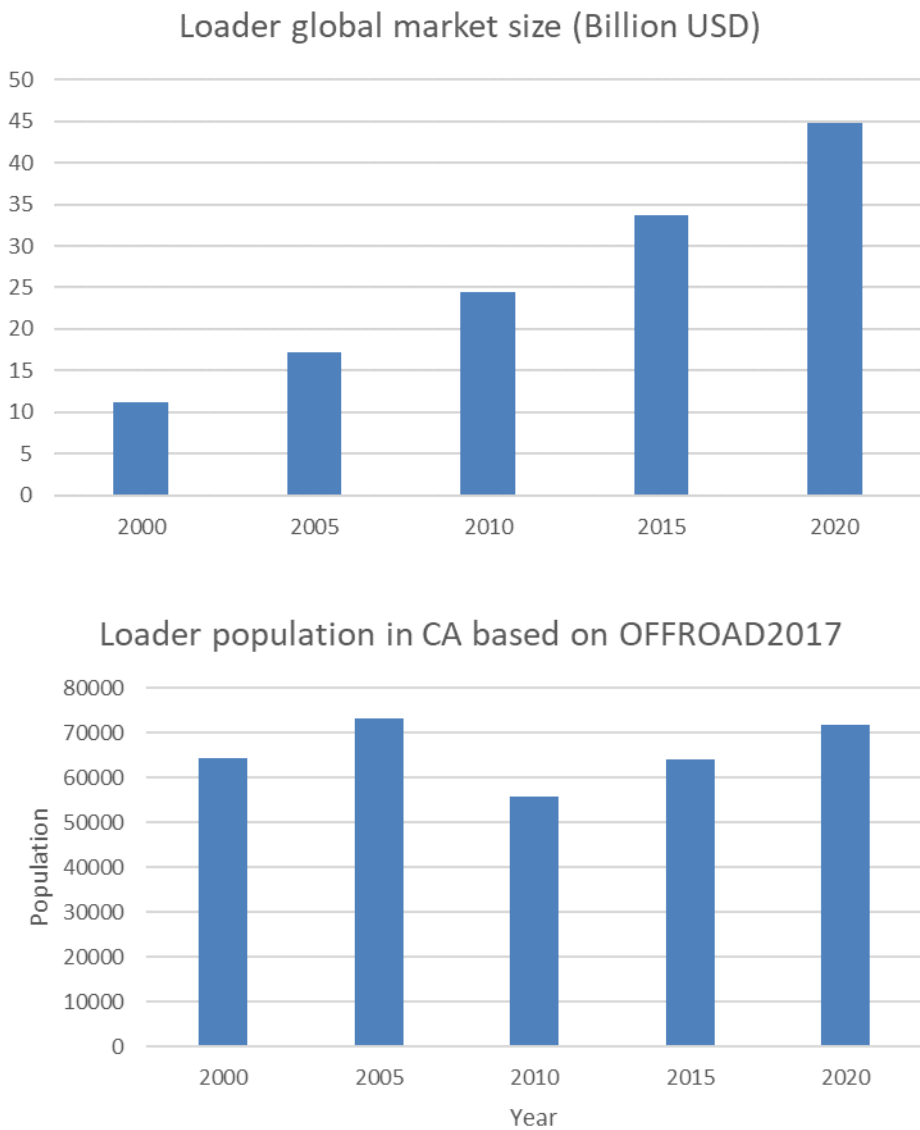


Figure 1-17. Global market size and California population of loaders during 2000-2020

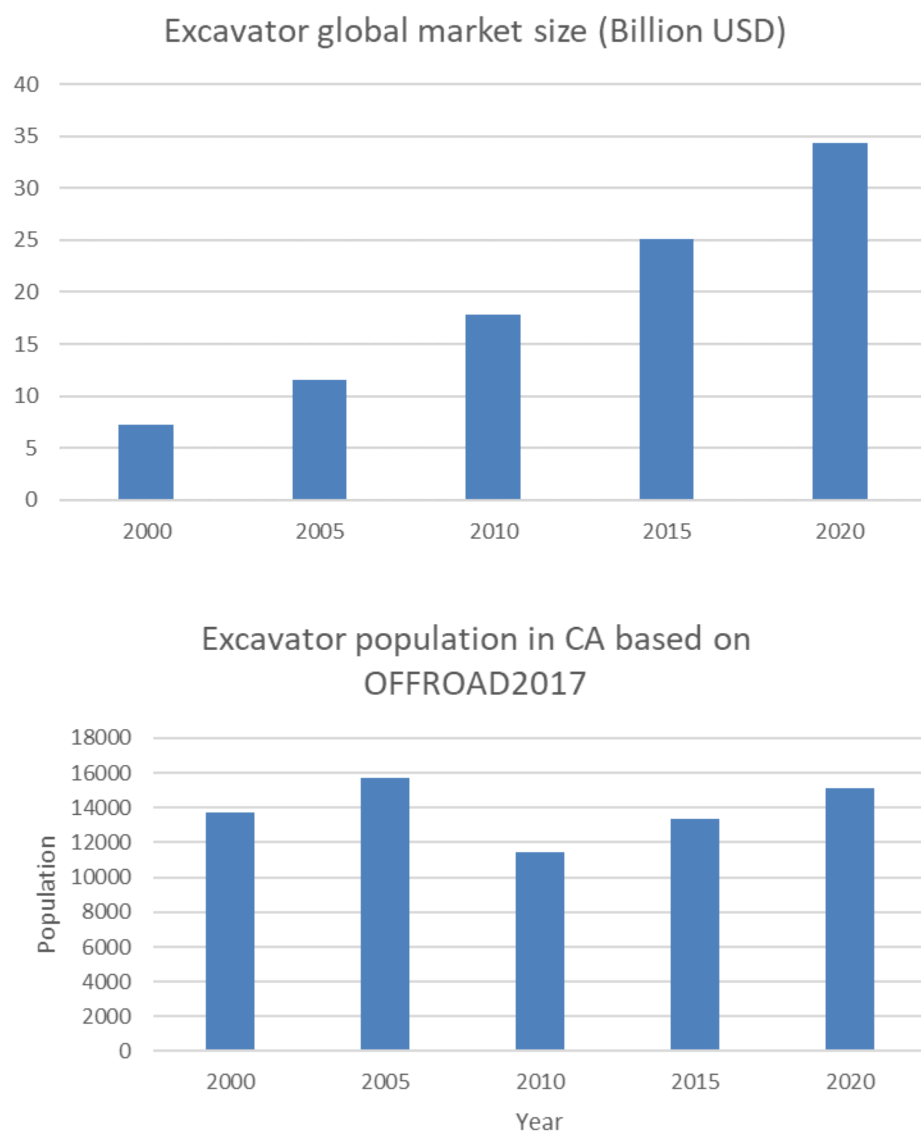


Figure 1-18. Global market size and California population of excavators during 2000-2020

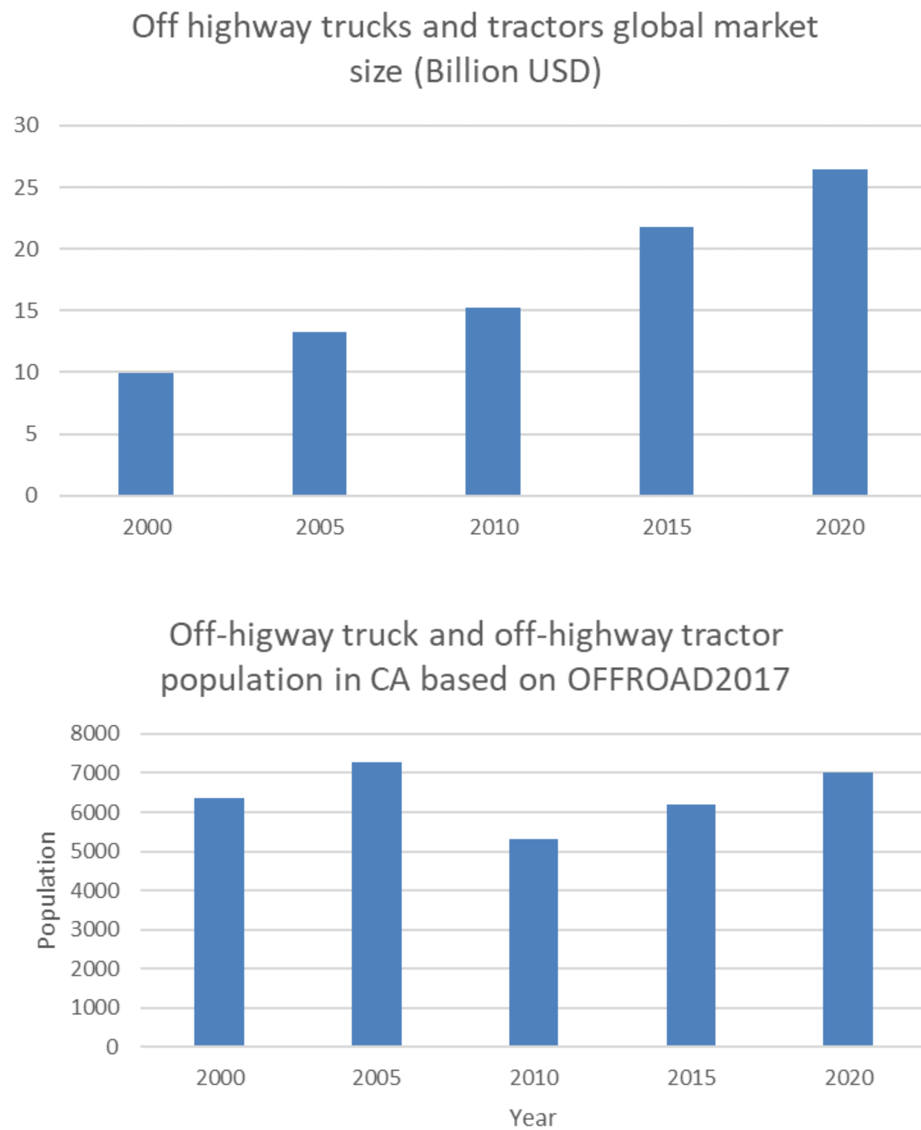


Figure 1-19. Global market size and California population of off-highway trucks and tractors during 2000-2020

Another source of market report provides plots of the trends of global market size from 2015 to 2025 for loaders and excavators [7]. They are shown in Figure 1-20 and Figure 1-21, respectively. Both plots show a similar trend where there was a dip in global market size in 2016 before growing again. The dip in global market size of excavators in 2016 is also reflected in the excavator sales in the U.S. in that year, as shown in Figure 1-22. However, the population of excavators in California did not experience the same drop in 2016 as the global market size and U.S. sales for excavators.

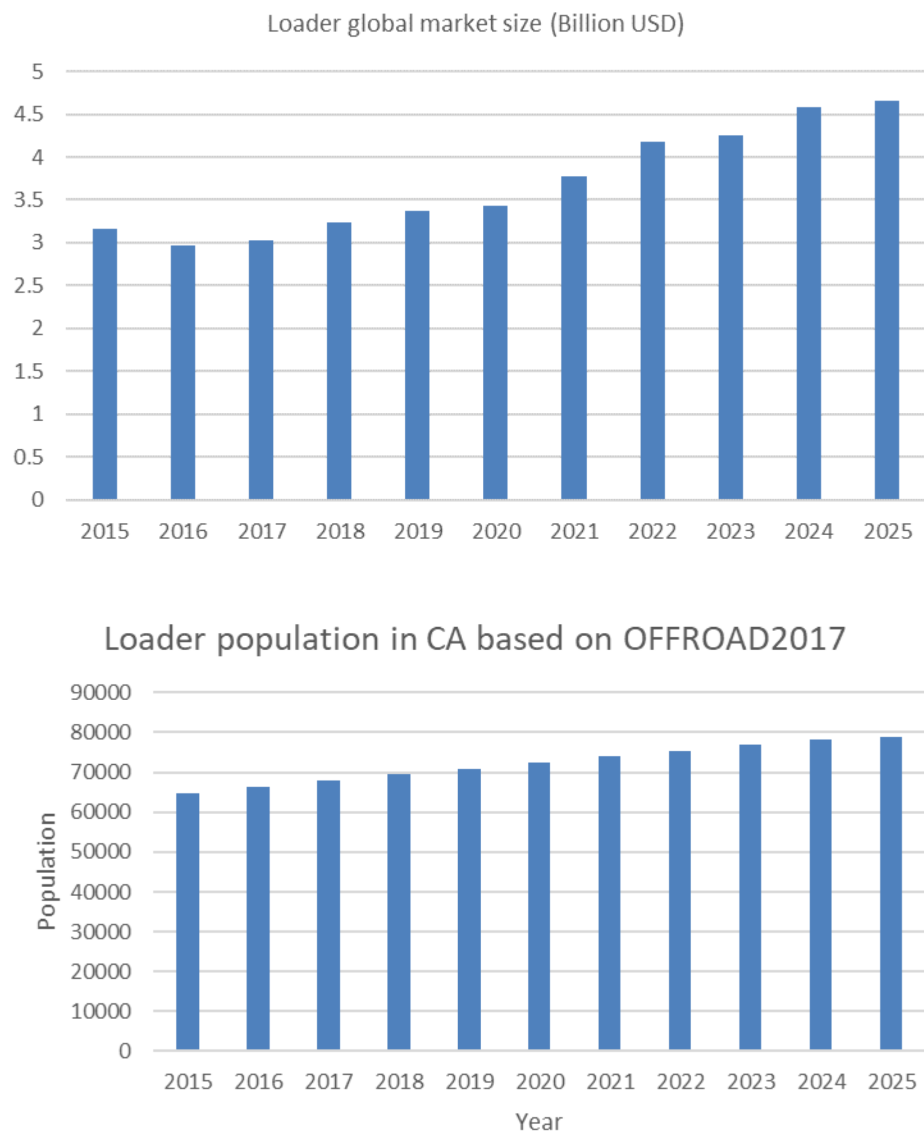


Figure 1-20. Global market size and California population of loaders from 2015 to 2025

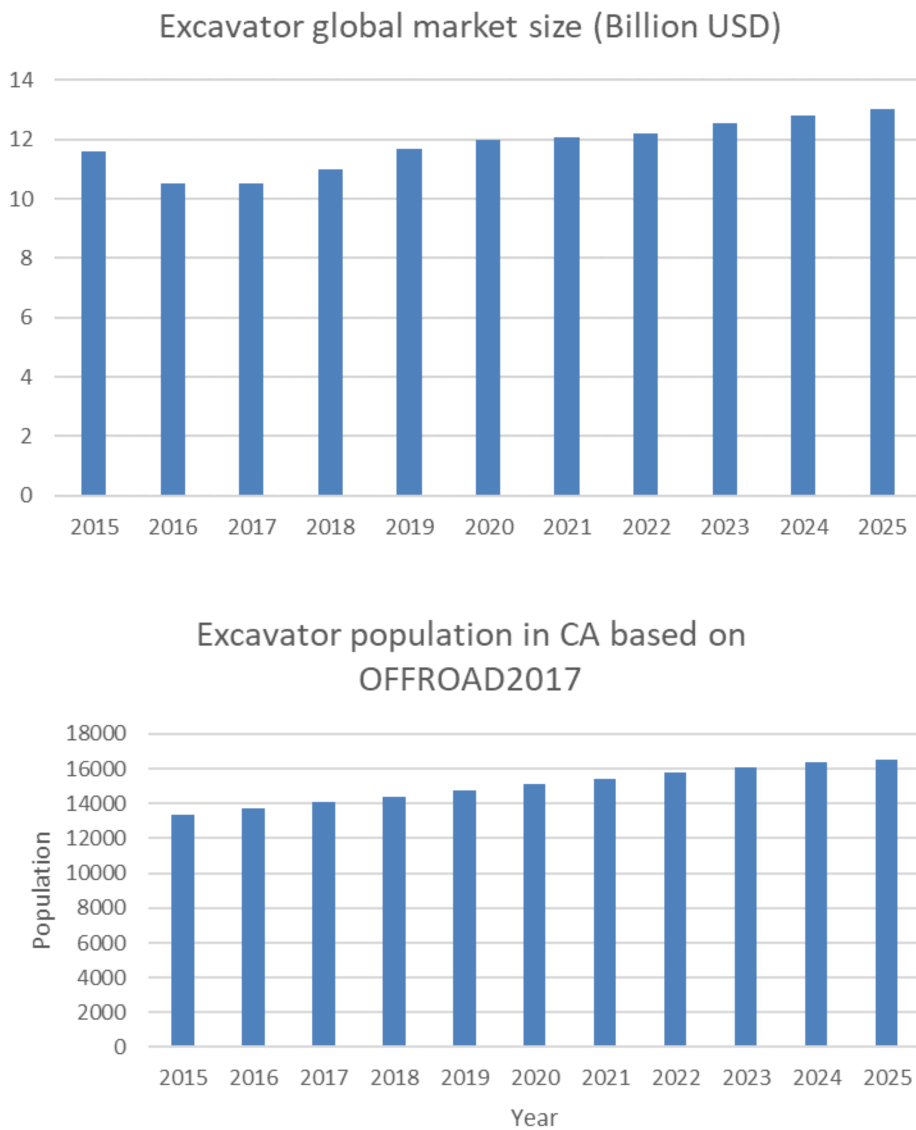


Figure 1-21. Global market size and California population of excavators from 2015 to 2025

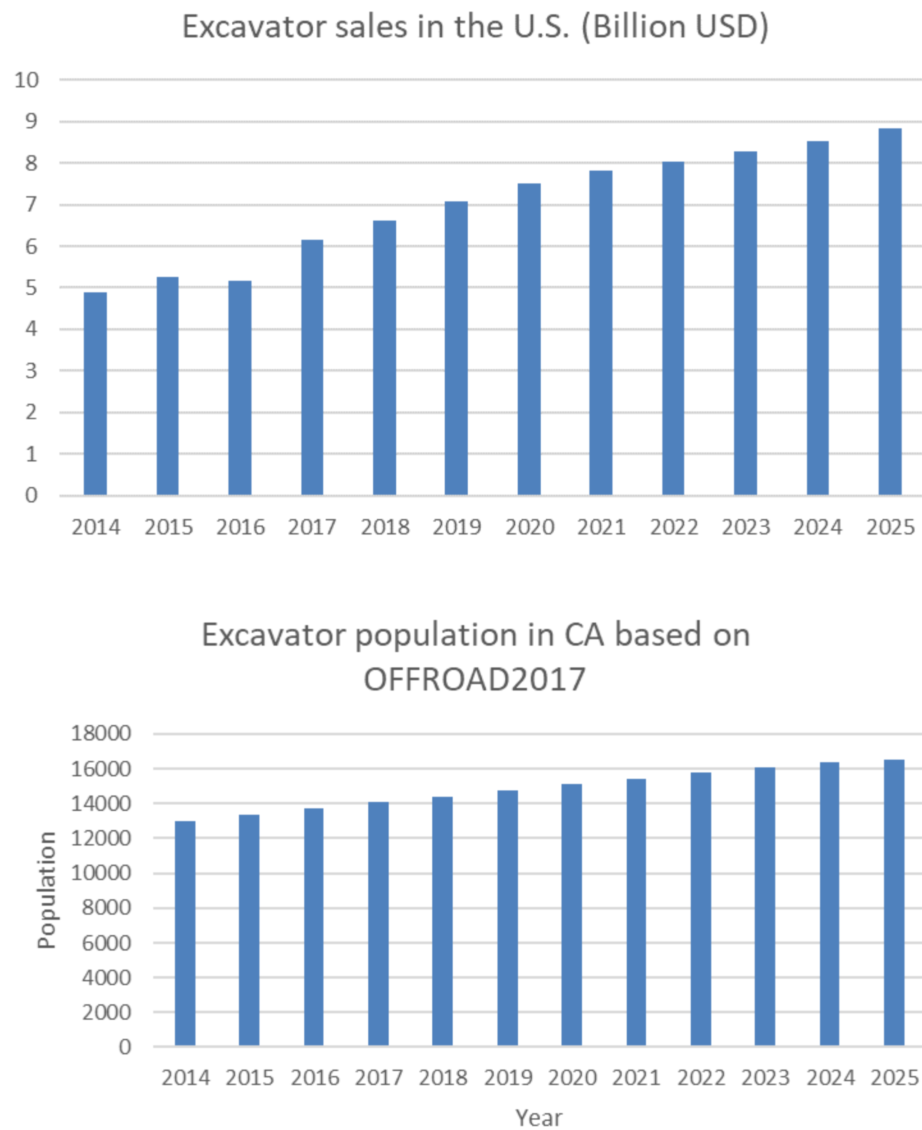


Figure 1-22. U.S. excavator sales and California population from 2014 to 2025

The findings from the comparison of population trends of selected types of construction equipment in California and their global as well as U.S. market size trends suggest that global and even U.S. market sizes for these types of equipment are not a good indicator of their number of population in California. This is partly because if the price varies, the monetary value of the market may not be directly related to the equipment population. Also, the market data represents the sales of new equipment. Population can decrease if the amount of retired equipment is more than the amount new equipment in a calendar year. Moreover, the delineation for equipment category in the market data is different from that in the OFFROAD2017 database.

In terms of market share, Caterpillar led the North American market as of 2011 with a 32% market share, as shown in Figure 1-23 [8]. Information on the current market share could not be found.

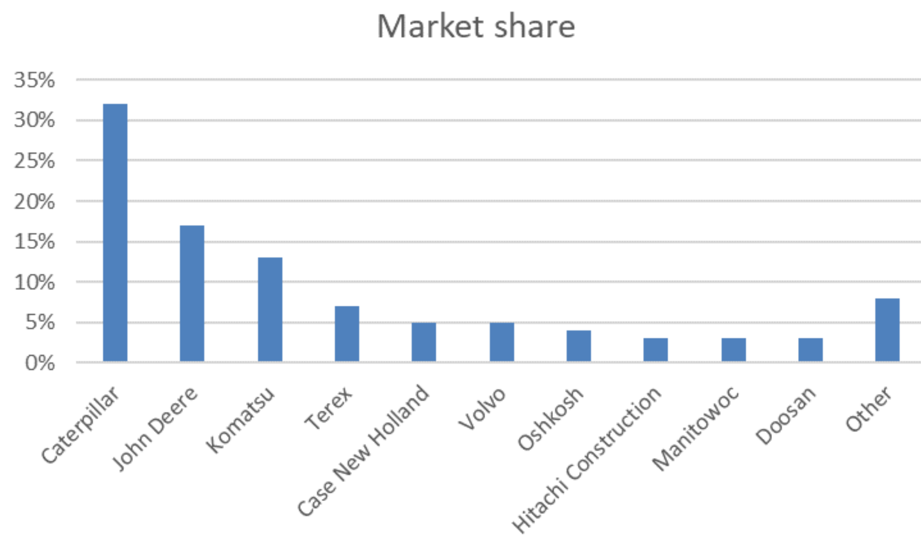


Figure 1-23. Market share of construction equipment in North America by manufacturer in 2011 [6]

For agricultural equipment, tractors are the primary equipment type of interest, but no information on its market share and trend could be found. Only one plot on agricultural equipment usage was found, which is shown in Figure 1-24. It does not provide much insight into the agricultural equipment market, but tractors can be used in many of the applications listed in the plot, including land development and sowing. The most common application is plant protection, which involves managing crop-damaging weeds, weather, diseases, and pests.

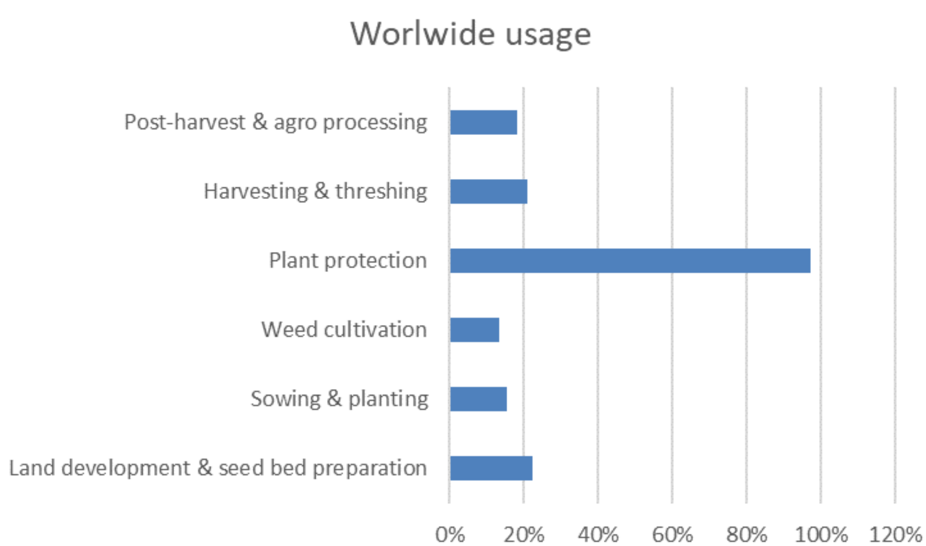


Figure 1-24. Agricultural equipment usage worldwide [9]

1.2 Objectives

The goal of this project is to research previously unexplored pathways for hybridization and electrification in off-road equipment that maximize climate and air quality benefits while remaining both technically and economically viable. The focus for this project is on off-road equipment used in construction and agriculture applications. The work plan of the project consists of the following objectives:

- Examine off-road equipment inventory in California and categorize their population as well as greenhouse gas (GHG) and criteria pollutant emissions by application.
- Perform a market share and market trend analysis for off-road equipment in construction and agricultural sectors.
- Conduct literature review of partially and fully electrified off-road equipment.
- Review electrified off-road equipment currently available on the market as well as those slated to come to market in the future.
- Analyze market viability of electrified off-road equipment through industry survey, and assessment of transferability of technology from on-road applications.
- Analyze real-world duty cycles and activity data of off-road equipment and compare them with those in the engine certification cycles.
- Estimate energy and emission inventories of off-road equipment and compare them with the current estimates in the California Air Resources Board (CARB)'s OFFROAD2017 model.
- Assess the feasibility of partially or fully electrified off-road equipment based on currently available technologies.
- Conduct electrification case studies on selected types of off-road equipment through activity-based battery charging and discharging analysis.
- Estimate +cost required to replace diesel equipment with electric equipment.
- Calculate the emission reductions from electrifying different equipment types, in terms of both GHG and criteria pollutant emissions.
- Analyze how incentive programs could be structured for different equipment types considering the best funding cost-effectiveness.

1.3 Report Organization

This report presents every aspect of the research activities that have been conducted during the course of the project. It is organized as follows:

- Chapter 2 presents the state-of-the-art of off-road equipment electrification in detail, and summarizes the available information on electrification techniques, challenges, and electric equipment availability in the market.

- Chapter 3 analyzes the real-world energy consumption of select off-road equipment, utilizing collected operational data. It provides equipment activity statistics, and compares real-world operation patterns with certification cycles.

- Chapter 4 provides technological feasibility assessment of select off-road equipment types, using recorded activity data. This part focuses on determining electric powertrain requirements employing technical simulation models, and assessing the feasibility of single-motor battery electric powertrains by equipment type. Alternate electrification approaches for infeasible types are also suggested.

- Chapter 5 presents a comprehensive cost-effectiveness estimation method developed to analyze state-wide off-road funding strategy across a wide range of equipment. Two major components of the developed framework: funding amount estimation, and funding cost-effectiveness estimation are described in detail. Strategies to utilize the funding cost-effectiveness results obtained to develop effective funding policies are also demonstrated.

- Finally, Chapter 6 provides conclusions of this research and recommendations for future research.

2 State of Off-Road Equipment Electrification

2.1 Literature and Technology Review

Electric vehicles (EVs) have become popular recently as a champion of emission-reduction and the environmental movement. The superior power and emission-free operation of these automobiles as well as the unique advantages they offer are bringing in a new generation of vehicles [10]. Though the EV field faced challenges due to limited range and insufficient infrastructure, it has recovered from those; and as the current trend suggests, it will not take long for such barriers to get removed. To date, much work has been done on electrification of personal and commercial vehicles [10] [11] [12], along with light-duty, small and mid-sized off-road vehicles such as sports utility vehicles (SUVs) and pickup trucks – some of which are becoming commercially available [13] [14] [15] [16]. However, off-road construction and agricultural vehicles are yet to be given such attention, and it is high time to concentrate on this field, as it has a huge potential to reduce air pollution, and benefit from electrification. These vehicles are often referred to as “equipment” as well, and these two terms (vehicles, and equipment) are used synonymously in this study.

Construction equipment has long been identified as one of the major pollutants in the USA [17], and electrifying the large number of agricultural equipment also holds significant promise in reducing emissions [18], thus improving air-quality. The work done so far in the off-highway heavy-duty vehicle segment focused primarily on series-hybrid diesel electric powertrains [19], and it is high time to improve on that by exploring other EV technologies suitable for implementation in this sector to provide better efficiency and benefits. However, the working conditions, and the performance criteria for EVs and off-road equipment are quite different; and because of that, the electrification of such equipment requires some considerations different than those for on-road EVs [20] [21]. For example, hybrid systems from on-road EVs are not directly applicable to hybrid excavators because of the dissimilar working environments [22]. Also, the components of off-road electric equipment have to withstand larger stresses compared to on-road EVs. For example, the power electronics must be capable of withstanding the elements such as mud and water, and hydrogen tanks for off-road fuel cell electric vehicles (FCEV) [10] must be rugged enough to maintain integrity upon impact.

Research has been conducted on some specific off-road equipment types. Yang et al. looked into the possibilities of reducing emissions from the transportation sector, which included agricultural and off-road vehicles [23]. Parsons et al. reviewed the battery technologies that are fit for off-road usage along with a study of hybrid drivetrains [24]. The permanent magnet synchronous generators suitable for off-highway heavy-duty series hybrid application were discussed in Aydin, et al. [25]. Wang et al. conducted a detailed study on hybrid excavators, demonstrating their configurations, control strategies, comparison, and challenges [22]. Hybrid excavator configurations employing supercapacitors as energy storage system (ESS) were discussed in Kwon, et al. [26]. Powertrains of this particular equipment were also the focus of Wang et al. [27]. Zhang et al. discussed the varied hybrid configurations of construction equipment, and presented the energy management strategies, both optimization-based and rule-based, employed in these machines [28]. A design concept of an off-road hybrid electric agricultural vehicle was presented in Munoz et al. [29]. A review of electrification of agricultural tractors was presented in Moreda et al. [30]. Table 2-1 provides a summary of these works. However, most of these studies were limited to single vehicle types, and there has been an absence of comprehensive studies providing a more holistic picture of the off-road equipment sector.

This research bridges that gap by reviewing the electrification status of major off-road construction and agricultural equipment, which is consistent with the list compiled by the California Air Resources Board (CARB) [3]. Heavy-duty equipment (with horsepower ratings of 75 horsepower and upwards) in these identified categories are the focus of this study. Such vehicles generally employ power takeoff (PTO) – which is the process of driving equipment accessories using power from the engine. Electrification of such equipment-driving mechanisms is included in this study along with the drivetrains, as this results in less use, or more efficient use of the internal combustion engines (ICE) and thus reduces emissions [31]. This claim was also supported by Wagh et al., who pointed out that alongside the drivetrain, accessories as well as safety and control features could also be electrified to provide notable benefits [32]. Along with a review of the configurations of electric off-road equipment presented in previous works, this section is focused on the energy recovery techniques employed by such machines. The advantages of electric off-road equipment, the issues shrouding the electrification attempts in such areas, and their potential solutions are also discussed. Steps are also proposed to facilitate electrification of off-road equipment.

Table 2-1 Overview of Some Previous Reviews

Reference	Year	Topic
Yang et al. [23]	2009	Analysis of emission from transportation sector in California and their mitigation
Parsons et al. [24]	2014	Off-road drivetrain and battery technologies
Aydin et al. [25]	2014	Permanent magnet synchronous generators for off-highway heavy-duty series hybrid application
Wang et al. [22]	2017	Hybrid excavators developed by different organizations and their comparison ESS configurations of hybrid excavators ESS comparison ESS control strategies Energy savings of different configurations Challenges of hybrid excavator ESSs
Kwon et al. [26]	2010	Hybrid excavators employing supercapacitors
Wang et al. [27]	2009	Powertrain and performance analysis of hybrid hydraulic excavators
Zhang et al. [28]	2019	Configurations and energy management strategies of hybrid construction equipment
Moreda et al. [30]	2016	Electrification attempt on agricultural tractors

2.1.1 Vehicle Architectures in Different Categories

While many publications focus on specific vehicle types (e.g., tractors, or excavators), or application sectors (e.g., construction, or agriculture), many study general multi-purpose off-road vehicle configurations. This section provides an overview of the notable works done on construction and agricultural vehicle electrification, with additional inclusion of the general off-road configurations of interest. Each subsection covers different hybrid and full-electric configurations; the hybrid system (HEV) uses an electric setup alongside the conventional ICE, while the full-electric (or battery electric) system (BEV) employs electric system exclusively. A separate classification worth mentioning is fuel cell electric vehicles (FCEV) – which use fuel cells to generate electricity for running its electric drivetrain [10]. Partial or full electrification of equipment attachments, which is conventionally done by the ICE through PTO, is also discussed in this section. The implementation level of different technologies (software simulation, or hardware implementation) is also discussed. The “hardware implementation” term is used for implementations using test-benches as well as vehicle-level deployment. The available development stages of industrial research are also mentioned.

2.1.1.1 General Off-road Vehicle Architecture

EV architecture general structures can be employed in relevant construction and/or agricultural use. The first step towards electrification comes in the form of hybridization. Zhang et al. showed the design of a battery management system (BMS) [33] for a light-duty parallel hybrid off-road vehicle [34], where they employed fuzzy programming to accomplish the task. Parsons et al. showed the design on a heavy military vehicle employing the series hybrid configuration with hub-mounted electric motors utilizing a 2-speed transmission – which can be adopted in heavy construction vehicles, as they had stated their design to be scalable to vehicles requiring individual motor capacity up to 400 kW [24]. A concept similar to Parsons, et al. [24] was previously presented in Jackson et al. [35]. A 2-speed transmission for hybrid heavy off-road machinery was also presented [36]. With sufficiently mature technology, the ICE can be totally discarded to move towards the BEV architecture. Baronti et al. proposed a BMS for $LiFeO_4$ batteries intended for off-road BEV usage, considering battery modules consisting of four cells. Their goal was to design a system which did not require any bespoke hardware, and could serve a wider range of applications [37]. Employing fuel cells to power an electric drivetrain presents an interesting possibility for vehicle electrification. The FCEV configuration can be a good choice for off-road EVs, as it is relatively easier to refuel in remote locations – provided the fuel is available on-site. FCEVs use hydrogen fuel cells, and thus on-site storage of hydrogen will be necessary for using such vehicles as construction or agricultural equipment. An off-road FCEV configuration is presented by Saeks et al. [38], where they proposed a flywheel energy storage system [10] to recover energy and aid in acceleration. Their system had four motors in each of the four wheels to provide four-wheel drive, and employed adaptive controllers with interconnections to facilitate front and rear wheel steering, as well as energy management and acceleration-deceleration. The works reviewed in this subsection are summarized in Table 2-2.

Table 2-2 Academic Literature Overview of General Off-Road EV Architecture

Reference	Year	EV Type	Components of Interest	Control Algorithm	Potential Vehicle Application	Implementation Level
Saeks et al. [31]	2002	FCEV	Fuel cell Flywheel Electric motor	Neural adaptive controller Adaptive dynamic programming controller	Off-road driving	Simulation
Zhang et al. [27]	2008	Parallel PHEV	Battery Electric motor	Fuzzy logic	Light off-road driving	Simulation
Baronti et al. [30]	2013	General	$LiFeO_4$ battery management system	N/A	Construction Agriculture	Simulation
Parsons et al. [16]	2014	Series HEV	Diesel generator Hub-mounted electric motor 2-speed transmission Battery	N/A	Military Construction	Simulation and Hardware implementation
Sinkko et al. [29]	2014	HEV	Permanent magnet synchronous motor 2-speed transmission	N/A	Construction Agriculture	Simulation

2.1.1.2 Construction Equipment

Electrification efforts on construction vehicles are the focus of this subsection. Special attention is paid to construction equipment with higher population or more CO_2 emission contribution. Such vehicle categories are identified from Figure 1-1 and Figure 1-2. This subsection will concentrate on the leading vehicle categories of these lists; namely, tractor-loader-backhoe, loader, excavator, off-highway truck, and scraper. Tractor-loader-backhoe is a tractor with a loader at the front and a backhoe at back. Escorts [39] proposed a concept of an electric backhoe-loader, but details on that are currently scant [40]. Skid steer loaders can be tracked or wheeled, and the wheeled ones can be termed as rubber tired loaders. A number of hybrid rubber tired loaders are already available commercially [41] [42] [43], while BEV versions of small equipment in this class were also displayed [44]. However, it appears that experiments with larger BEV loaders have also gained momentum [45]. It was described that a Caterpillar R1300G LHD (Figure 2-1) with electric motors and lithium batteries driving a mechanical drivetrain with gears [45]. This loader was not a skid steer. Another additional example of a hybrid electric vehicle in this category is the Caterpillar® 988K XE, which combined a switched reluctance electric drive with a Tier 4 diesel engine [46] for increased efficiency and convenience. It utilizes the switched reluctance machines as a generator and pump drive [47] [48]. Some additional hybrid loader projects were reported in Achten et al. [49]. It can be assumed that the electrification advancements made in the loader vehicle architecture can be transferred to tractor-loader-backhoes with similar power requirements.

Figure 2-1 Caterpillar BEV loader prototype; battery-powered electric motor was used here to run a mechanical drivetrain [45].

Excavators are fitted with digging equipment using a boom, and can be wheeled or tracked. Figure 2-2 shows a wheeled excavator. References [50] [51] successfully investigated the integration of electric systems in excavator booms for energy recovery, resulting in less energy consumption – and hence lower CO_2 emissions. Wang et al. studied different hybrid excavator configurations [22], where various drivetrain configurations were discussed. They identified the combination of electric motor with battery that was most frequently used for small excavators, whereas the medium ones favored supercapacitors (SC) (also known as ultracapacitors) instead of battery as the ESS. The superior power density of SC, and its faster power transfer in larger amounts as compared to the batteries [10] may have driven this choice. Use of batteries in excavator usage was also documented in Xiao et al. [52]; while hybrid ESS comprised of both battery and SC was also proposed [22] [53] [54].

Yao and Wand proposed a hybrid excavator using a supercapacitor to power its electric swing system [55]. Kwon et al. classified hybrid excavator configurations in three categories [26]: series (electric motor controls all movements, powered by ICE), parallel (both ICE and motor powers the system), and compound (an electric motor replaces the hydraulic swing motor facilitating energy recovery). They determined the compound system to be superior because of its greater reliability and shorter anticipated payback period. They also proposed a power control algorithm for hybrid compound excavators which was claimed to reduce fuel consumption by 24% with respect to conventional excavators [26]. This algorithm works by balancing power demand between a supercapacitor and the engine at each instance. In this hybrid structure, the supercapacitor, swing motor, and the generator (powered by the engine) are all connected to a pulse width modulation (PWM) converter (Figure 2-3). The said balance is attained by controlling this converter's DC-link voltage. The generator maintains a constant DC-link voltage utilizing a feedback mechanism, and the supercapacitor voltage is kept in a certain range through feed-forward mechanism; the engine speed is kept almost constant. The hydraulic pump is driven by the generator run by the engine. According to some operational set points, the system power is supplied or absorbed (during swing regeneration) by either the generator or the supercapacitor. When the supercapacitor voltage is within its rated operational range, it is used to power the swing, and the generator charges the supercapacitor; in such a scenario, the supercapacitor also absorbs any regeneration from the swing. If the supercapacitor voltage is higher than the rated value (thus indicating it cannot absorb any more energy), regeneration from the swing is used to run the generator in motoring mode, thus sharing the hydraulic load with the engine. In cases of zero swing power with a high supercapacitor voltage, the supercapacitor is discharged to share the hydraulic load with the engine by running the generator in motoring mode.

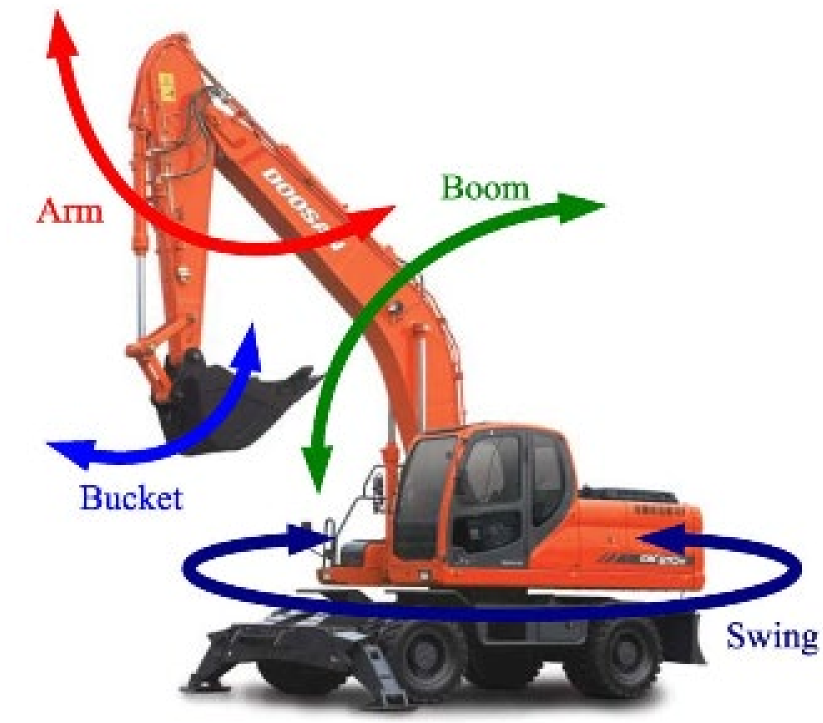


Figure 2-2 A wheeled excavator shown with its major components and movement directions [26]. The swing motion allows this equipment to rotate 360 degrees without engaging the drivetrain.

Wang et al. also conducted a comparative study on hybrid excavator configurations, and identified the parallel system to be the best based on cost and performance considerations [27]. They did not consider a compound system like Kwon et al. [26], but presented all the possible configurations for series and parallel systems – and the compound configuration of Kwon et al. [26] can be considered as part of the parallel configuration set of Wang et al. [27], thus making the argument behind this setup's supremacy stronger. A similar conclusion was made by Lin et al. [56] as well. Lee et al. simulated a plug-in hybrid excavator configuration for series, parallel, and dual mode and the model showed that dual mode could exploit the benefits of both series and parallel systems, but with higher cost and complexity [57]. Yoo et al. developed a hybrid system with SC to operate in series, parallel, and compound modes, then implemented the control system in a mid-sized excavator successfully [58]. Xiao et al. presented a control strategy for a parallel hybrid excavator employing ICE and SC to dynamically control the ICE's operating region for better system operation with little effect on performance [59]. Ge et al.'s approach to use a variable speed electric motor to drive a variable displacement pump to meet the dynamic energy demand of excavators resulted in 1.35 kW less power consumption during idling, and around 30% energy saving ratio, compared to pure displacement variable design [60].

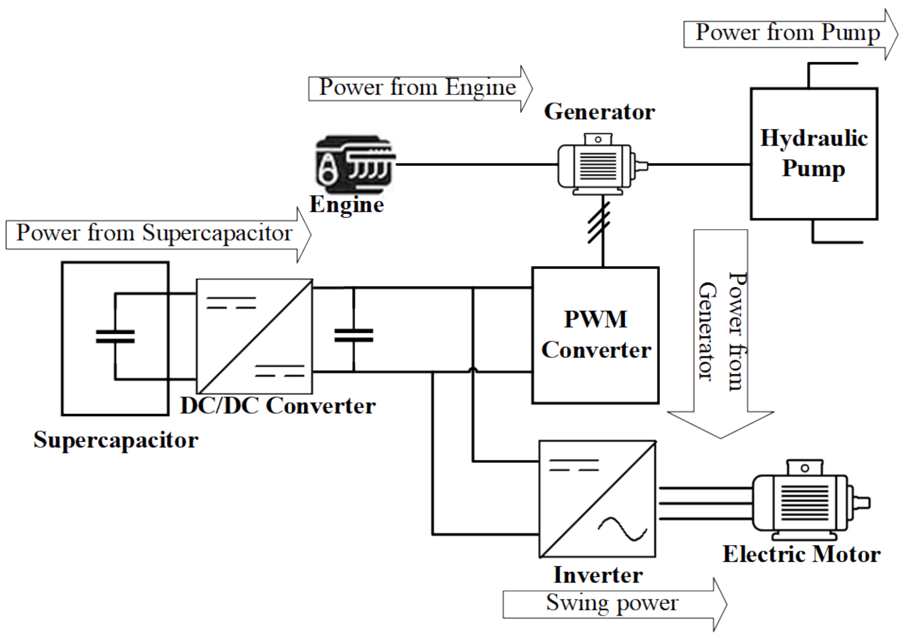


Figure 2-3 Hybrid compound excavator architecture presented by Kwon et al. [26]. A supercapacitor was used as the electrical energy storage system; the electric drivetrain runs the swing electric motor with engine assistance.

Off-highway trucks (Figure 2-4) are also known as off-highway vehicles (OHV), and mine haul trucks [61]. A large number of vehicles in this segment have been using series hybrid diesel electric drivetrains (electric drivetrains without high-voltage storage, powered by diesel engines [30]) with AC wheel motors [61] [62], but further efforts were made to recover the braking energy which was generally sent to brake resistors to be dissipated as heat in the conventional diesel electric system. Such an attempt was made by Richter et al. [61], where they successfully implemented a Sodium-Nickle-Chloride ($NaNiCl_2$) battery energy storage system in a Komatsu 830E [63]. Reference [64] presented a truck trolley system where the trucks were provided electricity from a dedicated substation through an overhead line, to make the vehicles all electric, and thus reducing the fuel consumption even more by transferring the ICE's power generation operation to a more efficient system. In this work, use of supercapacitors were also proposed to capture regenerated energy to use in stretches of the track where overhead lines could not be placed [64]. Esfahanian et al. proposed the use of road grade data to dynamically control the energy management system of a hybrid mining haul truck with storage; this approach allowed the batteries to operate even beyond safe state of charge (SOC) limits if there were downhill slopes within reach, which could replenish the battery's energy level within a safe operating window by using braking regeneration [62]. Use of AC-AC converter to run the AC motors in off-highway trucks without an intermediate DC converter has been proposed by Kwak et al. [19], where they presented a matrix converter architecture with phase redundancy that came with fault detection capabilities. Pilot projects pursuing a battery electric haul truck also surfaced; such an example is found in Lambert et al. [65], where a Komatsu 605-7 truck was reported to be retrofitted with a 700 kWh Lithium Nickel Manganese Cobalt Oxide (LiNiMnCo) (called NMC in industry-standard nomenclature) battery pack and a synchronous motor. Additionally, Mirzaei et al. presented software and hardware solutions for improved electric braking in such trucks, where the hardware solution was proved to be the most reliable, but more costly than the software one [66]. Electro-hybrid actuators to be used in off-highway equipment was proposed by Åman et al. to replace hydraulic pipelines with electric wiring, thus enhancing reliability, and also facilitating regeneration from hydraulic systems [67]. From this study, it has become evident that series hybrid implementation of off-highway trucks is widely spread in the industry (Table 2-3 lists several such commercial products). The reviewed research in this area focused on further novel electrification possibilities, such as integrating ESS for capturing regenerative energy, and employing overhead power lines for full-electric operation – among other things.

Figure 2-4 An off-highway series hybrid truck produced by Komatsu. A Tier 2 Diesel engine is used to generate electricity to drive the rear wheels through wheel motors [63].

In the off-road construction vehicle sector, significant hybridization effort has already been made in the excavator area. Hybrid excavators are available commercially, and are associated with a large body of research work (14 papers are listed in Section 2.1.1.2). The reason of this much interest in hybrid excavators is also justified. Hydraulic excavators are one of the most used construction equipment [68]. Their energy consumption is huge as well, yet the efficiency for converting that energy to useful work is significantly low – less than 30% if fuel to actuator efficiency is calculated. The emission of pollutants including particle matters and nitrogen oxides from these equipment is very high as well. The reason behind these is the incapability of the ICE to run in its high-efficiency region. It is run nearly at its rated speed, so that the hydraulic pressure stays at a sufficient level to facilitate smooth transition from light to heavy load

[26]. Also, the hydraulic system itself has an average efficiency of around 54% [60]. Thus, hybridization significantly improves fuel efficiency and reduce emission, as adding an electric system with an energy storage lets the ICE to run at its efficient region, while the storage acts as an energy buffer to supply the instantaneous power required. It further enhances practicality by absorbing the regenerative power which is wasted as heat in ICE excavators [26] [69]. A similar scenario is prevailing in the off-highway truck area – where the series hybrid system has become mainstream, and all-electric options are being considered. The other prominent vehicle types in the construction equipment category, such as tractor-loader-backhoes, and loaders demand more investigation in possible electrification techniques. Also, no such attempt was found for scrapers, to the best of the authors' knowledge. As this equipment is a major CO_2 emitter, it demands immediate attention. The academic and industrial works reviewed in Section 2.1.1.2 are summarized in Table 2-3 and Table 2-4 respectively.

Table 2-3 Academic Literature Overview on Electric Construction Equipment

Reference	Year	EV Type	Components of Interest	Control Algorithm	Implementation Level	Equipment Type
Kwon et al. [26]	2010	HEV	ICE Electric generator Electric motor Supercapacitor Hydraulic pump	Novel algorithm.	Simulation	Excavator
Yao et al. [55]	2013	HEV	ICE Permanent magnet synchronous motor Supercapacitor Electric swing system	Combination of proportional (P) controller and mixed sensitivity controller.	Simulation and Hardware implementation	
Xiao et al. [59]	2008	Parallel HEV	ICE Electric motor Supercapacitor Hydraulic pump	Dynamic work point.	Simulation	
Lin et al. [56]	2008	Parallel HEV, Series HEV	ICE Electric motor Hydraulic pump	Dynamic multi work point controller comprising of direct torque control, and closed loop proportional-integral (PI) control.	Simulation	
Lee et al. [57]	2013	Parallel, series, and dual mode power split PHEV	ICE Electric generator Electric motor Battery Hydraulic pump	Electric motor drives hydraulic pump, powered by battery; battery is charged by the generator run by ICE.	Simulation	
Yoo et al. [58]	2009	Parallel, series, and compound HEV	Diesel ICE Electric motor Electric generator Electric swing motor Supercapacitor	Electric swing system, electric power assistance of ICE, regenerated energy stored in SC.	Simulation and hardware implementation	
Ge et al. [60]	2017	HEV	ICE Speed variable electric motor Variable pump	Variable speed electric motor drives a variable displacement pump to meet dynamic energy	Simulation and hardware implementation	

Reference	Year	EV Type	Components of Interest	Control Algorithm	Implementation Level	Equipment Type
				demand.		
Wang et al. [70]	2013	HEV	ICE Electric generator Electric motor Supercapacitor Potential energy recovery system Electric swing system	Energy regeneration from swing system and boom.	Simulation	
Mazumdar [71]	2013	BEV	Electric drivetrain Overhead power line Regenerative braking Battery or SC energy storage system (ESS)	Driven by overhead power supply. Regenerated energy stored in ESS to use in short driving distances.	Simulation	Off-highway truck
Esfahanian et al. [62]	2013	HEV	ICE Electric motor Battery Regenerative braking	Road grade data used for dynamic energy management.	None	

Table 2-4 Industrial Research Overview on Electric Construction Equipment

Reference	Manufacturer	Model	EV Type	Components of Interest	Control Strategy	Equipment Type	Implementation Level
[41] [72]	John Deere	644K Hybrid Wheel Loader	HEV	Interim tier 4 diesel engine 3-phase alternating current (AC) motor/generator Water cooled inverter Water cooled brake resistor Battery	No reverse gear as electric motor can perform this shift in direction, brake resistor consumes and dissipates excess energy generated during regenerative braking.	Skid steer loader/rubber tired loader	Hardware implementation
[42] [43]	John Deere	318E 320E 326E 328E 332E	HEV	Final/Interim tier 4 diesel engine Electrohydraulic powertrain	N/A		Hardware implementation
[44]	Tobroco-Giant	GIANT E-skid steer	BEV	Hydraulic wheel motor Battery	N/A		
[45]	Caterpillar	R1300G LHD	BEV	Lithium battery pack Electric motor Mechanical axles and drive-shafts	Electric motor used to run mechanical drivetrain through electric motor.	Rubber tired loader	Hardware implementation

Reference	Manufacturer	Model	EV Type	Components of Interest	Control Strategy	Equipment Type	Implementation Level
[47] [48]	Caterpillar	988K XE	HEV	Tier 4 diesel engine Switched reluctance electric machine for drivetrain, pump drive, and generator Specialized power electronics	N/A		Hardware implementation
[22]	Kobelco (modified)	70SR	HEV	288 Volt Li-ion battery set 20 kW electric motor/generator Electric swing	Energy supplied to the electrical load from the battery when needed, and absorbed during braking.	Excavator	None
[22] [73]	Kobelco	SK80H	HEV	288 Volt nickel metal hydride battery set 20 kW electric motor/generator 10 kW electric swing motor	Battery charging and discharging limit set according to concurrent state-of-charge to ensure maximum efficiency and lifetime.		Simulation
[22]	Caterpillar	N/A	Parallel HEV	ICE Electric motor/generator Battery	Operating mode and torque set according to load variation and SOC.		None
[22]	Komatsu	N/A	HEV	ICE Electric generator Electric motor Supercapacitor Electric swing system	Separate use of hydraulic motor and generator.		None
[22] [74] [14, 66]	Hitachi	N/A	Parallel HEV	ICE Electric generator Electric motor Supercapacitor Electric swing system	Control system comprised of master and slave controllers where the slave is used to monitor and govern the SC charge-discharge.		None
[22]	Doosan	N/A	HEV	ICE Electric generator Electric motor Supercapacitor	N/A		None
[22] [53] [54]	Kobelco	N/A	Series HEV	ICE Hybrid ESS (288 V, 6.5 Ah Ni-MH battery + 304 V, 11.4 F SC)	ESS assists during heavy load and stores surplus energy under light loads. Engine works in high efficiency region all the time, even stops when ESS energy is sufficient to drive loads.		None
[22]	Sumitomo	N/A	HEV	ICE Supercapacitor Electric motor	SC SOC set to a higher value to drive load at higher voltage with better efficiency.		None

Reference	Manufacturer	Model	EV Type	Components of Interest	Control Strategy	Equipment Type	Implementation Level
[61]	Komatsu	830E (modified)	Series HEV	ICE $NaNiCl_2$ battery Wheel motor	Battery used to recover braking energy to be deployed for power boost or enhanced engine efficiency.	Off-highway truck	Simulation and hardware implementation
[63]	Komatsu	830E-1AC	Series HEV	Tier 2 Diesel engine Electric generator Wheel motor Electric retarder (dynamic)	N/A		Commercially available
[75]	Komatsu	930E-4	Series HEV	Tier 2 Diesel engine Electric generator Wheel motor Electric retarder (dynamic)	N/A		Commercially available
[76]	Caterpillar	795F AC Mining Truck	Series HEV	ICE Electric generator AC induction wheel motor Electric retarder (dynamic)	N/A		Commercially available
[65]	Komatsu	605-7 (modified)	BEV	LiNiMnCo battery pack Synchronous motor Regenerative braking	The battery powers the motor and stores regenerative energy.		Hardware implementation

2.1.1.3 Agricultural Equipment

In CARB's off-road emissions inventory model [3], two agricultural equipment types are prominent: tillers because of their large population, and agricultural tractors for their high overall CO_2 emissions (Figure 1-5, Figure 1-6). Among these two, tillers are small equipment and thus out of the scope of this study. For large-scale tilling application, tractors are used with necessary attachments making tractors the equipment type of interest in the agricultural sector for this work. Tractors (Figure 2-5) have been identified as the most fuel-consuming mobile agricultural equipment [77], and this sector has attracted notable research interest.

Usinin et al. presented a series hybrid electric drivetrain for tractors [78], where the system consisted of an engine, generator, two traction motors, and required power electronics. Gas turbine and diesel engines were proposed as the engine choices; while electric machines and power electronics were designed to reduce cost [78]. Mousazadeh et al.'s design [79], employed two solar panels on their tractor which was capable of meeting 18% of the energy demand, and the rest was obtained from the grid to charge its valve regulated lead acid (VRLA) battery pack. This tractor successfully carried out several common light agricultural tasks including plowing, mowing, and towing. This equipment was mentioned as a PHEV, but based on the definitions of this report, it was a BEV because of its sole use of electric drivetrain devoid of any ICE, and it is categorized accordingly in Table 2-5. The authors in [79] conducted a comparative study on different battery technologies best suited for their solar-assisted tractor in a separate study [80], and concluded that the VRLA technology was the best considering the regional manufacturing capabilities. In other cases, however, employing Li-ion or any other chemistry superior than the aged lead-acid type can lead to better results. Ueka et al.'s design used an electric motor to drive a rotary tiller and employ four wheel drive in a battery electric tractor [77]. An electronically controlled continuously variable transmission (e-CVT) with PTO capabilities was designed by Rossi et al. for a parallel hybrid agricultural tractor [81], which was implemented in hardware. Florentsev et al. presented a pre-production version of a series hybrid tractor which used asynchronous traction motor and electricity-driven PTO [82]. A similar work was shown in Puhovoy et al. [83]. A fuel cell electric tractor was also demonstrated previously [84]. To enable high-voltage PTO capabilities, Moreda et al. proposed installing a PTO-dedicated high voltage generator on tractors [30]. Gonzalez-de-Soto et al. presented a hydrogen fuel cell powered PTO system for an ICE-driven tractor [31]. Their system comprised a fuel cell stack and a solar photovoltaic (PV) system for power generation, and batteries for storage. Additionally, Zhitkova et al. designed an electric motor for agricultural tractor use, suited for both low speed off-road operation and higher speed produce-transportation work [85]. Their work was verified through simulation. From this review, it can be seen that most of the works done are on HEV tractors; fuel cell drivetrains have been proposed in the past with more recent application of fuel cells to PTO [31]. More work is thus needed on BEV and FCEV tractors.

Overall, in the agricultural sector, even though tractors are significantly less in number in California [3], they are the major CO_2 emitter; and therefore the electrification attempt going into this vehicle segment is critical for meeting climate change goals, but there is still much more room to expand. The academic and industrial works reviewed in Section 2.1.1.3 are summarized in Table 2-5 and Table 2-6 respectively. Considering the current state of the fields under review in this work, it can be safely assumed that hybrid technology is an important intermediate step toward electrification. Figure 2-6 shows an infographic of the works reviewed in different subsections of Subsection 2-3.

Figure 2-5 Series hybrid tractor concept presented in [82] with electric drivetrain and PTO.

Table 2-5 Academic Literature Overview on Electric Agricultural Equipment

Reference	Year	EV Type	Components of Interest	Control Algorithm	Implementation Level	Equipment Type
Usinin et al. [78]	2013	Series HEV	Gas turbine / diesel ICE Synchronous reluctance generator Synchronous reluctance motor	Separate excitation for generator and motor, motor torque control by controlling armature current and magnetic flux.	Simulation	Tractor
Mousazadeh et al. [79]	2010	BEV	VRLA battery pack Electric motor Solar panel Electrically driven PTO	Solar panel supplied 18% of required power, rest taken from grid.	Simulation and hardware implementation	
Ueka et al. [77]	2013	BEV	Battery pack Electric motor Electrically driven PTO	A rotary tiller along with the four wheels driven by the motor through reduction gear.	Simulation and hardware implementation	
Rossi et al. [81]	2014	Parallel HEV	ICE Electric motor/generator e-CVT with PTO	Set up for using ICE's maximum torque operating region.	Simulation and hardware implementation	
Gonzalez-de-Soto et al. [31]	2016	ICE vehicle with fuel cell-powered PTO	ICE Hydrogen fuel cell Solar photovoltaic system Battery	The fuel cell system powers the PTO, while ICE runs the drivetrain. Battery stores excess energy.	Simulation and hardware implementation	

Table 2-6 Industrial Research Overview on Electric Agricultural Equipment

Reference	Manufacturer	Model	EV Type	Components of Interest	Control Strategy	Equipment Type	Reason of Prominence in CARB List	Implementation Level
[82]	Ruselprom	Belarus-3023	Series HEV	ICE Battery Liquid-cooled asynchronous motor/generator Liquid-cooled asynchronous traction motor Liquid-cooled power electronics Electric-powered PTO	ICE powered electric drivetrain, electricity driven PTO.	Tractor	CO_2 emission	Pre-production versions produced
[84]	New Holland	NH2	FCEV	Fuel cell stack Electric motors for traction and PTO	Traction and PTO operation handled by separate motors.			Hardware implementation

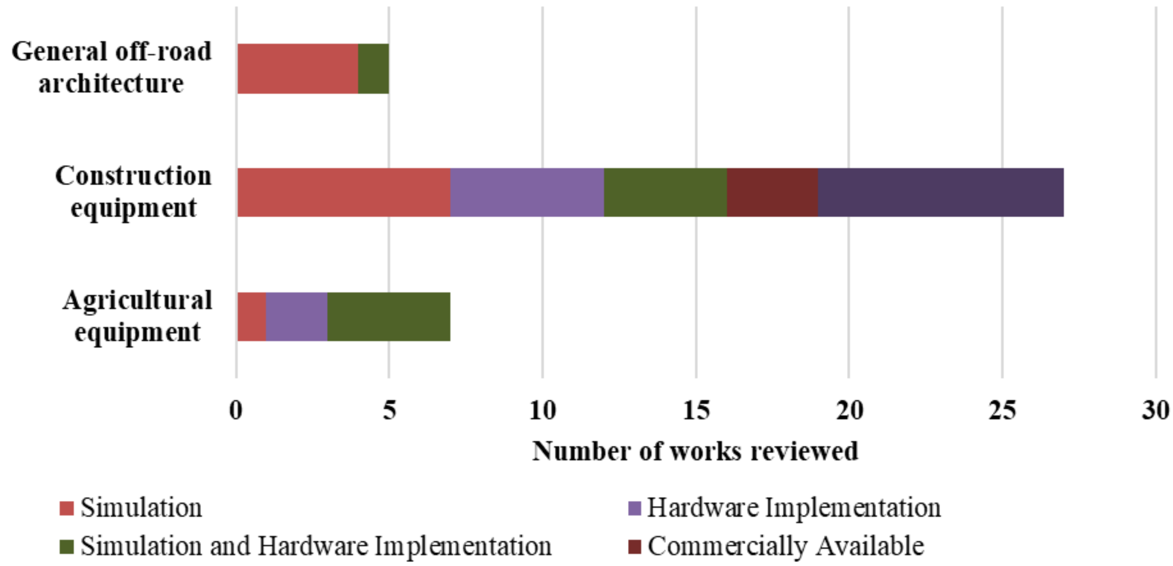


Figure 2-6 Comparative visualization of major works reviewed in section 2.1.1

2.1.2 Energy Recovery

In on-road electric vehicles, regenerative braking is commonly used for energy recuperation and increased energy efficiency [10]. Regenerative braking is used in limited off-road applications such as off-highway trucks, which use this technique to slow down without wearing the mechanical brakes, and there are excavators which employ swing and boom movements for energy recuperation [49]. In this subsection, regeneration techniques in addition to regenerative braking are thus discussed.

Operating loaders involves abrupt stops while piling material, lifting material, and moving it to other locations; these stops can generate electricity through regenerative braking [86] [87]. This strategy was implemented in the John Deere 644K Hybrid Wheel Loader [41] [72]. The braking energy recovery in loaders is less effective compared to on-road vehicle regenerative braking, since the relative resistance to motion is higher in off-road applications compared to the rolling resistance of on-road vehicles on typical road surfaces. For instance, higher lateral forces are needed for loaders to dig through material [49]. Regardless, several techniques exist which allow for higher efficiency through regenerative energy recuperation.

Capturing braking energy in ESSs in off-highway trucks was proposed in [62] [71], which is generally dissipated as heat. Gravitational energy can be used to generate electricity to be stored in ESS while lowering forklift-type systems [88]. Yoon et al. proposed capturing the potential energy from boom lowering of an excavator in an ESS consisting of battery and capacitors [50]. Ge et al. proposed a method [51] capable of capturing energy from such excavator operations as hydraulic energy. Another hydraulic energy capture system was presented by Ho et al. [89]. Xia et al. also presented a hydraulic potential energy capturing method applicable to machines utilizing hydraulic cylinders [90], which was implemented successfully in an excavator. Though such methods do not generate electric energy directly, these can still be useful in hybrid equipment where hydraulic systems work alongside the electrical powertrain. Lin et al. noted that with an electric recuperation system directly coupled with an excavator boom, the regeneration time-window was directly related to the duration of lowering the boom which could be too short for a battery to capture the total available energy; also, the electric generator had to work at different efficiency-points if the load-point shifted, lowering the overall efficiency. To counter this, they proposed using a hydraulic cylinder for fast capture of the potential energy, and then used it to run a generator to efficiently store the electricity energy in an ESS. They used supercapacitors for this purpose, but mentioned the use of batteries was also possible as the intermediate hydraulic cylinder can facilitate fast-capture of energy and then run the generator for a period best-suited for the battery to charge properly [91].

These justifications were also echoed in [92], where a hydraulic motor/generator was used to recapture energy from a parallel hybrid excavator's boom and stored in an ESS. It also pointed out that without the intermediate hydraulic system, even using supercapacitors as ESS would be unwise as the instantaneous large changes in power could affect the lifetime of the supercapacitors used. It was also identified here that the boom was the major source for regenerative energy in the 7-ton excavator used in that work, as 67% of total recapturable energy came from its movements. Wang et al.'s method also proposed to couple an electric generator with hydraulic cylinders for electricity generation from cylinder pressure, which could be consumed instantly by some other operating components, or stored in ESS for future use [93]. Chen et al. showed a method for capturing gravitational energy from excavator booms by running a permanent magnet brushless direct current (DC) motor, and storing the energy in supercapacitors [94]. Yoo et al. proposed energy regeneration and subsequent storage in supercapacitor from the swing movement in [58], whereas Wang et al. opted for recuperation from both swing and boom [70].

Other than these, generation of electricity by recapturing heat from turbocharged engines could be done by running the exhaust gas leaving the turbocharger through a second turbine-generator system, or by using thermoelectric generators – which could do the generation without involving any moving parts [30] [86] [95]. Therefore, such techniques can be applied to any construction or agricultural equipment employing a turbocharger. From this section, it is evident that most of the research work conducted were on excavators – consistent with the findings in Section II. The other construction equipment (tractor-loader-backhoe, loader, off-highway truck, and scraper) received limited attention, and agricultural equipment received none. It is also evident that using an intermediate hydraulic system for energy recuperation in excavators is the best way, and the boom is the main source to be targeted for energy recovery. The future research works can look into the vehicle categories and components (such as suspension and wheels) not covered in previous studies. The key technologies reviewed in this section are listed in Table 2-7.

Table 2-7 Energy Recovery Techniques in Reviewed Literature for Equipment Types of Interest

Reference	Year	Regenerative Component	Vehicle Application	Implementation Level	Equipment Type
Minav et al. [88]	2013	Lift	Construction	Simulation	Forklift
Mazumdar [71]	2013	Brake	Construction	Simulation	Off-highway truck
Esfahanian et al. [62]	2013	Brake	Construction	None	
[65]	2017	Brake	Construction	Hardware implementation	
Yoon et al. [50]	2013	Boom	Construction	Simulation	Excavator
Wang et al. [93]	2014	Hydraulic cylinder	Construction	Simulation	
Lin et al. [91]	2016	Boom	Construction	Simulation and hardware implementation	
Lin et al. [92]	2010	Boom	Construction	Simulation	
Chen et al. [94]	2017	Boom	Construction	Simulation and hardware implementation	
Yoo et al. [58]	2009	Swing	Construction	Simulation and hardware implementation	
Wang et al. [70]	2013	Swing and boom	Construction	Simulation	
Singh et al. [86]	2009	Turbocharger	Construction Agriculture	None	All turbocharged equipment
Yu et al. [95]	2015	Turbocharger	Construction Agriculture	None	All turbocharged equipment

2.1.3 Promises and Concerns of Off-Road Equipment Electrification

The advantages vehicle electrification offers initiated the drive towards such technologies, but it also came with its own limitations. These benefits, and shortcomings in the off-road equipment sector are often shared with the on-road vehicle segment, but also venture into some unique avenues because of the differences in the modes of operation.

2.1.3.1 Advantages

In off-road construction and agricultural equipment, high torque is a requirement for proper operation, and electric motors are capable of delivering instant high torque [32] [35] – making them superior over ICEs which have to reach a certain engine speed for maximum torque delivery. This capability of electric systems allows the elimination or reduction of the quintessential gear shifting required in ICE vehicle – enabling the operators to work with more ease and with higher efficiency [86]. Separate gears for reversing are also not required in many cases as electric motors can be made to change direction by controlling the flow of electricity. Electric drivetrains also employ far less moving parts as compared to traditional ICE systems [10], and thus reduce maintenance costs. Regenerative braking also reduces wear and thus replacement costs of mechanical brakes [66]. These in turn translate into lower overall operating cost, which gets further augmented by the decrease in fuel consumption – a major driving force that led the off-highway truck segment to adopt diesel electric systems [61]

[71]. Electric drivetrain increases the powertrain efficiency overall, be it hybrid or full electric; while also allowing decoupling of loads from the ICE in some vehicles, such as agricultural tractors [30]. This enhanced fuel efficiency is also setting the electrification trend in other equipment categories as well, such as loaders and tractors [30] [48]. ICEs tend to lose power at high altitude because of insufficient oxygen required to burn the fuel and generate power. Electric equipment will not suffer from this drawback, and this will facilitate easier operation, better efficiency, and also lower fuel cost. The reduced need of maintenance means less downtime, resulting in higher productivity [86]. Electric vehicles also allow more flexible design options [30], offering more space and better utilization of it. The major push behind vehicle electrification has always been environmental concerns such as lowering emissions and sound pollution [30] while improving air quality, but achieving such feats is also opening doors to new operational and economic benefits. One such possibility is the capability of operating the equipment closer to emission and noise sensitive areas and hours – which can increase productivity. Lower emissions also appear beneficial for underground operating scenarios, such as mines, where the air quality can be significantly improved if the equipment creates less air pollution [45]. These advantages, and their effects, are demonstrated in Table 2-8.

Table 2-8 Advantages of Equipment Electrification and Their Implications

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

2.1.3.2 Limitations and Solutions

The major criticisms against Evs include their long charging time and short range [10], which for both construction and agricultural equipment translate into shortened operating time and increased downtime. Also, as the off-road equipment have far superior and dynamic power requirements, sizing of the motors, and managing the weight of them as well as that of the ESS along with the control systems become major concerns while designing such vehicles [22] [32]. Proper placement of charging stations in wide operating areas, such as agricultural farms, can also appear challenging. However, solutions are becoming easier to implement as the EV technology matures. Because of the recent advancements in ESS, energy recovery, and charging systems, the range has been increasing significantly while charging duration has decreased. Moreover, though downtime for charging is a concern for operators, this can be compensated by the reduction in maintenance downtime. Designing off-road EV powertrains to meet the dynamic power needs has already been tackled in a number of studies – the most common approach being the use of gears to satisfy the varying power demand with smaller motor sizes [24].

2.1.4 Current Barriers and Solutions

The general perception of high price of EVs, and strong competition from conventional ICE-driven equipment are probable barriers for electrification in the off-road segment, but the current trend suggests a shift in this perception as some equipment types have already shifted towards partial electrification (e.g. excavators, off-highway trucks) and more equipment are being developed to run using electric systems. Beyond the shortcomings that are inherent to the early stages of EV adoption, which includes high cost and competition from established conventional vehicles [96], research and development in electrification of different types of off-road equipment is also needed.. However, the limited categories of off-road equipment adopting electrification demonstrate that these barriers are surmountable. The commercial use of electric drives in off-highway trucks demonstrates the viability of using electric powertrains in high-power applications, demonstrating that other high power applications can be electrified. To facilitate that, increased research and development aimed at electrifying major equipment categories, namely loaders and scrapers, are necessary. Along with industry interest, government efforts in the form of regulations, incentives, and grants can play a major role in increasing electrification in these sectors. Such actions may be needed to compensate for the higher cost of EVs. A nascent electric off-road equipment sector is likely to face difficulties with inadequate charging infrastructure as well, but if manufacturers invest in well-placed charging infrastructure while marketing their products, they may effectively promote adoption of EV off-road technology. Table 2-9 summarizes the barriers of off-road equipment electrification and their potential solutions.

The off-road vehicles subjected to this study are used in a wide variety of workplaces, each different than the other. In general, the use of these vehicles depends a lot on respective duty-cycles – which varies widely from each jobsite to the next. Because of this fact, it is not possible to make an individual optimal electrification recommendation that will be the most efficient for all the off-road equipment. Also, as the jobsites vary in condition and duty-cycles, equipment within the same category may benefit from different technologies depending on their intended use. This section thus lays out the general possibilities that can facilitate off-road equipment electrification by overcoming the current limitations, but it is possible that effective application of these techniques will vary in each use-case.

Table 2-9 Barriers of Off-Road Equipment Electrification and Potential Solutions

Barrier		Solution
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

Construction and agricultural equipment tend to have a significantly long service life, and it is not likely fleet operators will retire conventional equipment before its typical service lifespan. A plausible action in such scenarios can be retrofitting the existing vehicles with an electric powertrain, which can improve the vehicles while making use of their remaining service life, and continue serving the workforce until the new generation of purpose-built electric equipment arrive. Battery electrification of a Caterpillar 12M3 grader by Medatech is an example of successful retrofitting [97]. One solution to facilitate retrofitting can be the use of range extenders [10] to act as an on-board generator. Current tier 4 diesel engines have pretty low emission rates; if used as range extenders, they can operate within optimal regions, maximizing efficiency and minimizing emissions.

Operating electric equipment certainly calls for on-site charging facilities. An environment-friendly way to facilitate that would be to use renewable energy sources (RES) to power those chargers – which also has the potential to reduce costs. Redpath et al. demonstrated the charging of light agricultural vehicles through solar energy [98], and similar scaled up approaches can appear beneficial for heavy-duty agricultural vehicles as well. Use of wind power for such cases can also appear to be promising [99]. Agricultural farms can also generate electricity from biogas to run their EV fleet. Employing solar PV to charge EVs is a popular idea [100] [101] [102]. Bhatti et al. conducted a thorough study on this topic [103] where various such configurations were listed including PV-fed EV charging stations with connection to the grid, with intermediate ESS, and dedicated fuel-cell generators. Robalino et al. proposed using PV to charge EVs while generating hydrogen at the charging station for use by FCEVs [104]. Such charging stations, equipped with ESS, and a hydrogen generating mechanism, can serve BEVs, PHEVs, and FCEVs, while making use of all the generated electricity from the RES. Kam et al.'s proposed smart charging system with vehicle to grid (V2G) facility [105] can prove useful to realize energy-independent self-sustaining small agricultural farms. Second-life batteries (SLB) [106] can be employed in such charging stations as ESS to lower the cost. In the long term, this can become more efficient and cost-effective if used batteries from off-road equipment are repurposed in this way, extending the value of initial investments.

Proper placement of charging stations at jobsites with large areas is crucial, and is especially worth considering for agricultural applications where vehicles traverse large areas. Use of mobile power packs – which can power vehicles from energy stored in ESS – can prove useful in such cases. This technology is currently available for passenger vehicles [107], with more expected to enter consumer market soon [108]. Scaled up versions of such devices can cater to heavy-duty equipment in the field. Investigations in mobile ICE generators as well as fuel cells can also be conducted to determine their feasibility for such usage. Employing the FCEV architecture for off-road equipment can prove beneficial as well, as that will provide very short refueling times similar to conventional vehicles – resulting in shortened downtimes. To facilitate that, having on-site hydrogen supply will suffice. Some major reservations against fuel cells have been the high price, and safety concerns regarding the on-board hydrogen tanks [10]. However, as the technology is getting more mature, and more commercial FCEVs are emerging [109] [110], successful implementation of this technology in off-road equipment can be expected. Figure 2-7 presents the major proposals made in this section.

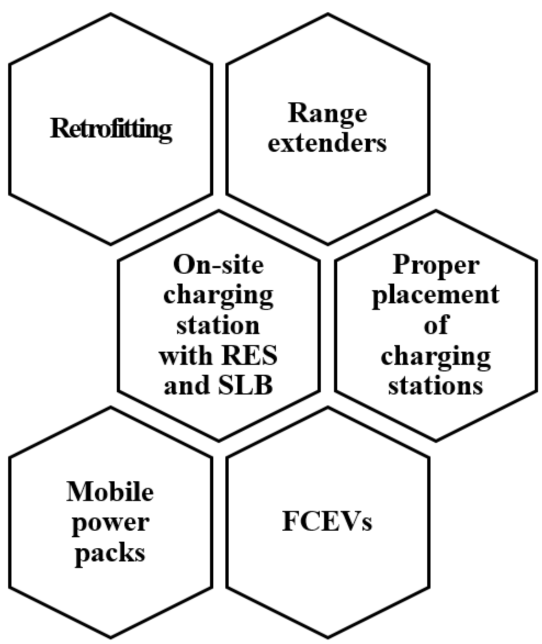


Figure 2-7 Potential technologies for facilitating off-road equipment electrification.

2.1.5 Summary of Findings

Though some work has been done in the off-road equipment sector already, those have been narrowly focused – only covering certain niches of the sector. The following points summarize the major findings of this section to indicate the current state of this field, and the areas needing attention.

- Excavators and off-highway trucks attracted higher amount of interest in electrification as compared to other construction equipment reviewed; enhanced efficiency and cost reduction have driven the commercialization of diesel electric off-highway trucks.

- Tractors have been studied in a number of studies among the reviewed literature on agricultural equipment.

- Tractor-loader-backhoes, loaders, and scrapers in the construction equipment category, and tractors from the agricultural equipment sector demand increased research on electrification potential due to their high population and impact on emissions.

- With current technology, the plug-in hybrid system can appear useful for immediate implementation.

- Along with batteries, supercapacitors attracted significant attention as the equipment tend to generate and require large power. For the same reason, intermediate hydraulic energy storage, and hybrid energy storage employing batteries and supercapacitors can prove beneficial for heavy-duty equipment usage.

- Along with the braking system, there are opportunities for energy regeneration from the power tools employed by off-road equipment; prominent examples being the boom and swing on excavators.

- Electrification of off-road equipment offer significant benefits in the terms of increased efficiency, and lower operating cost.

- The general shortcomings of EVs, including short range and long charging time, translate into concerns about decreased downtime for off-road equipment. The higher cost further challenges their survival in a competitive market. However, increased research and development can aid in overcoming the current issues: higher cost, limited energy capacity, long charging time, and charging infrastructure unavailability.

- An immediate solution to facilitating successful electrification of off-road equipment is retrofitting along with the use of range extenders, on-site power generation, and mobile power-packs.

Electrification of off-road construction and agricultural equipment is expected to improve operating efficiency while reducing operating cost and emissions. To provide a clear picture of the current state of such types of vehicles, notable studies conducted in the past have been reviewed in this section. An overview of the equipment architectures employed in different studies has been generated by this study to point out the current trends. The advantages, and limitations towards off-road equipment electrification have been discussed along with possible solutions. Proposals have been made to facilitate electrification attempts in this sector, while underscoring the major findings and future research directions.

2.2 Analysis of Available Electrified Off-Road Vehicles

2.2.1 Introduction and Methodology

The first step in the completion of this section was to conduct a market analysis of the market leaders in construction and agriculture for the United States. It is impactful to see movement toward electrified vehicles by any manufacturer, but having the larger players contributing would indicate that there is a stronger pull toward electrified technology. The larger players set the tone of the market so differentiating major and minor manufacturers was a key component of this analysis. To do this, market share research was completed and cross referenced to ensure accuracy. The charts below show the construction market share of the US from 2011 and a global construction market share from 2015. All companies from the 2011 chart that had a US market share above 5% were considered Major Manufacturers and the rest were considered Minor Manufacturers.

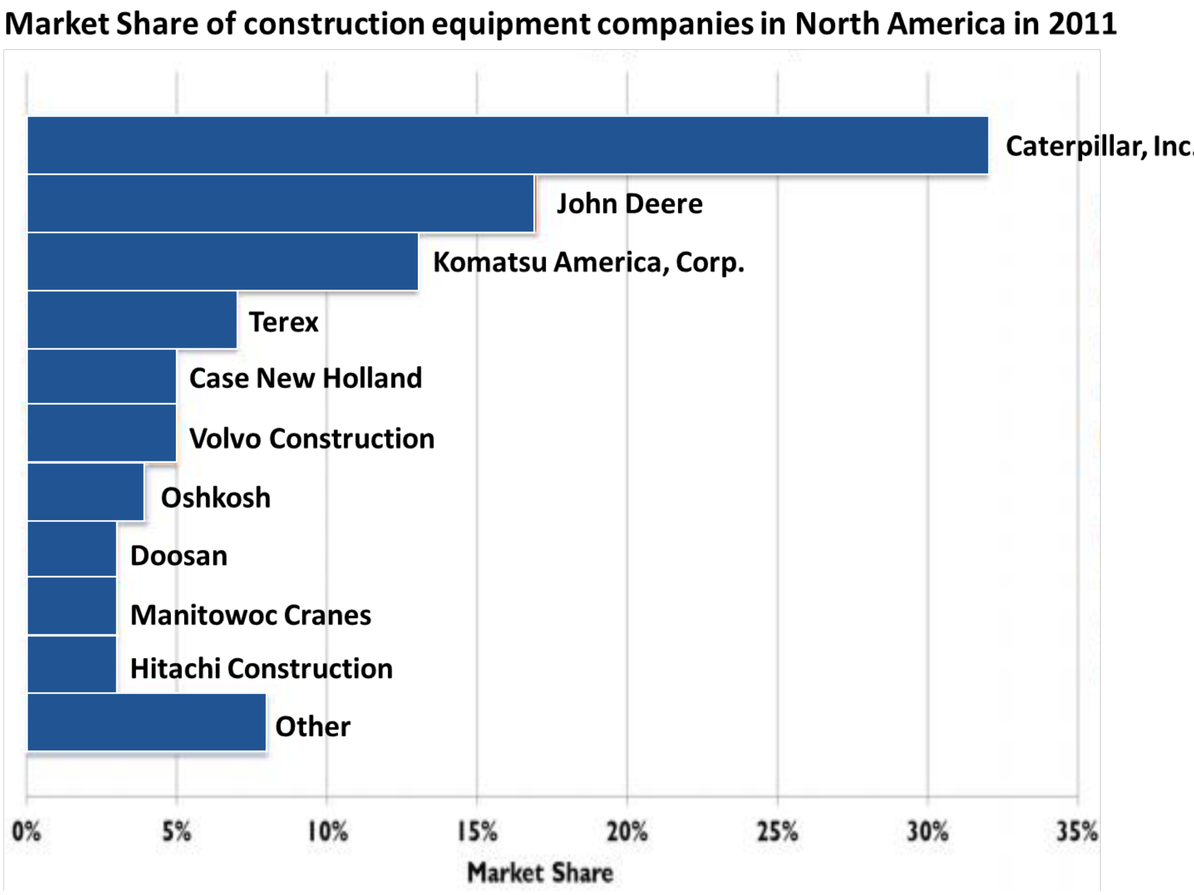


Figure 2-8 American Construction Market Share, 2011 [111]

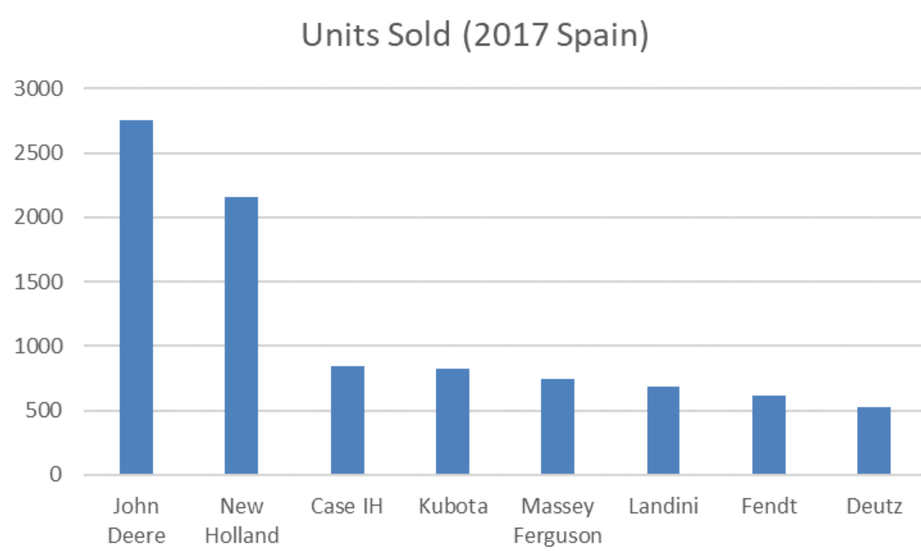


Figure 2-9 Agriculture Equipment Units Sold 2017 (Spain) [112]

Table 2-10. Global Construction Market Shares, 2015 [113]

Rank	Company	Country	Revenue ($ million)
1	Caterpillar	US	28,283
2	Komatsu	Japan	16,877
3	Hitachi Construction Machinery	Japan	7,790
4	Volvo Construction Equipment	Sweden	7,785
5	Terex	US	7,309
6	Liebherr	Germany	7,129
7	John Deere	US	6,581
8	XCMG	China	6,151
9	Sany	China	5,424
10	Doosan Infracore	Korea	5,414
11	Zoomlion	China	4,376
12	JCB	UK	4,117
13	Kobelco Construction Machinery	Japan	3,689
14	Metso	Finland	3,550
15	Oshkosh Access Equipment (JLG)	US	3,507
16	CNH Industrial	Italy	3,346
17	Hyundai Heavy Industries	Korea	2,711
18	Wirtgen Group	Germany	2,666
19	Manitowoc Crane Group	US	2,305
20	Atlas Copco Construction Technique	Sweden	2,171

Source: Access International May-June 2013 p. 14.[22]

2.2.2 Currently Available Electrified Vehicles

After this distinction was made, research was conducted on the currently available and announced but unavailable electrified offerings of major and then minor manufacturers. The research was recorded in the form of a word document that can be found in Appendix B. Extended discussions on torque and power outputs of motors employed in current equipment, and a list of available off-the-shelf motors are presented in Appendix C. The list of vehicles that are currently available can be found in Table 2-11.

Table 2-11. Available Electrified Off-Road Vehicle Spreadsheet (Some data removed for document fit)

Type of Vehicle	Company	Model Name	Electrification Tech	Horsepower (HP)	Hybrid or ZEV	Available?	Major or Minor Company	Price	Lifetime Warranty	Fuel improvement (ZEV = NA)	Size	Industry
Tractor	AGCO	Fendt e100 Vario	Electric	67	ZEV	Limited Availability	Minor			NA	Compact	Agriculture
Dozer	CAT	D6E	Electric Drive Train	235	Hybrid	Available	Major	350000	7 Years	35%	Heavy	Construction
Excavator	CAT	336E	Swing Regeneration	308	Hybrid	Available	Major		5 Years	37%	Heavy	Construction
Dozer	CAT	988K	Electric Drive Train	492	Hybrid	Available	Major		3 Years	25%	Heavy	Construction
Mini Excacavator	CAT	300.9D	Plug in Electric	18	ZEV/Diesel	Available	Major	20000			Compact	Construction
Loader	Deere	944K	Hybrid Drive	536	Hybrid	Available	Major	700000		11%	Heavy	Construction
Excavator	Komatsu	HB215LC	Swing Regeneration	185	Hybrid	Available	Major	150000	5 Years	20%	Heavy	Construction
Forklift	Komatsu	AE 50	Electric	NA	ZEV	Available	Major	15000	5 Years	NA	Compact	Construction
Dozer	Wacker Neuson	WL20e	Electric	21	ZEV	Available	Minor	50000	2000 hours	NA	Compact	Construction
Mini Excavator	Wacker Neuson	EZ17e	Electric	NA	ZEV	Available	Minor	22.5% more than diesel		NA	Compact	Construction
Excavator	JCB	19C	Electric	27	ZEV	Available	Minor			NA	Compact	Construction
Mining Truck	Komatsu	830 R	Hybrid Drive	2500	Hybrid	Available	Major				Heavy	Mining
Mining Truck	Komatsu	930 E-4	Hybrid Drive	2700	Hybrid	Available	Major				Heavy	Mining
Cart	Deere	TE 4x2	Electric	NA	Electric	Available	Major	11659		NA	Compact	Miscellaneous
Electrification Kit	Deere	Electrification Kit	Hybrid Drive	NA	Hybrid	Available	Major			25% (Varies)	NA	Miscellaneous
Electrification Kit	Terex	HyPower	Hybrid Drive	NA	Hybrid	Available	Major		5 Years	10%	NA	Miscellaneous

Included in the sheet are several standardized data types that that can be used to separate the vehicles into different groups. With few exceptions the currently available vehicles can be broken down into several different categories: Swing Hybrid Excavators, Full Electric Mini Excavators, and Hybrid Versions of Diesel Vehicles. An example of each category will be given below.

Caterpillar D6E

The CAT D6E is a hybrid version of the C9.3B. The hybrid version yields several improvements over the traditional diesel vehicle: A fuel efficiency improvement of up to 35%, instantaneous acceleration, reduced maintenance costs of up to 12% and a claimed 50% more efficiency due to added technology.

Komatsu HB215LC Excavator

The Komatsu HB215LC Excavator is a swing hybrid electric excavator that uses breaking swinging momentum to charge batteries for later use. The 215LC Excavator boasts a less noisy more comfortable operating experience and a fuel reduction of 20%.

Wacker Neuson EZ17e

The Wacker Neuson EZ17e is a mini sized full electric excavator. The price is estimated at between 20-25% higher than its diesel equivalent. But for that added cost the purchaser gets a host of benefits: cheaper fueling, no noise and lower maintenance costs. Finally, this vehicle can be used in building shells with bad air circulation, where the diesel equivalent would create unsafe air conditions.

Takeaways

While almost all the major market players have electrified products on the market, the market is still lacking a breadth of choices. The current slate of vehicles consists mostly of hybrids and mini-sized full electric vehicles. Further options exist almost entirely in the pilot and demo phases, but manufacturers have been advertising demos of electrified vehicles since as early as the mid-2000s, and most of them never end up going to market. The perceived reason for this lack of movement is the lack of market feasibility of the new vehicle designs. While the technology exists to construct these vehicles and make them, the business case isn't strong enough. The largest barriers to market feasibility for these vehicles are duty cycle compatibility and incremental cost. But there are a variety of issues to market feasibility that have impeded the growth of battery electric vehicles (BEV) that will be discussed in the industry feedback section of the report.

Despite the lack of larger BEV vehicles, there is a fledgling market for electrified off-road vehicles. There are several factors that help this slate of vehicles become more market feasible. There are several constants about all electrified vehicles that are appealing compared to the diesel alternatives. All electric vehicles are cheaper to fuel than their diesel alternatives, due to energy capture and the use of electricity over more expensive diesel fuel. Further electrified vehicles increase ease of use and tend to have a higher user approval rate than diesel. Lastly there are several niche markets that electrified vehicles can be utilized in. A prime example is the use of fully electric mini excavators in building shells. The lack of diesel fumes keeps the air breathable for workers despite bad ventilation. How important each of these factors are and how they compare in importance to the short comings of the vehicles will be assessed in greater detail in upcoming sections.

2.2.3 Electrified Vehicles Coming to Market

This section was approached the same way as the previous section on Currently Available Electrified Vehicles. Data about the vehicles was recorded into a spreadsheet based on important factors. However, vehicles that were announced more than eight years ago (as of 2019), without updates, were not included as they can safely be assumed to be a dead design. Table 2-12 shows the list of electrified vehicles that fit these criteria that have not been released yet.

Unlike the currently on market section, the vehicles in this section vary greatly. There's a great deal more innovation in terms of design, and a bevy of zero emission options. It is also worth noting that there are BEV agriculture vehicles as opposed to the one hybrid tractor that is currently available. Below are examples that highlight the upcoming direction of the electrified off-road vehicle industry.

Volvo L25

The Volvo L 25 is a fully electric compact Dozer. It boasts an 8-hour runtime, which can charge 80% of its battery in 2 hours. Like all zero emission vehicles it creates no pollution and little to no noise. The L25 is scheduled to be available in 2020. Beyond the L25, Volvo is currently planning to release a full line of electric light and mid-sized vehicles throughout the 20s.

Hidromek H4

The Hidromek H4 is a fully electric heavy-duty excavator that was previewed at Bauma 2019. The vehicle has a runtime of 8 hours on one charge (the time to full charge was not advertised) and is one of the few BEV full sized vehicles beyond the prototype stage. Although Hidromek is a smaller player in the US market, they are a much larger player in the European market.

CAT/Pon 323F Z-Line

The CAT/Pon 323F Z-Line is a pilot project full sized CAT 323F diesel excavator, that was converted to a battery electric model. The vehicle was electrified by the Norwegian company Pon and is currently being used in several construction sites in Norway. The vehicle will operate for 5-7 hours on a full charge. And while the vehicles are currently in use in a pilot project capacity, the vehicle has no timeline for market release.

John Deere Gridcon Electric Tractor

The John Deere Gridcon Electric Tractor is a fully electric autonomous and battery-free tractor. The vehicle has no onboard power source or cockpit. The vehicle is given routes by computer mapping software and is tracked by GPS. The power source comes from a 1 km long power cable that always stays plugged in. The tractor has a coiling and uncoiling mechanism that allows the tractor to release and recover the chord without wearing out the chord. This vehicle is still in the prototype phase and there is no date set for its release.

Table 2-12. Announced Electrified Vehicles (Some data removed for document fit)

Type of Vehicle	Company	Model Name	Electrification Tech	Horsepower (HP)	Hybrid or ZEV	Available?	Major or Minor Company	Fuel improvement (ZEV = NA)	Size	Niche Operation	Industry
Tractor	John Deere	SESAM	Electric	268	ZEV	Prototype	Major	NA	Heavy	NA	Agriculture
Tractor	John Deere	Gridcon Electric Tractor	Giant Power Cable	268	ZEV	Prototype	Major	NA	Heavy	Autonomous	Agriculture
Tractor	Carraro	Ibrido	ZEV/Diesel	27	Hybrid	No Release Date	Minor		Compact	Small for Vineyard Use	Agriculture
Tractor (Altered Design)	Multi-Tool	Multi-Tool Trac	Plug in Hybrid	60	Hybrid	Release Date	Minor		Compact	Adjustable Track Length	Agriculture
Excavator	Komatsu	Electric Mini Excavator	Electric	24	ZEV	No Release Date	Major	NA	Light	Safe Breathing in Building Shells	Construction
Excavator	Volvo	CE 300E	Swing Regeneration	213	Hybrid	No Release Date	Major	14%	Heavy	NA	Construction
Dozer	Volvo	L25	Electric	NA	ZEV	Release Date	Major	NA	Compact	Usable in ZE Zones	Construction
Excavator	Volvo	EC25	Electric	22.9	ZEV	Release Date	Major	NA	Compact	Usable in ZE Zones	Construction
Dozer	Volvo	LX2	Electric	NA	ZEV	Prototype	Major	NA	Heavy	NA	Construction
Mini Excacavator	Volvo	EX2	Electric	NA	ZEV	Prototype	Major	NA	Heavy	NA	Construction
Hauller	Volvo	HX2	Electric	NA	ZEV	No Release Date	Major	NA	Compact	Autonomous	Construction
Excavator	Wacker Neuson	EZ26e	Electric (Plug In Mode)	NA	ZEV	Prototype	Minor	NA	Compact	NA	Construction
Lifter	Manitou/ Deutz	TCD (w/BEV Engine)	Electric	80	ZEV	Release Date	Minor	NA	Compact	Usable in ZE Zones	Construction
Mini Excacavator	Takeuchi	e240	Electric	63	ZEV	No Release Date	Minor	NA	Compact	Safe Breathing in Building Shells	Construction
Excavator	Liebherr	R9200 E	Electric Drive Train	1139	Hybrid	No Release Date	Minor		Heavy	NA	Construction
Wheel Excavator Loader	Mecalac	E12	Electric	100	ZEV	No Release Date	Minor	NA	Compact	Safe Breathing in Building Shells	Construction
Excavator	CAT/Pon	323F Z-line	Electric (Conversion)	164	ZEV	Prototype	Major	NA	Heavy	NA	Construction
Excavator	Hidromek	H4	Electric	NA	ZEV	No Release Date	Minor	NA	Heavy	NA	Construction
Mining Truck	Liebherr	T236	Electric Drive Train	1200	Hybrid	No Release Date	Minor		Heavy	Safe Breathing Upderground	Mining
Wheel Loader (Underground)	CAT	R1300G	Battery Electric	165	ZEV	Prototype	Major	NA	Heavy	Safe Breathing Upderground	Mining

Takeaways

A review of the market will show that new innovative designs are more prevalent than in the already market ready sector, however 16 of the 26 vehicles examined have no release date, a fact that could be telling of several things. While the technology is there, the vehicle doesn't have the specifications to succeed in a competitive market. Or that the designs are still improving at a rapid enough rate that it is not worth it to spend the resources to bring the prototype to market. Regardless nearly half of the vehicles examined here aren't coming to market any time soon.

While there is a good deal of heavy-duty full electric vehicles being previewed in this section, most of these heavy-duty vehicles are still prototypes, meaning they will not be market ready anytime soon. There are several reasons for this lack of market velocity for the slate of heavy-duty vehicles than the slate of medium and light-duty vehicles. Batteries are often the most expensive part of a new electric vehicle. Heavy duty vehicles often require more battery storage than their lighter counterparts leading to higher incremental costs over comparable diesel vehicles. And while there will always be a higher initial cost of non-electrified vehicles, the incremental cost is likely high enough to be a nonstarter for most heavy-duty vehicles. However, there are a bevy of factors to consider when assessing the market viability of these vehicles.

Currently available and upcoming off-road mining & construction as well as agricultural equipment are listed in Appendix B, with all available and upcoming models from all manufacturers, presenting photos and more detailed descriptions.

2.2.4 Results from Select Demonstrations of Hybrid Construction Equipment

In recent years CALSTART administered two separate construction equipment demonstration projects for the California Energy Commission. The first involved a hybrid-electric mid-sized wheel loader with Volvo Construction Equipment. The Second was a two-phase demonstration of a 36-ton hydraulic-hybrid excavator with Caterpillar. Project summaries and demonstration results are shown below:

Volvo Hybrid-Electric Wheel Loader

The Volvo CE hybrid electric wheel loader project was planned and delivered as a two-phase demonstration program. The first phase took place in Redwood Landfill and Recycling Center in Novato, CA, and the second phase at Moreno Valley Transfer Station in Moreno Valley, CA. Both the hybrid electric wheel loader (LX1) and the reference machine (L150H) were operated by Waste Management's experienced operators who were trained and supported by Volvo CE engineers.

Prior to delivery of the hybrid electric wheel loader (LX1) from Eskilstuna, Sweden in November 2016, the conventional diesel-powered wheel loader (L150H) was transported first to Moreno Valley Transfer Station in May, 2016 and to Redwood Landfill and Recycling Center in July, 2016. The intention was to perform data logging which could be used to develop a repeatable cycle which would reflect average work at the site. Such cycle would ensure that the fuel consumption for both hybrid and reference machine is measured while the machines perform exactly the same work. This is essential to be able to measure fuel efficiency in a good way. Unfortunately, at both sites, we were unable to use a test set up with a repeatable cycle since it was considered to disturb site operation too much. Instead, it was decided that the fuel efficiency measurements would be performed in real-life work applications.

Phase 1 demonstration began at the Redwood Landfill and Recycling Center in November 2016 and ran over a period of 2.5 months. The two machines accumulated a total of 191 hours of representative data used for the fuel efficiency results. Both machines performed typical functions which included pushing green waste material left by trucks into piles, pushing and lifting material to a pile near a grinder, pushing and lifting ground material from the grinder into piles and loading and carrying ground material from piles to other piles for covered aerated static pile composting.

On average, the hybrid electric wheel loader was 55% more fuel efficient compared to the conventional diesel-powered reference machine (L150H). The hybrid electric wheel loader produced 35% less GHG emissions, a reduction corresponding to roughly 45.2 lb/h.

The in-service emission test at Redwood Landfill and Recycling Center showed a 38% reduction in fuel consumption and greenhouse gas emissions, a slightly better result compared to the longer fuel efficiency test. Both machines performed well in NO_x, PM and THC emissions relative to their respective engine emission standard. As expected, the LX1 with its Tier 4 Interim engine had higher emissions in absolute numbers than the L150H, which has a Tier 4 Final engine. The hybrid electric wheel loader had some downtime due to prototype component failure. Operator feedback was generally positive. The operator liked how quiet the LX1 is, the smooth direction changes, and the powerful hydraulics.

Per CEC request to demonstrate renewable diesel fuel, Golden Gate Petroleum set up the fuel tanker on-site, and the renewable diesel fuel was used in both the hybrid electric wheel loader and the conventional diesel-powered wheel loader for the entirety of the demonstration period. The renewable diesel fuel was easily incorporated and did not affect performance of either machine.

Phase 2 demonstration began at the Moreno Valley Transfer Station in March 2017 and ran over a period of 2 months. The two machines accumulated a total of 184 hours of representative data used for the fuel economy results. Both machines performed typical functions which included pushing material left by garbage trucks into piles and pushing material into holes in the floor leading down to tunnels where trucks stop to be loaded.

On average, the hybrid electric wheel loader was 50% more fuel efficient compared to the reference machine. For a 95% confidence interval, the fuel efficiency improvement is between 38% and 60%. The hybrid electric wheel loader had 33% lower average fuel consumption than the reference machine and therefore produced 33% less GHG emissions, a reduction corresponding to roughly 47.0 lb/h.
The hybrid electric wheel loader had some battery issues at Moreno Valley Transfer Station with some downtime. Operator feedback was mostly positive. Good

acceleration, low in-cab noise level, smooth direction changes and visibility were appreciated features of the LX1.

Productivity, usually measured in ton/h, was not possible to measure properly at either facility. Such a productivity measure was not relevant in this type of application since the material was moved in different ways (pushed, stacked in piles, carried, packed down) and the density of the material as well as the distance it moved varied significantly from day to day. Operator feedback from both facilities indicated that the jobsite productivity was somewhat worse with the hybrid electric wheel loader.

Fuel efficiency test results come from charge sustaining operation of the LX1 which means that the batteries have the same state of charge at the start and end of each day. Calculating what impact plug-in charging would have had on fuel efficiency shows that it would have reduced fuel consumption by 43% at Redwood Landfill and Recycling Center and by 40% at Moreno Valley Transfer Station.

Caterpillar Large Hydraulic-Hybrid Excavator Demonstration

The Caterpillar off-road large-size hybrid excavator project was planned and delivered as a two-phase demonstration. Phase 1 was the demonstration of an excavator with kinetic (swing) energy recovery hybrid technology and Phase 2 was the demonstration of an excavator with both, kinetic (swing) and potential (boom) energy recovery hybrid technology. The Phase 1 and Phase 2 excavators with hybrid technologies were evaluated by performance testing and field follow studies conducted at customer’s sites in California.

Phase 1 excavators with swing hybrid technology were located at customer’s sites in San Francisco and Sacramento areas over the period of 7.5 months. Two 336E H machines accumulated a total of 1,155 hours. The machines were performing typical earthwork functions such as mass excavation, trenching, truck loading, slope shaping, leveling and general cleanup. In Phase 1 performance testing of same level 90° truck loading was conducted comparing the 336E H to the standard 336E hydraulic excavator. As a result, collected data from 23 runs, 138 trucks and 3 different operators indicated that there were no statistically significant differences in productivity between the hybrid and standard machines. This is consistent with the design intent as the hybrid objective was to maintain productivity while lowering fuel consumption.

On average the hybrid excavator consumed 21% less fuel (L/hr) [with ±3% confidence interval] and therefore produced 21% less GHG emissions (kg/hr) compared to the standard machine. The hybrid excavator was 30% more fuel efficient (ton of material moved per liter of fuel burned) [with ±3.5% confidence interval] and therefore produced 30% less GHG emissions (ton of material moved per kg of greenhouse gases produced) compared to the standard machine. The machines ran well with no reliability issues noted, while operator feedback was very positive. Based on positive field test and performance results, Caterpillar chose to accelerate commercialization of the 336E H hybrid excavator. It was officially launched in April of 2013 and is in full production and available in North America, Europe, Japan, Australia, and New Zealand.

The Phase 2 excavator with integrated swing and boom energy recovery hybrid technology accumulated approximately 147 total hours at two different customer sites in the San Diego area over a 79-day period. The machine performed typical earthwork functions such as mass excavation, trenching, truck loading, compacting, material mixing, leveling, and general cleanup. The machine ran well with no significant reliability or durability issues noted.

Operator feedback was very positive with comments that the hybrid system was transparent to the operator. A scientifically-based comparative performance test was completed at the second customer site during the Phase 2 field follow. Same level 90° truck loading and bench 90° truck loading tests were conducted comparing the hybrid to a non-hybrid, base-line (Tier 4 Final) machine. Utilizing data from 64 runs, 128 trucks, 685 cycles (bucket fills) and 2 different operators, there was no significant statistical difference in productivity between the hybrid and the standard machine. This was accomplished by design as the hybrid objective is to maintain productivity while lowering fuel consumption. Compared to the standard machine, the hybrid excavator consumed on average 24% less fuel (L/hr) and therefore produced 24% less GHG emissions (kg/hr). The hybrid excavator was on average 34% more fuel efficient (ton of material moved per liter of fuel burned). Therefore, the hybrid produced 34% less GHG emissions (tons of material moved per kg of greenhouse gases produced) than the baseline. Based on the added fuel savings of the Phase 2 hybrid excavator as well as the positive customer feedback from the field follow, the commercial viability of the Phase 2 demonstration machines is also expected to be positive.

It is important to note that the reported fuel efficiency improvements are relative differences from back-to-back, "controlled" tests between a hybrid and non-hybrid machine for a specific set of conditions (machine configuration, job site, operator, soil type, application, etc.). If those conditions substantially change, the comparison can become invalid. For that reason, Phase 2 fuel savings should NOT be compared to the Phase 1 fuel savings. The results may imply that the Phase 2 technologies are only slightly more efficient than the Phase 1 technologies, but this is not the case. The Phase 2 testing was conducted on a different machine with different operators and different site applications making a comparison to Phase 1 results not practical.

2.3 Analysis of Vehicle Marketability Factors

As previously alluded to, there are factors that limit the market viability of the vehicles in question. A large portion of the vehicles designed for demos are not brought to market because of these issues. To better understand the issues, interviews were conducted with leaders in the industry. This information gathering process was broken down into two different data gathering expeditions. First free form conversations about the state of the industry were conducted in order to paint a picture of the factors that contribute to the success or failure of vehicles in the industry. Second in an effort to quantify the importance of each factor, surveys were created and sent to the individuals who participated in interview. Each interview was conducted by ranking a list of factors previously discussed in the interviews on importance of a scale from 1-10. The results were then aggregated in order to gauge the importance of each factor. The identities of the manufacturers were kept anonymous as per request.

The interview revealed that the electric/hybrid off-road equipment market did not develop to the extent as expected in 2010, but was gaining momentum in recent years. Battery technology and user acceptance were two major factors that required improvement to galvanize this industry. Government regulations could play a major role in developing the market; however; those should be carefully constructed so that incapable equipment were not forced into usage, tarnishing the reputation and perception of electric equipment. Research on driving down component and battery costs were also mentioned to be necessary. For customers, electric equipment appeared attractive because of increased productivity and enhanced company branding. The productivity increment comes from various factors such as low noise, reduced fatigue, instant acceleration, reduced repair downtime, etc. Electrification also grants more control on the equipment, and thus reduces error. The manufacturers confirmed that technology transferability is an essential part of their business model, which would help in volume production of electric equipment, driving down the cost. However, the concern of lower part quality which might come from technology transferability was also sounded. Additionally, it was stated that electrification might boost equipment sales as electric equipment would reduce cost of a project, while improving its project delivery and efficiency. Moreover, electrification would also aid in automation. These factors were expected to engender the electric equipment uptake. Detailed methodology and results from the interview are further elaborated in the first two subsections of Appendix A.

After performing the initial research on the market of presently and soon to be available electrified vehicles in the construction and agriculture sections, we had discussions with various manufacturers to get their unique perspectives on the emerging market for electrified vehicles. CALSTART formulated a list of relevant questions on the topic to illuminate the strengths, weaknesses and areas that requite improvement of the electrified off-road market.

We found that the largest barriers to electrified off-road vehicles in the current market are: incremental cost, and lack of user acceptance. The lack of user acceptance seems to stem mostly from the fact that the technology hasn’t been operated by most users. When customers are given the chance to operate electrified vehicles there are a myriad of factors that lead to customers enjoying the electrified products more than their diesel counterparts.

While the operational costs of many of electrified vehicles are significantly lower than their diesel siblings, the incremental cost is significantly higher, to the point that incremental cost becomes a major issue for consumers. The added benefits of electrified vehicles must not only be significant, but also guaranteed before a majority of customers will spend 50% more on a new technology.

However, there are several drivers that can help bridge this gap. Regulations may be an effective way to move the market toward more hybrid and electric technologies. However, regulations can cause damage to the industry if they are too heavy-handed. Incentive programs like Carl Moyer are effective in lowering the incremental cost and improving the total cost of ownership (TCO) of electrified vehicles. The effectiveness of programs like Moyer can be seen in the bump in sales manufacturers see when these types of incentive programs still have money. Finally, progressive large market cities like Paris or Los Angeles are moving the market by starting to require stricter noise and emissions standards for construction in the city. Large markets requiring hybrid and electric vehicles will likely be a significant driver of the hybrid and electric vehicle markets. When consumers become more familiar with the benefits of electrified tech, market shares of this technology will improve.

After receiving a myriad of useful information from the industry interviews a questionnaire process was crafted in order to uncover the most important points. Creating a ranking system helps not only synthesize the information gathered but helps decipher which points are the most important. The questionnaire took the most popular answers for each question and asked for a score of 1-10 for how true or important each answer was, 0 being not true or important and 10 being very true or most important. Results obtained through this process is detailed in the last two subsections of Appendix A.

The consistent theme of the answers to these questions is that manufacturers believe that an improvement in price (through several different methods), duty cycle or an increase in diesel vehicle regulations are the factors that will quickly and strongly improve the market share of electrified vehicles in the off-road space.

2.4 Concluding Remarks

The activities undertaken in support of this task have revealed that the industry—manufacturers and users—fully understands and appreciates the benefits of electrification and hybridization technologies. In the past 6 years all the major equipment manufacturers have made significant investments in advanced powertrains. The segment for larger excavators and wheel loaders now includes many options for hybrid configurations. As well, the market for small-capacity excavators now includes many all-electric options. This is illustrated by Volvo's announcement that all the mini-excavators they offer from 2020 forward with be battery-electric.

It is important to understand that movement toward greater hybridization and electrification in these segments will be guided by the end-user's need to perform work functions as opposed to their motive needs and that fuel saving and cost-saving technologies will be accepted only if they can increase productivity at the same time. Efficiency in these segments is measured in amount of material moved per unit of fuel or alternatively, the amount of fuel used per hour of operation. If a hybrid or electric powertrain can handle more material in a certain time period or with an equivalent amount of fuel, only then will the operator assess the economic payback. Productivity will always be the prime factor.

The industry interviews also revealed that adoption will be accelerated through policies such as zero-emission zones. This is already evident in several European cities. Manufacturers and suppliers also agree that a key enabler of increased market penetration will be lower battery costs. These segments share that issue with the on-road segments. The benefits of CARB incentives to quicken the adoption of zero emission commercial vehicles and material handling equipment will be shared by the construction and agriculture segments since there is high commonality of major components and systems, especially batteries.

There are two substantial barriers that must be overcome for full commercialization to occur in these segments. The first is a significant incremental cost for full electrification. The incremental cost components consist primarily of high costs associated with energy storage, battery management systems, infrastructure interfaces, and advanced controls. Energy storage—in the form of advanced batteries— remains the largest and most significant component cost. Costs of advanced lithium-based batteries have fallen dramatically in the past five years and are forecast to continue that fall. It is common to see costs for lithium-ion batteries at just over $200 per kilowatt-hour. This is a drop of nearly 75% since 2010. Forecasts from the DOE and others show that the cost in 2025 will be less than $100 per kilowatt-hour. At the same time, energy density for these advanced batteries is improving at a rate of 5-7% per year. These are strong signals to industry about the future of batteries. However, these trends will only be maintained if production volumes—led by the on-road and off-road transportation sectors—continue to grow by recent rates. The second barrier is user acceptance of electric equipment, and users' confidence in the electric equipment's ability to fulfill the work demands. Even though there are positive feedback from many users, skepticism remains regarding the energy capacity of electric equipment and charging infrastructure requirements.

There is significant reluctance among major industry players—most notably manufacturers—to provide viewpoints on future trends due to the highly proprietary and competitive nature of their business. However, those who did offer opinions agreed that government guidance and incentives were needed and that the on-road segments can play a key role in advancing key component technologies such as batteries. It should be noted that these viewpoints were obtained from interviewing a small number of interviewees from two equipment manufacturers. Larger interviews or surveys of both the industry and fleets are recommended in order to get additional feedback from a more diverse and representative group of stakeholders.

3 Analysis of Real-World Energy Consumption of Selected Off-Road Equipment

3.1 Data Collection and Processing

The equipment duty-cycle and activity analysis in this project utilized real-world data from two sources: 1) activity data collected from construction equipment by researchers at the University of California at Riverside (UCR) under CARB Contract 17RD013 titled "Activity Data of Off-road Engines in Construction", and 2) activity data collected from agricultural equipment by the project team. The activity data analysed in this project consists of data from 20 units of construction equipment in seven different types and two units of agricultural tractors and cover a horsepower range of 85 to 560 hp. These equipment types are among the top contributors to the nitrogen oxides (NOx) and particulate matter (PM) emission inventories for the off-road construction and agricultural categories. Table 3-1 lists the informaton about each equipment.

Table 3-1. Equipment included in the duty cycle and activity analysis

Equipment Category	Equipment Type	Equipment ID	Manufacturer	Model Year	Model	Weight (lbs)
Construction	Crawler Tractor	N18024	Caterpillar	2017	D9T	129191
		N18025	Caterpillar	2017	D9T	129191
	Excavator	N18029	Caterpillar	2019	325FLCR	62560
	Grader	N18019	Caterpillar	2014	140M3	43950
		N18022	Caterpillar	2016	140M3	56337
		N18023	Caterpillar	2016	140M3	56337
		N18020	John Deere	2012	772GP	44570
		N18014	John Deere	2013	672G	41520
	Off-Highway Tractor	N18021	Caterpillar	2015	836K	143300
		N18027	Caterpillar	2018	836K	136687
	Rubber Tired Loader	N18016	Caterpillar	2013	938K	35290
		N18018	Caterpillar	2016	938M	44533
		N18030	Caterpillar	2016	966M	69445
		N18015	John Deere	2018	644K	42980
		N18026	Volvo	2018	L120H	47620
	Scraper	N18028	Caterpillar	2018	627K	37664
		N18043	N/A	N/A	N/A	N/A
	Tractor/Loaders/Backhoe	N18012	John Deere	2008	410J	15000
		N18013	John Deere	2008	710J	23000
		N18011	John Deere	2011	710J	23000
Agricultural	Agricultural Tractor	JD_413	John Deere	2016	5085E	7937
		JD_414	John Deere	2018	5100MH	8900

3.1.1 Construction Equipment

Under Contract 17RD013, the test equipment was recruited from a variety of agencies and construction companies. These equipment may not completely represent all the construction equipment in California, but they cover the commonly used equipment types in the industry. Selected pictures of the construction equipment are presented in Figure 3-1.

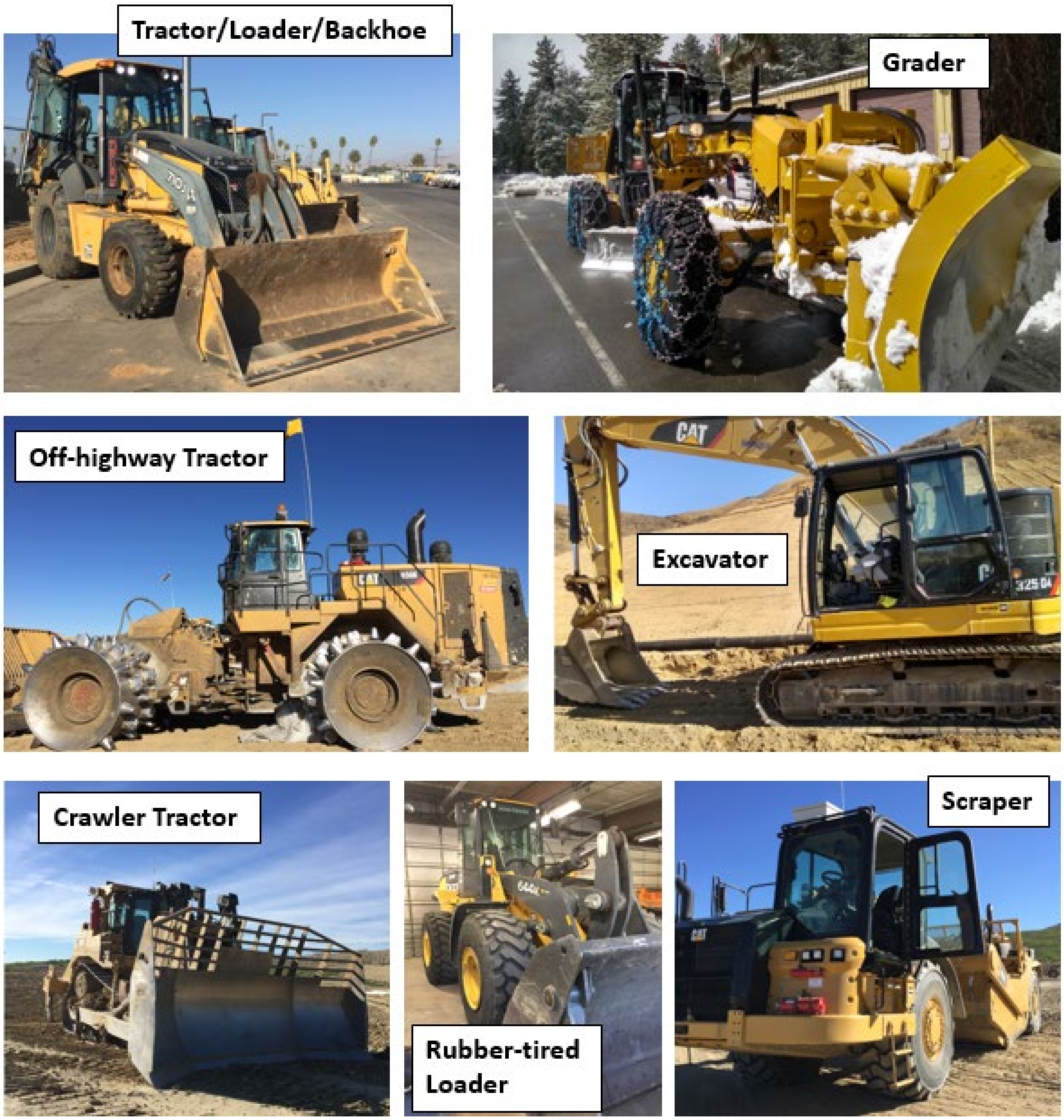


Figure 3-1. Examples of construction equipment from which in-use activity data were collected

3.1.2 Agricultural Equipment

Agricultural tractors are the most significant source of emissions in the agricultural equipment category, contributing roughly 78% of the NOx and 80% of the PM emissions from the agricultural sector according to the OFFROAD2017 model in calendar year 2018 [3]. Activity data from two agricultural tractors were collected in this project following the data logging procedures described in Section 3.1.3. The tractors were provided by UCR's Agricultural Operations Department. A selected picture of one of the tractors is presented in Figure 3-2.

Figure 3-2. Agricultural Tractor

3.1.3 Data Collection Methods

The equipment and engine activity measurements were made with portable activity measurement system (PAMS) data loggers obtained from the U.S. Environmental Protection Agency (EPA) via an existing Cooperative Research and Development Agreement (CRADA). These data loggers were maintained and utilized in accordance with EPA protocols, and as such met the highest standards for data measurement quality. The data loggers used were capable of collecting a wide range of data from the engine control unit (ECU) on the equipment, including exhaust temperatures for aftertreatment systems, fuel consumption, engine load, engine speed, mass air flows, etc., as well as filtered global positioning system (GPS) data, on a second-by-second basis. The data loggers communicate with the ECU through industry standard communication protocols. The GPS measures the equipment's location (latitude and longitude), speed, and altitude, from which road grade can be derived. The data loggers are small and can be easily attached to the ECU connector in the cab on the operator's side, as shown in Figure 3-3.

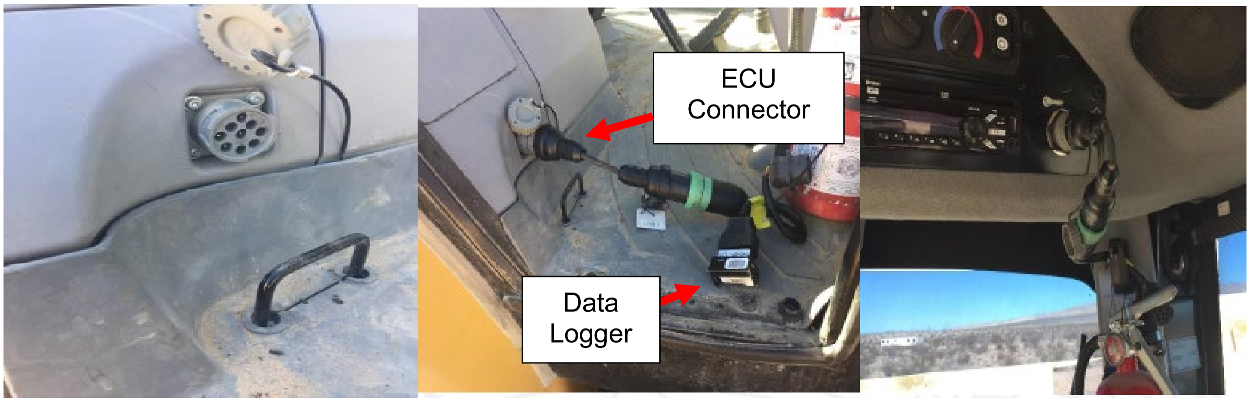


Figure 3-3. Data logger utilized for the equipment and engine activity measurement

Given the diversity of ECU parameters that were available for different engine manufacturers and different engine model years or technology categories within the same engine manufacturer, the data loggers were not set up with a configuration file consisting of a specific set of ECU parameters that would be collected. Instead, the data loggers were configured in such a manner that they collected all available data provided by the ECU. The configuration file only included a constraint that the available ECU parameters were collected at a frequency of 1 Hz to prevent the collection of very large files that could hinder the data collection itself or the subsequent data analysis. Key parameters that were available and used included engine speed, some measure of engine torque or load (either as a percent of total or for a given engine speed), accelerator position, and fuel rate. Others that might be available include exhaust temperature and aftertreatment temperature. The data loggers can store up to 6 months' worth of data. They also have the ability to transmit the recorded data wirelessly to a data server over a cellular network, but this feature was not used in this data collection effort.

Data recorded by a data logger are separated into individual files where a file includes data from the "key-on" event to the "key-off" event, as illustrated in Figure 3-4. The key-on event is when the ignition key is switched on, which powers on the electrical system of the equipment. The data logger receives an electrical signal, prompting it to create a new data file and start recording the data. The key-on event is usually followed by an "engine-on" event when the engine is turned on. This engine-on event represents the start of a "trip" in the context of this research as it has implication on the equipment's start emissions. After a certain period of engine operation, the engine is turned off, which represents the end of the trip. This "engine-off" event is then usually followed by a key-off event when the data logger stops recording the data and closes the data file. The amount of time from an engine-off event to the next engine-on event is called a "soak period", which also has impact on the equipment's start emissions and evaporative emissions. For heavy-duty engines, any engine start with the preceding soak period longer than 12 hours is considered a "cold" start.

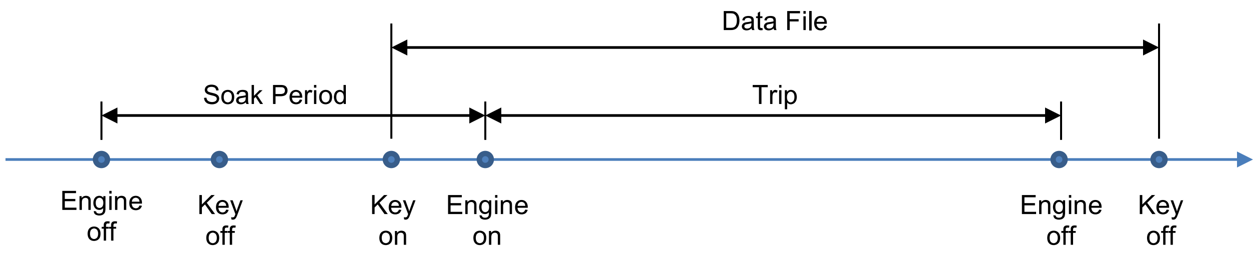


Figure 3-4. Illustration of events associated with a data file

It should be noted that the events discussed above do not always occur in the order presented in Figure 3-4. Sometime a key-on event may be followed by a key-off event, for instance, when the equipment operator switches the key on and then switches it off without turning on the engine. In this case, a data file will be created by the data logger but it will not be considered a trip in the context of this research. As another example, an engine-off event may be followed by an engine-on event without key-off. In this case, the data file will contain more than one trip.

3.1.4 Data Processing Procedures

In this research, the data loggers were installed and left on the equipment for a period of one month or longer. After the data collection period, the data loggers were retrieved and the data were downloaded. The downloaded data were then processed following the procedures that have been developed for on-road heavy-duty vehicles under the previous data collection programs for CARB and EPA to ensure the consistency and the level of quality assurance/quality control (QA/QC) needed for emissions modeling and inventory development. In the QA/QC of ECU data from on-road heavy-duty vehicles, field range, character type, variable length, and others were verified against SAE J1939 specifications. Similar procedures were applied to the ECU data from off-road equipment.

There were multiple steps of data processing as described below.

1. **Data Conversion:** The data logger creates two binary files for each trip—a .GPS file that logs the GPS data and a .IOS file that logs the ECU data. DawnEdit software provided by the data logger vendor was used to convert the two data files into a comma-separated values (CSV) file. During the conversion, the software time-aligned the GPS and ECU data streams and created a single CSV file.

2. **Data Quality Assurance/Quality Control:** The CSV files were put through several data QA/QC procedures. One focus of these procedures was on the timestamp data field. There are two sources of timestamp data: 1) GPS and 2) internal clock of the data logger. The data logger's internal clock only reports timestamp down to minutes. While the GPS reports timestamp down to seconds, there may be parts in the data where the GPS timestamp could obviously be incorrect or missing. For those parts in the data, the timestamp from the data

logger's internal clock was used to estimate the timestamps for the data records. Another focus of the data QA/QC procedures was on the vehicle speed. There are two sources of this data—GPS-based vehicle speed and ECU-based vehicle speed—and we have scripts that can be utilized to reconcile them to result in a composite vehicle speed as discussed in [114].

3. **Trip Identification:** A trip in the context of engine activity in this research is from an engine-on event to an engine-off event. Therefore, trips need to be identified and indexed in the data files before they could be used for analyses. Engine speed is used to identify engine-on and engine-off events. An engine off event is defined as having engine speed below 300 rpm. This threshold value is selected based on our previous observations that there is some noise in the engine speed data. A "Trip ID" data field is then added to identify each unique trip in the data files. Sometimes, a key-on event is followed by a key-off event, resulting in a data file being created by the data logger although it is not a trip. In this case, a Trip ID is not assigned. In other times, an engine-off event is followed by an engine-on event without key-off, resulting in the data file containing more than one trip. In this case, each trip is assigned a unique Trip ID.

4. **Data Aggregation:** As data for each piece of equipment consists of many data files, these individual data files are concatenated in chronological order into a single data file. The aggregate data file is essentially a very large data table where the columns include all the data fields in the GPS and ECU data. Some columns are empty as the data for those data fields are not available. Each row in the data table represents one second of data. Every second of data can be uniquely identified by timestamp.

3.2 Vehicle Activity Analysis

3.2.1 Analysis Methods

The data processing described in Section 3.1.4 resulted in 22 aggregated data files, one for each of the 22 pieces of off-road equipment in eight different categories listed in Table 3-1. These data files were used to calculate a number of statistics related to both equipment and engine activities, which are presented later in Section 3.2.2. While some statistics are self-explanatory, other statistics are not as they involve unique vehicle activity metrics and concepts. These activity metrics and concepts are described below.

3.2.1.1ECU-Based Engine Brake Power

Engine brake power is calculated as described in SAE J1939-71 using parameters in the ECU data and according to the following equations:

$$\mathrm{T}_{Net} = \frac{(\mathrm{T}_{Ind} - \mathrm{T}_{Fric})}{100} \times \mathrm{T}_{Ref} \qquad (1)$$

$$P_{Brake} = \frac{T_{Net} \times N}{5252} \tag{2}$$

where T_{Net} is engine net brake torque in ft-lb; T_{Ind} is indicated torque as a percentage; T_{Fric} is nominal friction torque as a percentage; T_{Ref} is reference torque in ft-lb; N is engine speed in rpm; and P_{Brake} is engine brake power in hp.

Although the parameters for reference torque, T_{Ref}, are included in the ECU data, their values were not reported. In this analysis, reference torque values were based on reported maximum torque values in the specifications for the specific equipment and engine models. The selected reference torque values are presented in Table 3-2, which also provides other information about the engine of each data logged equipment.

3.2.1.2 Estimated Engine Brake Power

In order to calculate engine brake power according to Eq. 1 and Eq.2, several parameters in the ECU data are required. For 15 pieces of equipment (marked with '*' in Table 3-2), one or more parameters had a significant amount of missing or invalid data. For these cases, engine brake power was not directly calculated, and instead a regression model was developed to estimate the engine brake power from fuel and engine speed data. There are seven pieces of equipment that had fuel, engine speed, and engine brake power data. These seven pieces of equipment were divided into two groups by engine manufacturer—Caterpillar and John Deere. The Caterpillar group consisted of two pieces of equipment, and the John Deere group consisted of five. The functional form of the regression models for power is provided in Eq. 3, and the regression coefficients are provided in Table 3-3. For three of the 15 pieces of equipment without sufficient data to directly calculate engine brake power, fuel rate data was also not available, and thus engine brake power was not estimated. These three are the two crawler tractors and the rubber-tired loader N18026. For the remaining 12 pieces of equipment, the regression models were applied based on the equipment's engine manufacturer.

$$P'_{brake} = \beta_1 F + \beta_2 N \tag{3}$$

where P'_{Brake} is estimated engine brake power in hp; F is engine fuel rate in liters per hour; N is engine speed in rpm; and β_1 and β_2 are regression coefficients.

Table 3-2. Information about engine in the data logged equipment

Equipment Type	Equip-ment ID	Engine Manufacturer	Engine Year	Engine Model	Engine Family	Engine Serial Number
Agricultural Tractor	JD_413	John Deere	2016	4045HLV71	GJDXL04.5305	R557485
	JD_414	John Deere	2018	4045HLV78	JJDXL04.5315	R564501
Crawler Tractor	N18024	Caterpillar	2017	C18	HCPXL18.1HTF	RDP04162
	N18025	Caterpillar	2017	C18	HCPXL18.1HTF	RDP04241
Excavator	N18029	Caterpillar	2018	C4.4	JPKXL04.4MW1	W7N52256
Grader	N18014	John Deere	2012	6090HDW16	CJDXL09.0202	RG6090R032952
	N18019	Caterpillar	2014	C9.3	ECPXL09.3HTF	SYE03083
	N18020	John Deere	2012	6090HDW11	CJDCL09.0202	RG6090R031033
	N18022	Caterpillar	2016	C9.3	GCPXL09.3HTF	SYE13223
	N18023	Caterpillar	2016	C9.3	GCPXL09.3HTF	SYE12520
Off-Highway Tractor	N18021	Caterpillar	2015	C18	FCPXL18.1HTF	RDP01901
	N18027	Caterpillar	2017	C18	HCPXL18.1HTF	RDP05246
Rubber Tired Loader	N18015	John Deere	2017	6090HDW29	HJDXL09.0308	RG6090U044147
	N18016	Caterpillar/Perkins	2012	C6.6	CPKXL06.6BK1	C8N08875
	N18018	Caterpillar/Perkins	2016	C7.1	GPKXL07.0BN1	D8T11576
	N18026	Deutz AG	2017	D8J	HDZXLO7.8046	12136372
	N18030	Caterpillar	2016	C9.3	GCPXL09.3HTF	SYE14168
Scraper	N18028	Caterpillar	2018	C9.3	JCPXL09.3HTF	SYE25018
	N18043	N/A	N/A	N/A	N/A	N/A
Tractor/ Loaders/ Backhoe	N18011	John Deere	2010	6068HT067	AJDXL06.8117	PE6068L147191
	N18012	John Deere	2008	4045HT054	8JDXL06.8106	PE4045L060805
	N18013	John Deere	2008	6068HT067	8JDXL06.8105	PE6068L037632

Table 3-2(continued). Information about engine in the data logged equipment

Equipment Type	Equip-ment ID	Displacem ent (L)	Engine Max Torque (Nm)	Rated power (hp)	Rated RPM	Engine Hours	Certificatio n Tier
Agricultural Tractor	JD_413	4.5	540	85	2,400	1,219	4 interim
	JD_414	4.5	519	100	2,200	222	4 final
Crawler Tractor	N18024*	18.1	378	465	1,800	3,748	4 final
	N18025*	18.1	378	465	1,800	3,903	4 final
Excavator	N18029	4.4	488	122	1,800	822	4 final
Grader	N18014	9	850	170-225	N/A	1,922	4 interim
	N18019*	9.3	1,251	260	2,000	4,748	4 final
	N18020	9	1,323	275	N/A	5,674	4 interim
	N18022*	9.3	1,251	256	2,000	1,759	4 final
	N18023*	9.3	1,251	256	2,000	1,721	4 final
Off-Highway Tractor	N18021*	18.1	3,094	558	1,500	9,382	4 final
	N18027*	18.1	3,094	558	1,500	1,654	4 final
Rubber Tired Loader	N18015	9	1,065	232	1,700	396	4 final
	N18016	6.6	914	173	1,800	3,032	4 interim
	N18018*	7.01	854	188	2,000	1,014	4 final
	N18026*	7.755	1,320	276	1,500	83	4 final
	N18030*	9.3	1,531	307	N/A	4,295	4 final
Scraper	N18028*	9.3	1,251	272	1,900	239	4 final
	N18043*	N/A	N/A	N/A	N/A	N/A	N/A

Tractor/ Loaders/ Backhoe	N18011*	6.8	537	123	2,000	5,107	3
	N18012*	4.5	378	96	2,100	5,044	3
	N18013*	6.8	537	123	2,000	7,899	3

Table 3-3. Regression coefficients for the engine brake power model

Engine Manufacturer	β_1	B_2
Caterpillar	3.3941	-0.0034483
John Deere	4.5939	-0.0040714

3.2.1.3 Work

Work in this context represents the amount of energy produced by the engine, and is calculated as the summation of engine brake power over time. It is presented in the unit of horsepower-hours (hp-hrs). For the pieces of equipment where the engine brake power could not be calculated due to missing or invalid data, work was calculated using the estimated engine brake power when available.

3.2.1.4 Engine Idle Mode

Engine idle is determined based on engine speed and a calculation that distinguishes between true idle events and transient events in which the engine speed may dip into the idle range. The calculation identifies continuous blocks of activity longer than a minimum time threshold and with engine speed within an idle speed range specific to each unit of equipment. The minimum time threshold for determining idle events for all pieces of equipment in this analysis was five seconds.

Engine idle typically fluctuates within a range of values as depicted in the histogram of example data in Figure 3-5. The idle range was determined by first finding the mode of engine speeds in the general range between 500 and 1000 rpm. Once the mode was determined, the mean engine speed within ±15 rpm of the mode was determined (depicted in red in Figure 3-5). This mean engine speed value was considered the engine idle value and the range ±10 rpm of this value was considered the idle range (depicted in green in Figure 3-5).

3.2.2 Summary Statistics

Summary statistics of equipment and engine activity of construction and agricultural equipment included in this analysis are presented in Table 3-4 through Table 3-7. Table 3-4 presents some information about the equipment as equipment type, engine make, and engine size. Table 3-4 also provides information about the amount of data collected from each equipment, the duration of engine activity in idle versus non-idle mode, and the fraction of engine activity in idle versus non-idle mode expressed as a percent.

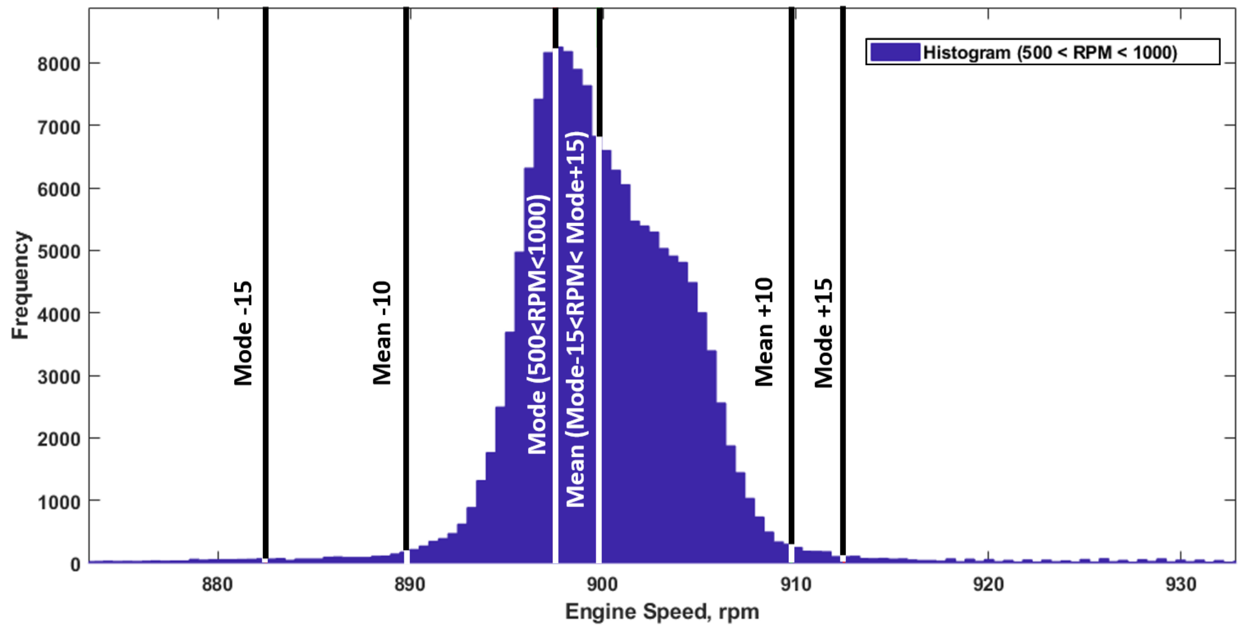


Figure 3-5. Histogram of example engine speed data within the range of 500 to 1000 rpm

Table 3-4. Equipment information and engine idle statistics

Equipment Type	Equip-ment ID	Engine Make	Engine Size (L)	Total (hrs)	Idle (hrs)	Non-Idle (hrs)	Idle (%)	Non-Idle (%)
Agricultural Tractor	JD_413	John Deere	4.5	81.5	24.6	56.9	30.2	69.8
	JD_414	John Deere	4.5	34.2	8.9	25.3	26.0	74.0
Crawler Tractor	N18024	Caterpillar	18.1	256.4	33.3	223.0	13.0	87.0
	N18025	Caterpillar	18.1	104.7	14.3	90.4	13.6	86.4
Excavator	N18029	Caterpillar	4.4	256.1	56.8	199.3	22.2	77.8
Grader	N18014	John Deere	9	13.3	6.2	7.1	46.4	53.6
	N18019	Caterpillar	9.3	263.0	67.6	195.4	25.7	74.3
	N18020	John Deere	9	62.4	13.1	49.3	21.0	79.0
	N18022	Caterpillar	9.3	72.9	16.7	56.2	22.9	77.1
	N18023	Caterpillar	9.3	67.4	12.0	55.4	17.8	82.2
Off-Highway Tractor	N18021	Caterpillar	18.1	223.7	38.7	184.9	17.3	82.7
	N18027	Caterpillar	18.1	253.7	68.6	185.0	27.1	72.9
Rubber Tired Loader	N18015	John Deere	9	38.6	5.5	33.1	14.3	85.7
	N18016	Caterpillar/Perkins	6.6	149.5	18.6	130.9	12.4	87.6
	N18018	Caterpillar/Perkins	7.01	111.3	29.1	82.2	26.2	73.8
	N18026	Deutz AG	7.755	112.6	22.6	90.0	20.0	80.0
	N18030	Caterpillar	9.3	222.0	27.5	194.5	12.4	87.6
Scraper	N18028	Caterpillar	9.3	54.6	7.3	47.3	13.3	86.7
	N18043	N/A	N/A	449.5	62.9	386.6	14.0	86.0
Tractor/ Loaders/ Backhoe	N18011	John Deere	6.8	66.3	39.5	26.7	59.7	40.3
	N18012	John Deere	4.5	79.9	44.8	35.1	56.0	44.0
	N18013	John Deere	6.8	59.9	28.4	31.5	47.4	52.6

Overall, the amount of data collected from each equipment varies greatly from as little as 13 hours to as much as 450 hours. The fraction of engine activity in idle mode also varies, ranging from 12% to 60%. Interestingly, there are several equipment types where the percent engine idle is similar across all the pieces of equipment within the same type. For instance, the two agricultural tractors have percent engine idle of 26% and 30%. It is 13% and 14% for the two crawler tractors, and also 13% and 14% for the two scrapers. For the five rubber tired loaders, the percent engine idle ranges from 12% to 26%. And for the three tractors/loaders/backhoes, it ranges from 47% to 60%.

Table 3-5 presents the number of days in range during which data was collected, the number of operating days, and engine start statistics. Statistics are presented for the following day counts:

- *Number of days in range* – The number of days between the first activity date and the last activity date for a given piece of equipment
- *Number of days operating* – The number of unique days that the equipment was operated
- *Number of weekdays in range* – The number of weekdays between the first activity date and the last activity date for a given piece of equipment
- *Number of weekdays operating* – The number of unique weekdays that the equipment was operated

Per day statistics are provided for the number of starts and the number of cold starts. Starts here are referred to engine-on events, and cold starts are defined as engine-on events with the preceding soak period greater than or equal to 12 hours. The use of equipment within 12 hours of the previous day’s activity results in cold start per day numbers less than one.

Table 3-6 provides summary statistics for engine brake power and fuel rate. The mean and median power and fuel rate statistics were calculated based on continuous, second-by-second data across all data for a given piece of equipment. Engine brake power statistics were based on the engine brake power calculated from ECU data when available. In the absence of ECU-based engine brake power, estimated engine brake power was used. The calculation of ECU-based and estimated engine brake power is described in Section 3.2.1. The source of engine brake power data for each piece of equipment is noted in Table 3-6. For three pieces of equipment, neither ECU-based engine brake power nor estimated engine brake power was available. The total fuel and total horsepower (HP) columns in Table 3-6 are based on aggregating the second-by-second data. In cases where ECU-based engine brake power was available, estimated engine brake power was not calculated, and thus there is no value in the total HP (estimated) column.

Table 3-5. Summary statistics for number of data collection days and number of engine starts

Equipment Type	Equip-ment ID	No. of Days in Range	No. of Days Operating	No. of Week days in Range	No. of Week days Operating	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	56	31	41	30	4.66	6.37	0.73	1.00
	JD_414	48	17	36	17	3.36	7.12	0.47	1.00
Crawler Tractor	N18024	28	28	22	22	2.64	2.64	0.45	0.45
	N18025	18	17	14	14	4.29	4.29	0.29	0.29
Excavator	N18029	148	46	107	41	1.06	2.76	0.37	0.98
Grader	N18014	87	27	64	26	1.33	3.27	0.41	1.00
	N18019	81	39	60	39	1.10	1.69	0.65	1.00
	N18020	27	10	20	10	2.30	4.60	0.50	1.00
	N18022	27	23	20	19	5.75	6.05	0.95	1.00
	N18023	22	22	18	18	4.00	4.00	0.94	0.94
Off-Highway Tractor	N18021	28	25	22	21	2.59	2.71	0.86	0.90
	N18027	28	26	22	22	2.05	2.05	1.00	1.00
Rubber Tired Loader	N18015	62	26	46	25	1.41	2.60	0.52	0.96
	N18016	26	17	20	16	2.85	3.56	0.70	0.88
	N18018	49	23	36	23	3.14	4.91	0.61	0.96
	N18026	34	27	25	22	4.84	5.50	0.88	1.00
	N18030	148	53	108	52	1.76	3.65	0.48	1.00
Scraper	N18028	28	18	22	17	11.73	15.18	0.77	1.00
	N18043	75	47	54	41	1.04	1.37	0.69	0.90
Tractor/ Loaders/ Backhoe	N18011	28	20	21	18	8.62	10.06	0.62	0.72
	N18012	29	22	23	21	8.57	9.38	0.70	0.76
	N18013	42	20	32	17	3.72	7.00	0.50	0.94

Table 3-6. Summary statistics for engine brake power and fuel rate

Equipment Type	Equip-ment ID	Median Power (hp)	Mean Power (hp)	Median Fuel Rate (gal/hr)	Mean Fuel Rate (gal/hr)	Total Fuel (gal)	Total HP (ECU Based) (hp-hr)	Total HP (Estimated) (hp-hr)
Agricultural Tractor	JD_413	8.7	16.7	0.95	1.28	104	1,361	N/A
	JD_414	20.5	23.8	1.33	1.54	53	812	N/A
Crawler Tractor	N18024	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	N18025	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Excavator	N18029	40.2	41.5	3.61	3.63	929	10,640	N/A
Grader	N18014	19.1	26.0	1.47	2.00	27	345	N/A
	N18019	30.9*	41.3*	2.69	3.52	925	N/A	10,861
	N18020	38.2	52.6	2.25	3.09	193	3,278	N/A
	N18022	42.1*	50.0*	3.66	4.24	309	N/A	3,646
	N18023	47.2*	53.0*	4.07	4.49	302	N/A	3,573
Off-Highway Tractor	N18021	226.1*	192.1*	18.03	15.32	3,426	N/A	42,966
	N18027	223.7*	182.2*	17.84	14.52	3,683	N/A	46,221
Rubber Tired Loader	N18015	18.8	34.7	1.68	2.69	104	1,339	N/A
	N18016	18.9	35.5	1.82	3.12	466	5,311	N/A
	N18018	17.3*	32.7*	1.65	2.83	315	N/A	3,633
	N18026	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	N18030	27.3*	54.0*	2.40	4.50	998	N/A	11,982
Scraper	N18028	49.1*	70.8*	4.20	5.81	317	N/A	3,864
	N18043	62.3*	114.0*	5.23	9.17	4,123	N/A	51,233
Tractor/ Loaders/ Backhoe	N18011	11.7*	30.5*	0.89	2.06	137	N/A	2,021
	N18012	8.0*	23.2*	0.67	1.65	132	N/A	1,850
	N18013	10.7*	31.9*	0.83	2.15	129	N/A	1,911

*Based on estimated engine brake power

Table 3-7 provides daily statistics for work and fuel use based on the number of unique operating days. For these statistics, a set of daily values were calculated for each day in the dataset of a given piece of equipment, and then the maximum, median, mean, and minimum statistics of these daily values are presented in Table 3-7. Daily work is based on the engine brake power calculated from ECU data when available. In the absence of ECU-based engine brake power, estimated engine brake power was used. The source of engine brake power data for the calculation of daily work for each piece of equipment is noted in Table 3-7.

Table 3-7. Summary statistics for daily work and fuel use

Equipment Type	Equip-ment ID	Max Daily Work (hp-hr/day)	Median Daily Work (hp-hr/day)	Mean Daily Work (hp-hr/day)	Min Daily Work (hp-hr/day)	Max Daily Fuel Use (gal/day)	Median Daily Fuel Use (gal/day)	Mean Daily Fuel Use (gal/day)	Min Daily Fuel Use (gal/day)
Agricultural Tractor	JD_413	176.7	30.5	45.4	1.8	12.30	2.75	3.47	0.17
	JD_414	190.9	43.1	50.7	1.2	12.27	2.79	3.29	0.13
Crawler Tractor	N18024	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	N18025	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Excavator	N18029	478.2	217.3	231.3	2.6	40.83	19.41	20.21	0.25
Grader	N18014	66.5	8.1	12.8	0.5	5.19	0.62	0.98	0.04
	N18019	509.2*	323.7*	278.5*	0.2*	42.67	27.81	24.33	0.10
	N18020	465.1	361.8	327.8	9.2	27.56	21.16	19.26	0.58
	N18022	396.2*	124.5*	158.5*	9.4*	33.26	10.58	13.44	0.84
	N18023	336.1*	165.8*	162.4*	7.6*	28.44	13.90	13.75	0.65
Off-Highway Tractor	N18021	2,526.5*	1,981.8*	1,718.6*	19.7*	201.34	158.28	137.04	1.67
	N18027	2,221.8*	1,960.4*	1,777.7*	318.5*	176.77	156.06	141.64	25.38
Rubber Tired Loader	N18015	235.8	20.4	51.5	0.8	17.47	1.71	3.99	0.06
	N18016	673.1	333.2	312.4	0.3	58.63	29.02	27.41	0.03
	N18018	435.0*	189.3*	165.2*	3.7*	36.82	16.41	14.33	0.34
	N18026	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	N18030	550.7*	201.1*	226.1*	4.1*	45.64	16.84	18.83	0.33
Scraper	N18028	509.0*	247.1*	241.5*	5.1*	41.62	20.37	19.83	0.44
	N18043	1,540.8*	1,182.3*	1,090.1*	0.5*	123.86	95.16	87.73	0.04
Tractor/ Loaders/ Backhoe	N18011	202.3*	101.1*	101.0*	1.5*	13.59	6.90	6.83	0.10
	N18012	269.0*	84.5*	88.1*	0.9*	19.34	6.03	6.29	0.06
	N18013	231.3*	87.8*	95.5*	0.4*	15.14	5.88	6.44	0.03

*Based on estimated engine brake power

3.3 Comparison with Certification Cycles

The engine activity statistics presented in the previous section suggest that the real-world, in-use characteristics of engine operation for the different types of construction and agricultural equipment vary greatly. In this section, we explore how the in-use engine operation characteristics compare to those of the certification cycles for off-road engines. The engine certification cycles used in this analysis include the following:

3.3.1.1Non-Road Steady Cycle

The ISO 8178 test is an international test standard for non-road engines. It is used for emission certification testing in the U.S. and other countries. It consists of a collection of steady-state engine dynamometer test cycles for various classes of engine and equipment. For the comparison in this analysis, the C1 test schedule was used. It is an 8-mode cycle for off-road engines, and is also referred to as the non-road steady cycle (NRSC). The engine speed and torque levels that make up of the 8-mode cycle are given in Table 3-8. Also given in Table 3-8 are weighting factors, which are used to weight the measured emissions in each mode.

Table 3-8. Characteristics of the 8-mode non-road steady cycle

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

3.3.1.2Non-Road Transient Cycle

The non-road transient cycle (NRTC) captures transient modes, and is designed to closely match engine work during normal operation. The cycle is 1,238 seconds in duration, and is defined based on normalized engine speed and torque as depicted in Figure 3-6. The normalized torque values are converted to a reference cycle based on an engine map for the specific test equipment, in a process called de-normalization.

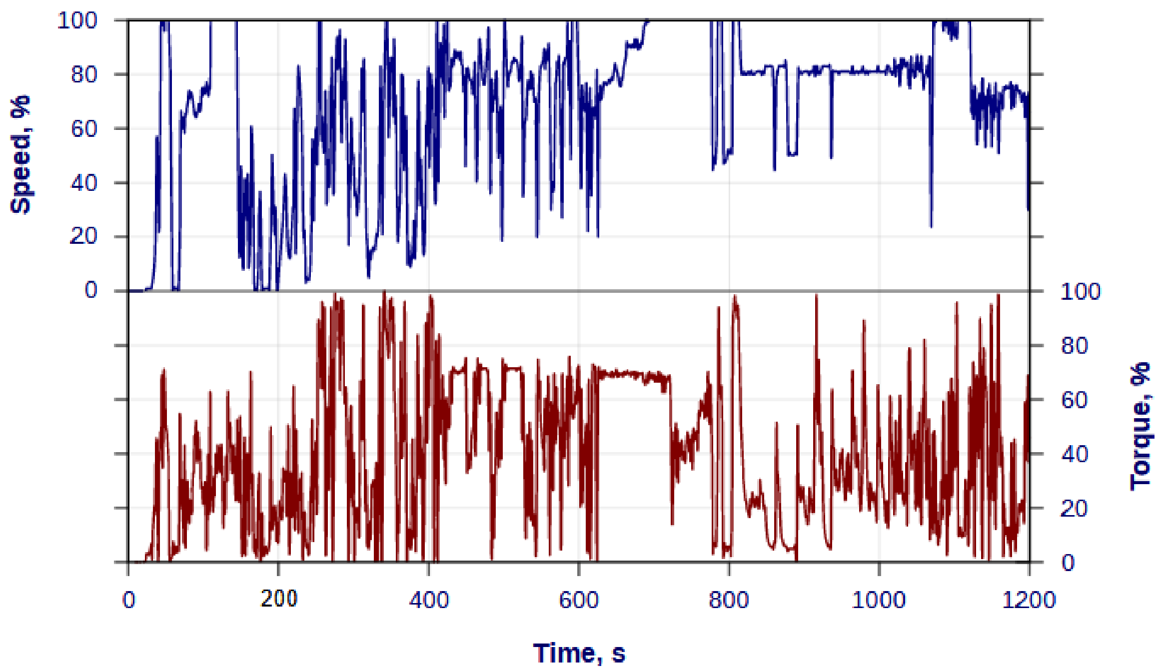


Figure 3-6. Non-road transient cycle [115]

Table 3-9 shows the data distributions of torque, expressed as a percentage of the maximum torque, for the certification cycles and the in-use activity data collected from each equipment. For the equipment without ECU-based engine brake power, torque was calculated based on estimated engine brake power and engine speed. Each row in Table 3-9 is color-formatted independently based on the percent torque values in each torque bin. Thus, the red cell(s) in each row represents the mode(s) of the data distributions for each equipment.

Table 3-9. Distribution of percent torque in the certification cycles and the collected engine activity data

	% 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

The comparison of the percent torque distributions shows that similarities and variations exist within equipment types and between equipment types. For instance, the percent torque distributions for tractors/loaders/backhoes and off-highway tractors are fairly consistent within their own type but different from each other. When compared to those for the certification cycles, the percent torque distributions for all pieces of the equipment are obviously different. The non-road transient cycle or NRTC has two modes of percent torque, the higher one in the 70%-75% bin. And the non-road steady cycle or NRSC (also known as type C1 8-mode steadystate cycle) has three modes in the 45%-50%, 70%-75%, and 95%-100% bins. On the other hand, the modes of percent torque distributions for the equipment are less than 25%, and mostly in the 5%-10% bin. In fact, all the equipment except the excavator (N18029) rarely operate their engine at higher than 60% torque. Based on the analyzed in-use engine activity data, the certification cycles are not likely to be representative of how the engines of the equipment types included in this analysis operate in real world.

Figure 3-7 shows the comparison of continuous torque and engine speed data between the NRTC and the collected in-use data from a grader (Equipment N18014). For the NRTC, the percent torque and engine speed values were scaled to match the range of data from the equipment. The comparison consists of: 1) scatter plots of torque versus engine speed, and 2) histograms along each axis that indicate the frequency of torque and engine speed values in various bins. In this figure, it is easy to see that the ranges and distributions of torque and engine speed differ between the NRTC and the collected in-use data. Also, there is a significant portion of in-use data in the zone with engine speed lower than 900 rpm and torque higher than 200 Nm that is not represented by the NRTC. Comparison plots for the other pieces of equipment are provided in Appendix D.

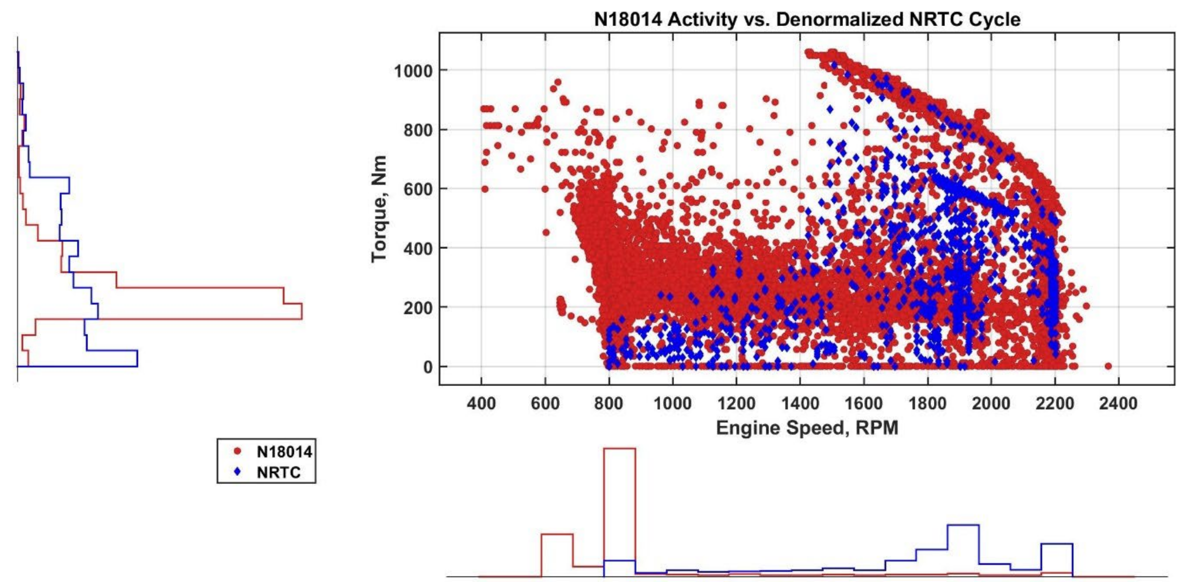


Figure 3-7. Comparison of torque and engine speed between the denormalized NRTC and in-use data of a grader

The significant differences in engine torque and engine speed between in-use activity data and the certification cycles shown in the comparisons above suggest that the certification cycles are not likely to be representative of how the engines of these equipment types operate in real world. Therefore, the energy demands of these equipment type estimated using the certification cycles may not accurately reflect their real-world energy demands, and should not be used as a basis for assessing whether and how these equipment types can be electrified.

3.4 Synthesis of Energy and Emissions Inventories

In this analysis, the in-use activity data compiled in this project were compared to outputs from the OFFROAD2017 model [3]. The OFFROAD2017 model provides data regarding population, activity, and emissions of off-road equipment in California. The data are disaggregated by a number of parameters such as calendar year, location, equipment type, equipment model year, and horsepower bin. By specifying these parameters, appropriate activity and emissions data were obtained from OFFROAD2017 for comparison with each equipment in the compiled dataset. The daily emission data provided in OFFROAD2017 were multiplied by 365, following the current practice for using this inventory database. The fuel, NOx emission, and PM2.5 emission rates were applied to the in-use activity data to estimate the fuel use and emission inventory for each piece of equipment. The observed in-use activity data and the corresponding emission inventory estimates are presented in Table 3-10 in comparison with the activity and emission inventory data from OFFROAD2017. For each piece of equipment, the differences between the in-use activity data and the activity data from OFFROAD2017 range from -90% to 456%. This implies that the equipment's fuel use and emissions estimated based on their in-use activity data will also differ from if estimating based on the activity data from OFFROAD2017 by the same magnitude. However, it should be noted that the in-use activity data used in each comparison is from a single piece of equipment, which may not be representative of all the equipment in that type, model year, and horsepower bin. Also, the activity data in the OFFROAD2017 model are obtained from a different set of sample in a different time period and setting. Therefore, these differences do not necessarily indicate that the OFFROAD2017 model underestimates or overestimates the level of equipment activity (and emissions inventory), but rather point to the high variability in the usage of individual pieces of equipment even of the same type, size, and model year.

Table 3-10. Comparison of observed activity and estimated emissions for the equipment with outputs from OFFROAD2017

Equipment Information				Observed Activity				Estimated Statewide Inventory		
Equipment Type	Equip-ment ID	Model Year	HP	Total (hrs)	No. of Days in Range	Hours per Day	Hours per Year	NOx (ton/yr)	PM 2.5 (ton/yr)	Fuel (gal/yr)
Agricultural Tractor	JD_413	2016	85	81.5	56	1.46	531	4,589.33*	334.47*	44,221,805*
	JD_414	2016	100	34.2	46	0.74	271	1,860.46*	97.43*	14,607,073*
Crawler Tractor	N18024	2017	465	256.4	28	9.16	3,342	11.49	0.37	2,052,211
	N18025	2017	465	109.5	18	6.08	2,220	7.63	0.24	1,363,054
Excavator	N18029	2019	122	256.1	146	1.75	640	1.49	0.05	269,379
Grader	N18014	2013	235	13.3	87	0.15	56	0.09	0.00	3,041
	N18019	2014	260	263.0	81	3.25	1,185	1.40	0.05	239,745
	N18020	2012	275	62.4	27	2.31	843	2.00	0.01	66,880
	N18022	2016	256	72.9	27	2.70	986	0.87	0.03	152,285
	N18023	2016	256	67.4	22	3.07	1,119	0.99	0.03	172,799
Off-Highway Tractor	N18021	2015	558	223.7	28	7.99	2,916	4.97	0.16	868,672
	N18027	2018	558	253.7	28	9.06	3,307	7.55	0.24	1,355,772
Rubber Tired Loader	N18015	2018	232	38.6	62	0.62	227	0.76	0.02	134,638
	N18016	2013	173	149.5	26	5.75	2,099	32.44	0.15	639,461
	N18018	2016	188	111.3	49	2.27	829	2.51	0.09	430,328
	N18026	2018	276	112.6	34	3.31	1,209	4.05	0.13	716,270
	N18030	2016	307	222.0	148	1.50	548	2.85	0.10	488,386
Scraper	N18028	2018	272	54.6	28	1.95	711	0.42	0.01	75,394
	N18043	N/A	N/A	449.5	75	5.99	2,188	N/A	N/A	N/A
Tractor/ Loaders/ Backhoe	N18011	2011	123	66.3	28	2.37	864	6.84	0.43	127,729
	N18012	2008	96	79.9	29	2.75	1,005	121.74	7.11	1,892,666
	N18013	2008	123	59.9	42	1.43	520	12.85	0.76	235,731

*Estimated for all model years combined as OFFROAD2017 does not provide data by model year for agricultural tractor

Table 3-10(continued). Comparison of observed activity and estimated emissions for the equipment with outputs from OFFROAD2017

Equipment Information		OFFROAD2017 Statewide Inventory for Calendar Year 2019							Activity Differ-ences (%)
Equipment Type	Equip-ment ID	Model Year	HP Bin	Total Popula-tion	Total Activity (hr/yr)	NOx (ton/yr)	PM 2.5 (ton/yr)	Fuel (gal/yr)	
Agricultural Tractor	JD_413	All	100	34,766*	20,728,670*	5,152.01*	375.48*	49,643,651*	-11
	JD_414	All	175	17,161*	11,128,463*	4,451.58*	233.12*	34,950,773*	-58
Crawler Tractor	N18024	2017	600	72	43,029	2.07	0.07	369,252	456
	N18025	2017	600	72	43,029	2.07	0.07	369,252	269
Excavator	N18029	2019	175	145	116,519	1.87	0.06	338,516	-20
Grader	N18014	2013	300	13	7,082	0.90	0.01	30,461	-90
	N18019	2014	300	44	25,377	0.69	0.02	117,183	105
	N18020	2012	300	17	10,104	1.41	0.01	47,274	41
	N18022	2016	300	35	21,569	0.54	0.02	94,309	61
	N18023	2016	300	35	21,569	0.54	0.02	94,309	83
Off-Highway Tractor	N18021	2015	600	39	26,275	1.15	0.04	201,516	331
	N18027	2018	600	47	35,030	1.69	0.05	304,478	345
Rubber Tired Loader	N18015	2018	300	155	208,973	4.50	0.15	797,018	-83
	N18016	2013	175	108	97,327	13.95	0.07	275,102	132
	N18018	2016	300	134	149,929	3.38	0.12	579,355	-26
	N18026	2018	300	155	208,973	4.50	0.15	797,018	-10
	N18030	2016	600	147	154,969	5.49	0.19	940,580	-48
Scraper	N18028	2018	300	18	9,181	0.30	0.01	54,098	39
	N18043	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Tractor/ Loaders/ Backhoe	N18011	2011	175	53	22,815	3.38	0.21	63,167	102
	N18012	2008	100	1,112	701,906	76.45	4.47	1,188,633	59
	N18013	2008	175	170	112,659	16.35	0.97	300,099	-21

*Estimated for all model years combined as OFFROAD2017 does not provide data by model year for agricultural tractor

4 Technical Feasibility of Electrifying Off-Road Equipment

4.1 Technological Feasibility

4.1.1 Motor Sizing

As described in Section 3.2.1, the ECU data collected from the equipment was used to determine the power and torque output from the diesel engine. In this analysis, it is assumed that the diesel engine is replaced with an electric motor while keeping the components from the driveshaft to the wheels unchanged. This approach focuses on answering the question of whether the power and torque requirements of the existing diesel equipment can be met by an electric version of the same equipment. With this approach, the power and torque demanded from the diesel engine during the in-use operation of the equipment were analyzed. Then, the specifications of an electric motor that would satisfy those power and torque demands were determined.

Electric motor specifications include peak rating (performance available for a short duration) and continuous rating (performance available throughout the operation duration). For each piece of equipment, the two ratings for both torque and power were determined from the boxplots of the corresponding data. These plots for equipment JD_413 are shown in Figure 4-1. A boxplot shows summary statistics of the data, where the central line in the box represents the median value. The top and bottom edges of the box represent the 75th and 25th percentiles. The lines at the end of each whisker indicate 1.5 times the interquartile range of the data, and data points outside of this range are considered outliers. The maximum non-outlier data point is reported as “Upper Adjacent” in Figure 4-1, and its value is used to determine the required continuous rating of the electric motor. The outliers are shown with the ‘+’ symbols, and their highest value is reported as “Maximum” in Figure 4-1. This maximum torque or power is required momentarily by the equipment, and electric motors that have peak performance rating above this maximum value are thus capable of meeting this torque or power demand. The box plots for all the equipment are given in Appendix E for torque demand and Appendix F for power demand, respectively.

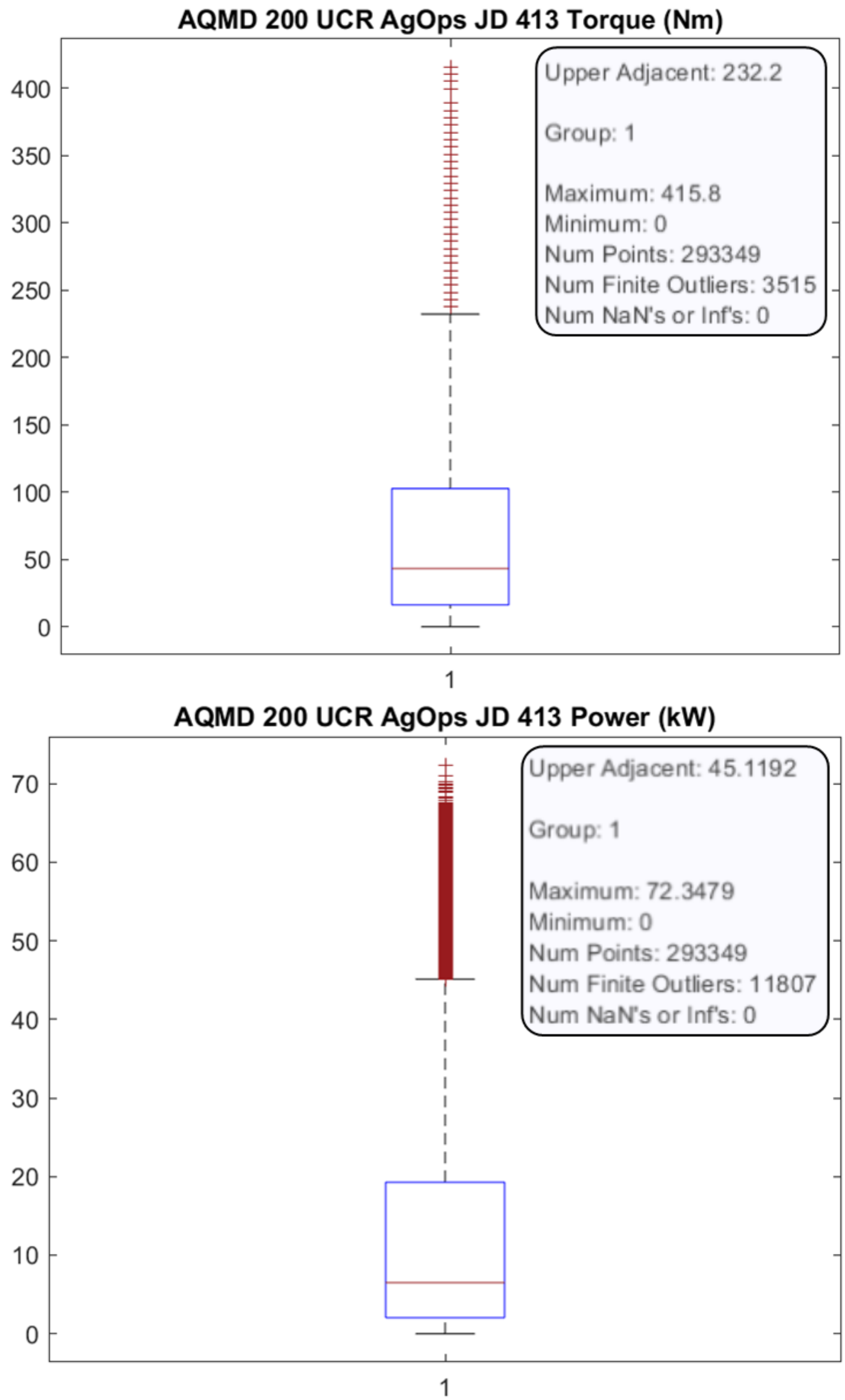


Figure 4-1. Box plots for equipment JD_413: (top) torque demand and (bottom) power demand.

Table 4-1 summarizes the required statistics obtained from the box plots of all the equipment. In this table, the values marked with '*' are based on estimated torque or power as described in Section 3.2.1. The other values are based directly on the ECU data. There is no data for the two crawler tractors and one rubber tired loader (Equipment N18026), and thus they are excluded from this table and the analyses hereafter.

Table 4-1. Torque and power demands based on in-use activity of the equipment

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*

**Based on estimated torque or power*

Appendix C describes some commercially available electric motors whose performance ratings are summarized in Table 4-2. The performance ratings of these motors vary greatly. The peak torque ratings range from 350 to 3445 Nm while the continuous torque ratings range from 145 to 2060 Nm. The peak power ratings range from 140 to 440 kW while the continuous power ratings range from 64 to 260 kW. The equipment torque and power demands listed in Table 4-1 were compared with the motor performance ratings shown in Table 4-2 to determine which of these motors are capable of replacing the diesel engines in the studied equipment without any loss of performance.

Table 4-2. Torque and power ratings of some commercially available electric motors

Series	Model	Torque Ratings (Nm)		Power Ratings (kW)	
		Peak	Continuous	Peak	Continuous
UQM 200 series	PowerPhase HD 220 [116]	700	350	220	120
	PowerPhase HD 250 [117]	900	360	250	150
	PowerPhase HD 950T [118]	950	400	145	100
TM4 SUMO [119]	HV2700-9P	2700	2060	250	195
	HV3400-9P	3400	2060	250	195
	HV3500-9P	3445	1970	370	260
Borg Warner HVH410-150 [120]	-	~2000	1400	160	120
EVO Axial Flux Electric Motor [121]	1	600	260	220	94
	2	700	290	280	128
	3	1200	520	440	188
	4	350	145	140	64

Table 4-3 identifies the available motors capable of meeting the performance demands for each equipment. All the equipment with good ECU data (the motor choices marked with bold uppercase ‘**X**’) has at least three choices of commercially available electric motors. The equipment with estimated torque and power data (the motor choices marked with *italic* lowercase ‘*x*’) have at least one choice for the scrapers, while the others have four or more choices. The only exception here are the off-highway tractors for which none of these commercially available motors can directly meet the performance requirements. This may call for a more powerful electric motor or a hybrid powertrain.

Table 4-3. Available electric motors suitable for the equipment studied

Equipment Type	Equip-ment ID	Engine Max Torque (Nm)	Rated power (hp)	Available Motors										
				UQM PowerPhase HD 220	UQM PowerPhase HD 250	UQM PowerPhase 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
Agricultural Tractor	JD_413	540	85	X	X	X	X	X	X	X	X	X	X	
	JD_414	519	100	X	X	X	X	X	X	X			X	
Excavator	N18029	488	122				X	X	X	X			X	
Grader	N18014	850	170-225		X	X	X	X	X	X			X	
	N18019	1,251	260				x	x	x	x				
	N18020	1,323	275				X	X	X					
	N18022	1,251	256				x	x	x					
	N18023	1,251	256				x	x	x				x	
Off-Highway Tractor	N18021	3,094	558											
	N18027	3,094	558											
Rubber Tired Loader	N18015	1,065	232				X	X	X	X			X	
	N18016	914	173				X	X	X	X				
	N18018	854	188				x	x	x	x				
	N18030	1,531	307				x	x	x					
Scraper	N18028	1,251	272						x					
	N18043	-	-						x					
Tractor/ Loaders/ Backhoe	N18011	537	123				x	x	x	x			x	
	N18012	378	96		x	x	x	x	x	x			x	
	N18013	537	123				x	x	x	x			x	

*Based on estimated torque or power

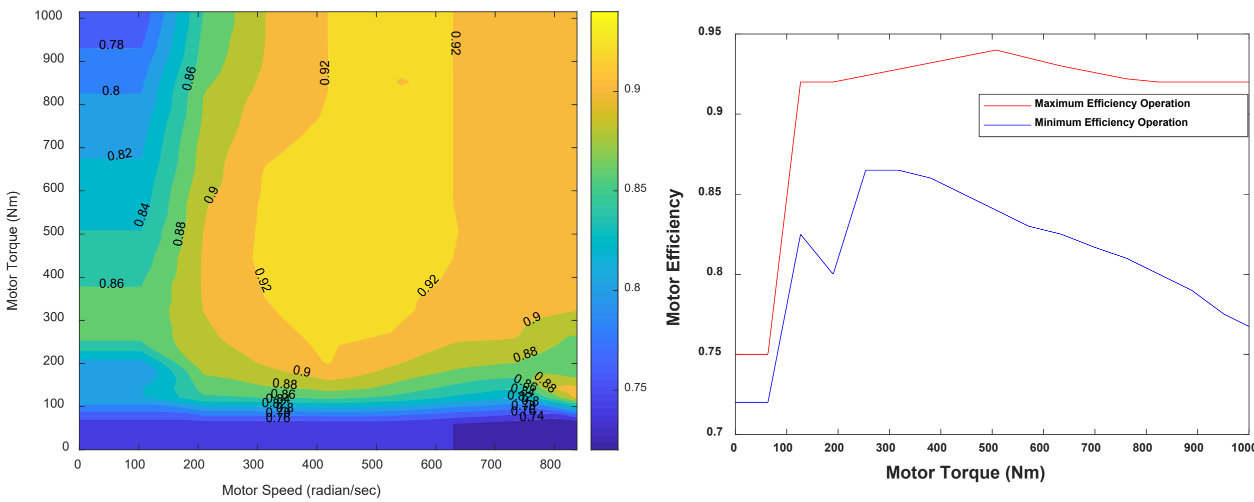
4.1.2 Battery Sizing

The battery in an electric powertrain supplies electric power to the motor. In order to determine the instantaneous motor power consumption, or the instantaneous battery power supply, the power demand at each time instance has to be divided by the motor efficiency value at the corresponding operating point in the motor efficiency map, as stated in equation (1).

$$Maximum\ Motor\ Power\ Consumption = \frac{Motor\ Power\ Demand}{Minimum\ Motor\ Efficiency} \quad (1)$$

In order to do this, the motor efficiency map of UQM PowerPhase 145 heavy-duty electric motor was obtained from the Autonomie powertrain simulation tool [122]. This map is shown in Figure 4-2(a). For each motor speed-torque pair, there is a corresponding efficiency value which can be visualized by the colored contours. For the

studied equipment, we had the torque and power values required of the motor. For a given level of torque required, the motor operates at a certain speed, which is determined by the motor controller. If this controller is designed to choose a certain speed for each required torque level, we can get the corresponding motor efficiency value for that speed-torque point, which can be utilized to calculate the motor power consumption at that moment. The motor controller may be designed to operate at the speed providing the maximum efficiency, the minimum, or any value in between. For maximum efficiency operation, the battery power consumption will be the minimum, and vice versa. Both of these boundary cases were included in this analysis to provide both the best- and the worst-case estimates of the battery size. Figure 4-2(b) shows the motor efficiency values for maximum and minimum efficiency operations derived from the motor efficiency map in
Figure 4-2(a).



(a) (b)

Figure 4-2. (a) Efficiency map of UQM PowerPhase 145 heavy-duty electric motor obtained from Autonomie; (b) Motor efficiency curves for the maximum and minimum efficiency operations.

The calculated instantaneous power consumption (at 1 Hz) can be summed for each operating day to determine the total daily energy consumption:

$$\text{Daily Energy Consumption } (kWh) = \sum_{i=1}^{n} (\text{instantaneous Power Consumption } (kW))_i \,/3600 \qquad (2)$$

where $n =$ number of operation instances or operating seconds in a day. For each equipment, the maximum daily energy consumption value of the maximum efficiency operation of the electric motor was taken as the minimum battery size required to support all the equipment operations recorded in the in-use activity data. Similarly, the maximum daily energy consumption value of the minimum efficiency operation of the electric motor was taken as the maximum battery size required. As it is more realistic to assume that electric off-road equipment would be produced with a standard battery size for each equipment model in each equipment type, the daily energy consumption data were combined by equipment type and their distributions analyzed. For each equipment type, the maximum value (rounded up by 1 to meet any fractional kWh power demand) of the daily energy consumption distribution was used to determine the required battery size so that it could fully meet all the daily operations recorded in the data. No data from the two crawler tractors in Table 3-10 is available, and thus it is not possible to carry out this analysis for that equipment type. Also, there is only one piece of equipment in the excavator type, thus this analysis represents its daily energy consumption statistics. The other equipment types have at least two pieces of equipment.

The battery sizes determined through this analysis are referred to as "Usable Battery Size" in Table 4-4. Assuming that the battery will be lithium-ion battery, which is used in most of the current electric on-road vehicles and off-road equipment, the actual or nominal battery size should be at least 20% larger than the usable battery size to prevent the states of deep discharge and over-charge, which could adversely affect battery efficiency and battery life [123] [124]. Therefore, an extra 30% (larger than the minimum of 20% for conservative estimate) was applied to the usable battery size to calculate the "Equipped Battery Size" column in Table 4-4. This additional battery capacity can also provide the energy needed if any activity duration extends beyond the rated operating duration of the equipment. This equipped battery size was then rounded up to the closest order of 10 to produce a more practical target for battery packaging. The results are shown in the "Rounded Equipped Battery Size" column. This battery is expected to be fitted to the electric equipment. According to this column, the final battery sizes for the different equipment types range from 330 kWh (for tractors/loaders/backhoes) to 3,530 kWh (for off-highway tractors). The ability of these battery sizes to supply enough energy for the equipment to carry out the work on a day-to-day basis is studied in Section 4.1.3, which will provide further insight.

Table 4-4. Required battery sizes for equipment types

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

It should be noted that the battery electric top handlers, developed by BYD and Taylor Machine Works, that are being demonstrated at the Ports of Los Angeles and Long Beach can be considered as a reference to determine how large of a battery pack can be accommodated in an off-road equipment. These top handlers have 931 kWh Lithium Iron Phosphate ($LiFePO_4$) battery packs [125]. Based on the final battery sizes in Table 4-4, it can be stated that the determined battery sizes for off-highway tractors and scrapers are probably too large to be fit onto the equipment. For these equipment types, hybridization may be a more realistic technology option at this time. However, even after considering the existence of a 931 kWh equipment, concerns of charging power requirement based on operation schedule and effects of the battery weight remained. Each equipment type could be uniquely affected by these issues based on their activity, even if these issues did not affect the top handler. The next sections investigate these concerns.

4.1.3 Activity Simulation and Charging Power Requirement

To evaluate the operational feasibility of battery electric equipment, the 19 pieces of equipment whose engine brake power could be calculated or estimated were simulated with a battery electric powertrain consisting of a UQM PowerPhase 145 heavy-duty electric motor, and a battery pack with the usable sizes presented in Table 4-4 for each equipment type. The simulation assumes that the electric equipment is used to perform the work in the collected in-use activity data to see if the determined battery size is sufficient to accomplish the work that was performed by its diesel counterpart. In addition, the simulation was done in a time series fashion in order to take the battery recharging requirement into account. To do that, the second-by-second data recorded when the equipment was in operation were considered as “active events”, and the time gaps between two consecutive sets of active events were considered as “inactive periods”. At the very beginning of the recorded data, the equipment is assumed to have a full charge of usable battery (i.e., 100% state of charge or SOC for the usable battery). For each active event or second of equipment operation, the battery supplies the necessary power for the equipment to carry out the work. The battery continues to supply power until the usable battery is exhausted (i.e., 0% usable battery SOC), after which the simulated electric equipment is considered to be unable to perform additional work until its battery is recharged. It should be noted that 0% usable battery SOC in this simulation means draining out the usable battery. However, the equipment will still be able to use the remaining 30% reserve energy in the equipped battery if needed, for example, to work beyond the limits of the usable battery or to travel to the charging station. As this simulation is carried out to determine the efficacy of the usable battery to perform the activity it has been sized with (thus verifying the usable battery sizing method), the simulation considers only this battery size.

Inactive periods provide opportunities for charging the battery of the simulated electric equipment. However, inactive periods less than or equal to two hours were considered as “short breaks”, during which the usable battery SOC of the simulated electric equipment remains unchanged. The assumption here is that short breaks may not provide sufficient time to take the equipment to a charging station or set up other forms of charging arrangement. During inactive periods longer than two hours, the simulated electric equipment is assumed to be charged by a charging station until the next active event or reaching 100% usable battery SOC, whichever comes first. On most days, any equipment would have at least one inactive period, usually during nighttime, that can be used for overnight charging of the battery. Depending on the work required, some pieces of equipment may have additional inactive periods during the work shift that can be used for opportunity charging of the battery as well. Note that this simulation assumes that both the overnight charging and the daytime opportunity charging are performed on-site. If there is no charging facility on-site and the equipment needs to travel to one that is far away, then the charging assumption needs to be updated to reflect the charging strategy to be adopted in such a case. For example, the amount of time needed for the equipment to travel to and from the charging facility will reduce the amount of time that it can be charged. Or, if the operator relies on a mobile charging solution such as battery trailer to be delivered to the jobsite in the evening for overnight charging, there may not be energy left in the battery trailer for daytime opportunity charging in the next day.

For operational feasibility analysis, the usable battery sizes in Table 4-4 were considered, along with four different charging power levels: 50 kW, 150 kW, 200 kW, and 350 kW. As some of the battery sizes were quite large, it was essential to investigate the optimal charging power level to attain the maximum activity fulfillment. Without sufficient charging power, these batteries might not gain enough usable battery SOC during available downtime to support the following activity demands.

The simulation result for the rubber tired loader N18016 with 50 kW charger is shown as a “diary plot” in Figure 4-3. Each active event is represented by a dot (“.”) in the figure, placed according to the date and time of the event. The SOC of the usable battery pack is shown in a color scale where dark brown indicates 100% and bright orange means 0%. The values in-between are depicted through shades of these two boundary colors. This plot presents a visual representation of the operating hours and duration of the equipment on a daily basis throughout the whole data collection period, as well as the usable battery SOC at different stages of operation. Diary plots for the other pieces of equipment are given in Appendix G. According to the plot in Figure 4-3, the simulated electric rubber tired loader started with 604 kWh of usable battery when the activity began at 11:00 on September 21, 2018 (dark brown, indicating 100% usable battery SOC). This first active event is barely noticeable on the plot. Nonetheless, it required some energy which was supplied by the battery in this simulation. The battery was discharged based on the calculated power demand for each active event thereafter, and was charged during possible charging periods. Active events where the usable battery had run out, and thus could not supply the required power, would generate red dots (0% SOC of usable battery).

During possible charging periods, the battery was recharged (can be noticed by the change in color), after which some or all of the active events that followed would be satisfied. It should be noted that this charging/discharging simulation does not assume a specific daily work pattern, and is solely based on the real-world activity data collected from the equipment. For example, the data for October 14-17 indicate that the equipment was used during nighttime and rested during daytime. Thus, on these days the battery was charged during daytime. On the other hand, the battery was not recharged during any of the short breaks, and thus the usable battery SOC remained the same over these breaks (the color remains the same). One such example can be seen for the short break on October 9 around 12:50.

The equipment was able to fulfill all the activity demands (Table 4-5), as intended by the battery sizing strategy. There appears to be a very bright orange dot on October 15; however, this is not 0% usable battery SOC, rather a value very close to 0 (0.07555). The simulated equipment never ran out of battery, which can be verified from "% Active Events Fulfilled" column of Table 4-5. The reason this equipment reached near-zero usable battery SOC on October 15 is that this day is the one with maximum daily power consumption, which the usable battery is sized upon. Because of that, the equipment almost completely drained the usable battery on this day. Despite that, the equipment would not suffer any battery damage as the equipped battery is still retains 30% reserve capacity. Thus, the equipment would run safely if the usable battery was depleted. From this simulation, it is clear that 50 kW charger is sufficient for the rubber tired loader N18016 with the specified battery size.

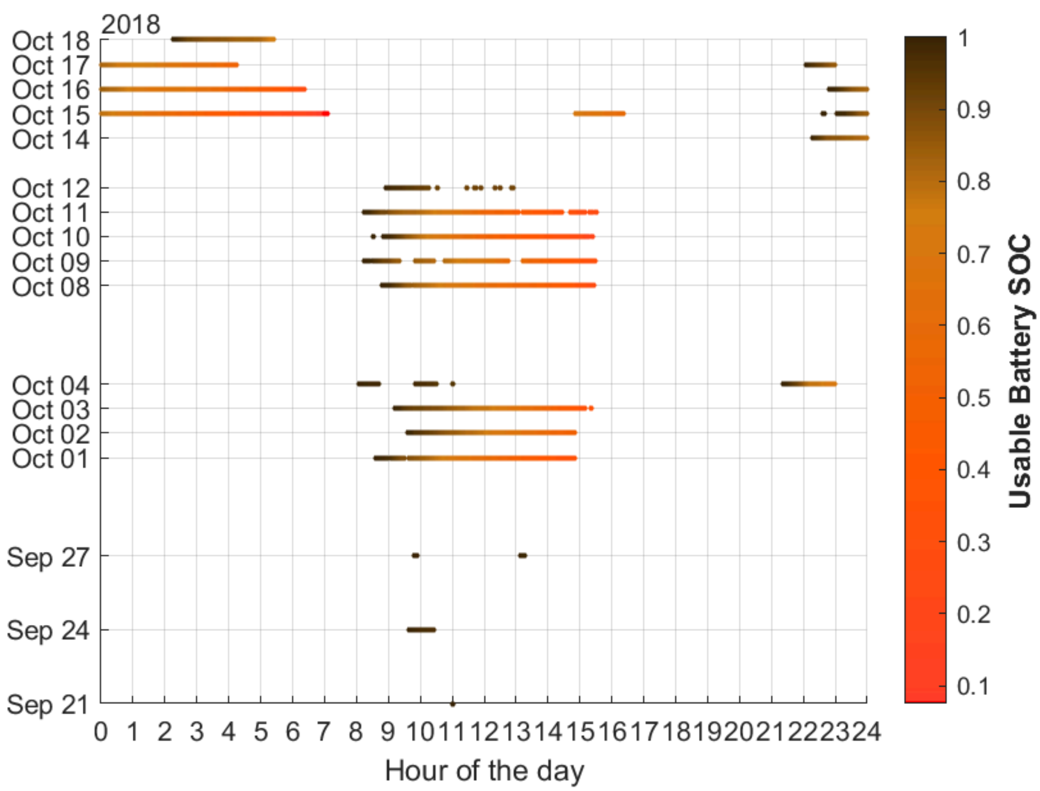


Figure 4-3. Case study for battery electric rubber-tired loader N18016 with recorded activity data, considering 50 kW charger. The SOC colormap shows the usable battery SOC.

Table 4-5 shows the performance statistics from this analysis for all the studied equipment. This table clearly shows that a 50 kW charger is able to charge the batteries enough to fulfill all the recorded activity demands for four equipment types—excavator, grader, rubber tired loader, and tractor/loaders/backhoe. There is no need for higher charging power levels, which are costlier, for these equipment types. On the other hand, two equipment types—off-highway tractor and scraper—can benefit from higher charging power levels (marked in green in Table 4-5) because of their very large battery sizes. Table 4-5 shows that 200 kW and 150 kW chargers are needed for off-highway tractor and scraper, respectively, while no equipment type requires 350 kW charger.

Table 4-5. Performance of the simulated electric equipment with full-capacity battery sizes and different charging powers

Equip-ment Type	Usable Battery Size (kWh)	Equip-ment 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

The effect of higher charging power level on the usable battery SOC can be clearly seen by comparing Figure 4-4 and Figure 4-5. The scraper N18043 has a full-capacity battery size of 1,423 kWh. Figure 4-4 shows that the 50 kW charger is not able to fully charge the usable battery even from overnight charging, as is evident from the usable battery SOC plot being light green or yellow at the beginning of many days. On the other hand, the 150 kW charger is able to fully charge the battery overnight for all the operating days, as shown in Figure 4-5. The seemingly red dot in Figure 4-5 is due to the usable battery SOC being near-zero but not zero.

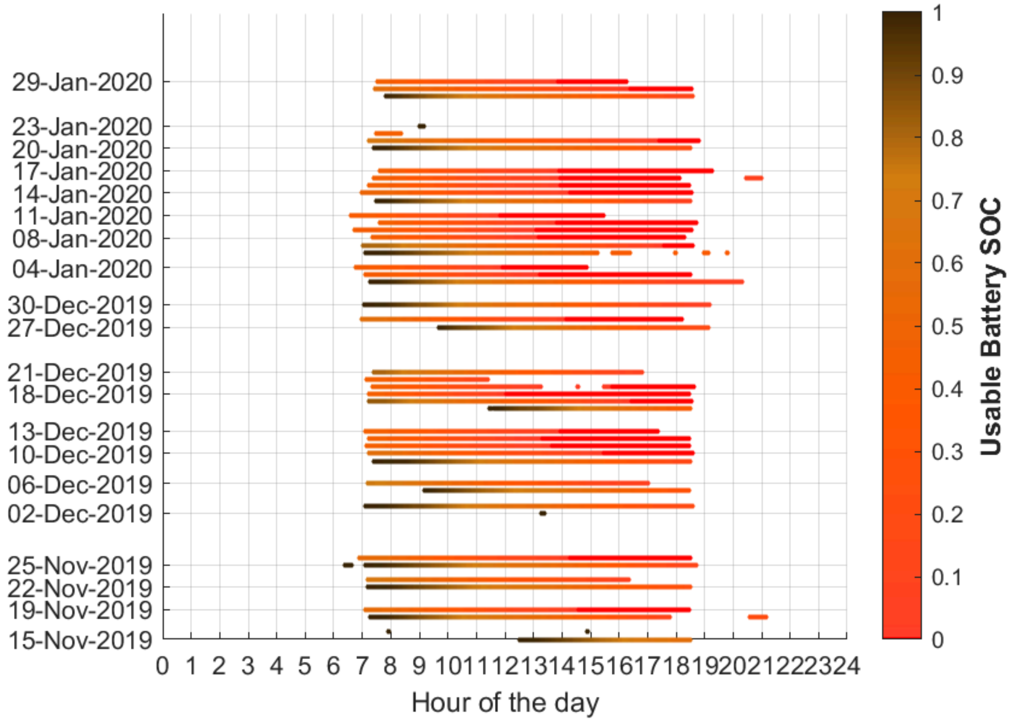


Figure 4-4. Case study for battery electric scraper N18043 with recorded activity data, considering 50 kW charger.

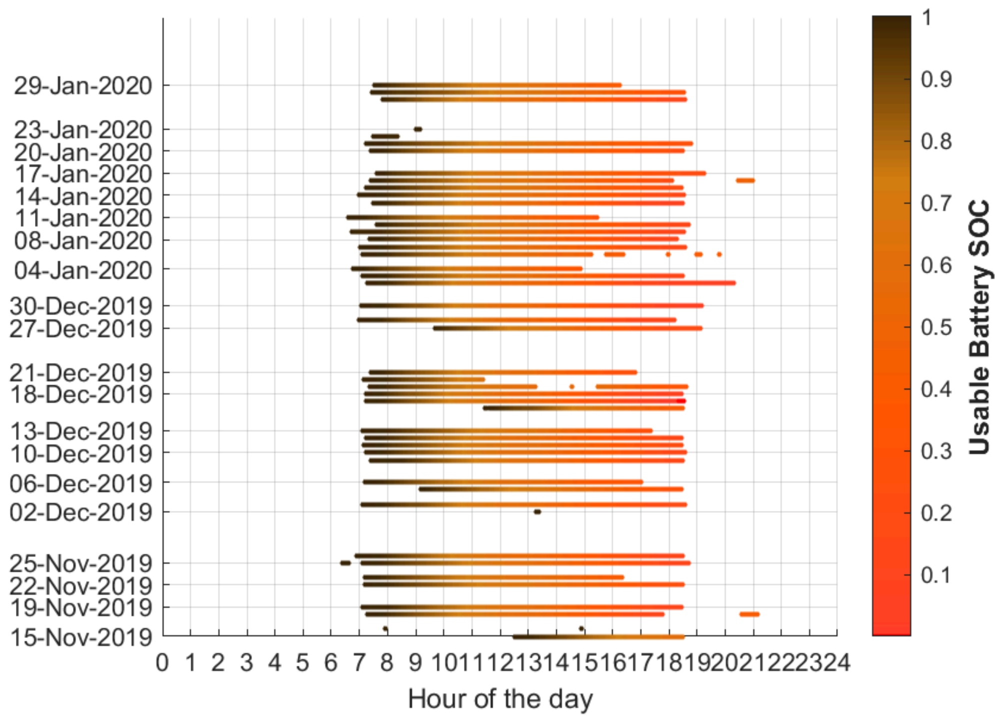


Figure 4-5. Case study for battery electric scraper N18043 with recorded activity data, considering 150 kW charger.

It should be noted that these simulation results are conservative because the minimum efficiency operation of the electric motor was assumed. Also, the simulation did not consider regenerative energy that could be captured by the electric motor acting as a generator during equipment operations. Thus, the required usable battery sizes could potentially be smaller. In addition, this simulation assumed an extra 30% battery capacity as a reserve, which is also conservative. On the other hand, this simulation did not account for the impact of battery weight on the energy consumption of the equipment when they move around. All these factors should be considered when refining the simulation for the purpose of designing specific equipment.

4.1.4 Hybridization and Electrification

Based on the motor and battery sizing analyses, it is clear that the off-highway tractors and the scrapers are not fit for adopting a full battery electric powertrain at this point in time. There is no motor suitable to meet the torque demands of the off-highway tractors, considering a single-motor setup (Table 4-3), and the required battery sizes for both off-highway tractors and scrapers are unrealistically large (Table 4-4). Therefore, these two construction equipment types can be suggested for hybridization. In order to determine the nature of hybridization appropriate for these two equipment types, hybrid electric equipment with similar specifications that are being sold or demonstrated by manufacturers can be referenced. An assumption is that the hybrid powertrain configuration and technology used in those equipment may be used to hybridize off-highway tractors and scrapers as well.

Table 4-6 shows some basic specifications of the equipment requiring hybridization. No data on scraper N18043 is available. Table 4-7 shows the specifications of demonstration equipment that are similar to the specifications from Table 4-6 in some aspects, for example, having similar weight or rated power. The information in Table 4-7 are compiled from Appendix B. Most of these equipment are not on the market, and thus, their detailed specifications are mostly unavailable. Therefore, only the ones with some useful information are included in Table 4-7. Even for those equipment, only the information on weight, rated power, certification tier, and electrification technology can be obtained. It can be seen that in Table 4-7, hybrid equipment having higher weights (loaders and mining trucks) are all diesel-electric. The weights and rated power of the equipment in Table 4-6 are comparable to these. Specifically, the weight and rated power of the two off-highway tractors are below those of the Liebherr T236 mining truck. Similarly, the weight of the scraper N18023 is comparable to that of the loader John Deere 644K. From these comparisons, the off-highway tractor and scraper types can be suggested to adopt diesel-electric architecture for hybridization. It may also be possible to employ a series hybrid setup for these equipment types. This can be achieved by adding an energy storage to the diesel-electric system, which enables the storage and later usage of regenerated energy (e.g., regenerative braking energy which is otherwise dissipated by retarders in diesel-electric system). Series hybrids and diesel-electrics have simpler systems than parallel and series-parallel hybrids, and designing a parallel hybrid to achieve an optimum performance for each use case can be challenging [126]. Given these reasons, these two equipment types can be recommended for hybridization with diesel-electric or series hybrid technology.

Table 4-6. Specifications of equipment requiring hybridization

Equipment Type	Equipment ID	Manufacturer	Model	Weight (lbs)	Rated Power (hp)	Certification Tier
Off-Highway Tractor	N18021	Caterpillar	836K	143,300	558	4 final
	N18027	Caterpillar	836K	136,687	558	4 final
Scraper	N18028	Caterpillar	627K	37,664	272	4 final
	N18043	N/A	N/A	N/A	N/A	N/A

Table 4-7. Specifications of some demonstration equipment

Equipment Type	Manufacturer	Model	Weight (lbs)	Rated Power (hp)	Certification Tier	EV Technology
Loader	John Deere	944K	117,947	536	Tier 4	Diesel-electric
	John Deere	644K	40,435	N/A	Tier 4	Diesel-electric
Mining Truck	Komatsu	830-1AC	N/A	N/A	N/A	Diesel-electric
	Komatsu	840-E	N/A	N/A	N/A	Diesel-electric
	Liebherr	T236	200,000	1200	N/A	Diesel-electric
Excavator	Liebherr	R 9200 E	420,000	1140	N/A	Battery electric
Agricultural Tractor	Multi-Tool Trac	N/A	N/A	210	N/A	Plug-in hybrid electric

A similar analysis for battery electrification was performed by examining the specifications of available, upcoming, and prototype battery electric equipment listed in Appendix B. The results are presented in Table 4-8, which shows that there exist battery electric agricultural tractors, in both heavy and compact categories. Thus, full electrification of this equipment type is possible, corroborating the earlier technical feasibility analysis results. The same goes for excavator and loader, which are both deemed feasible for full electrification in the technical feasibility analysis and having battery electric models available in both heavy and compact forms. Additionally, Table 4-8 provides information on other equipment types, namely dumper, tandem roller, telehandler, and warehouse vehicle that have battery electric models demonstrated by manufacturers. This indicates that full electrification is also technically feasible for several other equipment types beyond those analyzed in this study.

Table 4-8. Compiled specifications of available, upcoming, and prototype battery electric equipment

Equipment Type	Manufacturer	Model	Weight (lbs)	Rated Power (hp)	Heavy/Compact
Agricultural Tractor	John Deere	SESAM	N/A	N/A	Heavy
	John Deere	Gridcon	N/A	N/A	Heavy
	AGCO	Fendt e100 Vario	N/A	67	Compact
Dumper	Wacker Neuson	DW15e	N/A	N/A	Compact
Excavator	Caterpillar	300.9D	N/A	13	Compact
	Pon Catterpillar	323 Z-Line	N/A	N/A	Heavy
	Komatsu	N/A	10,000	24.4	Compact
	Volvo	EC25	N/A	N/A	Compact
	Wacker Neuson	EZ17e	N/A	N/A	Compact
	Wacker Neuson	EZ26e	N/A	N/A	Compact
	Takeuchi	e240	N/A	N/A	Compact
	Hidromek	H4	N/A	N/A	Heavy
	Libherr	R 9200 E	462971	850	Heavy
	Mecalac	E12	N/A	N/A	Heavy
	JCB	19C-1E	4409	N/A	Compact
Loader	Volvo	L25	N/A	N/A	Heavy
	Volvo	HX2	N/A	N/A	Heavy

	Wacker Neuson	WL20e	N/A	N/A	Compact
	Caterpillar	R13000G LHD	N/A	N/A	Heavy
Tandem Roller	BOMAG	BW 120 AD-5 E	N/A	24.8	Compact
Telehandler	Deutz/Manitou	MT 1135	N/A	82	Heavy
Warehouse Vehicle	John Deere	TE4x2	N/A	6	Compact

5 Cost-Effectiveness of Electrifying Off-Road Equipment

Construction equipment electrification has been receiving increasing research attention in recent times, as this sector stays as one of the last major portions of the transportation sector yet to achieve significant amount of electrification. Electrification has been adopted as the solution to the highly polluting transportation sector. And as research in all facets of vehicle electrification become more sophisticated and purpose-oriented, more affordable electric vehicles (EV) appear as commercial products, and popularity of electric vehicles rise in the medium- and heavy-duty sectors followed by the light-duty segment, the lack of electrification in the off-road equipment sector becomes more apparent.

Traditionally, incentivization has been employed to entice consumers in adopting new technologies which are more expensive than their traditional counterparts. It has been done for many years for on-road electric vehicles. A study conducted on the battery electric vehicle (BEV) incentives in Norway showed that up-front price reduction such as tax and value-added tax (VAT) exemptions is a very effective motivation for consumers to choose BEVs [127] [128]. Around 3400 Norwegian BEV owners participated in the survey leading to this outcome from [127], and 80% of them quoted such exemptions as a critical factor in their BEV adoption. European union countries such as Denmark, Sweden, France, and the United Kingdom all provide some form of incentive for EV purchase [129]. EVs have been highly incentivized in China since 2009 [130].

In the United States (US), incentives have been an important factor to provide significant impetus to the EV market [131]. Following in those footsteps, several incentives has been initiated to proliferate the use of cleaner technologies in the off-road sector. The state of California offers multiple such incentives. The Funding Agricultural Replacement Measures for Emission Reductions (FARMER) program of the California Air Resources Board (CARB) has been funding equipment used in agricultural operation such as tractors, pump machines, and heavy-duty trucks [132]. CARB's Clean Off Road Equipment Voucher Incentive Project (CORE) program incentivized specific zero-emission off-road freight equipment [133] [134] [135].

The Surplus Off-Road Opt-In for NOx (SOON) program of the South Coast Air Quality Management District (South Coast AQMD) provided funding assistance to large fleets to purchase commercially available low-emission heavy-duty engines, oxides of nitrogen (NOx) exhaust retrofits, repowers or equipment replacements [136] [137] [138]. They also host the Carl Moyer program, which funds replacing, repowering, and retrofitting older, heavy-duty diesel vehicles and equipment with an objective to commercialize the cleanest technologies available. The program funds a wide range of off-road projects including construction, agricultural, cargo handling, marine engine, locomotive, and ship-side shore power. Moreover, it also funds select on-road categories as well as eligible infrastructure procurement for clean energy transportation [139].

The San Joaquin Valley Air Pollution Control District (SJVAPCD) offers funds for replacing mobile, self-propelled, off-road equipment with diesel engine rated at 25 horsepower or greater. The funding amount is determined by the equipment type and horsepower. For eligibility, the replacement equipment need to satisfy additional requirements on regional operation as well as emission standards as regulation [140]. SJVAPCD also has a trade-up program specifically for agricultural tractors which grants funding based on application type and horsepower [141].

There is thus a raft of incentives available for adopting zero-emission technologies in the off-road equipment sector. However, there are hardly any capable commercial electric equipment which can be acquired by utilizing these grants. Because of this, when funding electric equipment, the incentive programs has been restricted to certain categories. For example, FARMER funded electric utility terrain vehicles (UTV) having a maximum horsepower of 25, and the electric equipment Carl Moyer managed to fund are cargo handling equipment.

The incentive programs require deliberate designing to focus on certain equipment types and sizes. They also have certain criteria for a funding application to meet to be eligible for funding. As mentioned earlier, these include operation and emission clauses. But these come after the focus group (e.g. equipment type, size etc.) has been identified. To determine the group, cost-effectiveness of incentive acts as a major decision variable. It basically shows an estimate of how effective an incentive is to achieve its goal. If emission reduction is the primary objective, then the cost-effectiveness shows how much money is spent to achieve a unit of emission reduction. Programs such as Carl Moyer utilizes cost-effectiveness to determine eligibility of certain grant applications, as well as to determine how much fund can be allocated to certain categories based on cost-effectiveness thresholds specific to those categories [139].

To determine the cost-effectiveness of any future incentive in any category, it is necessary to determine the amount of fund required, and the potential effects of that incentive. For example, if an incentive is designed to replace diesel excavators with electric ones for emission reduction, incentive cost-effectiveness calculation will require the funding needed to do so, and the potential emission reduction by doing so. But the requirement of knowing the funding amount beforehand makes it difficult for designing incentive programs for off-road equipment. Incentives should be launched for equipment types that will provide the most benefit; and to identify them, cost-effective analysis needs to be done on all the equipment types. However, there are very few commercial off-road equipment available currently [142], and even for them, the pricing information is often unavailable in the public domain. For many equipment types, electric versions do not even exist. Prototypes exist for some type, but their prices are far too high to extract any meaningful cost-effectiveness analysis. Such an example is the Cat 323F Z-line excavator, which costs almost three times more than a comparable diesel-powered equipment [143]. This hinders the development of effective incentive programs, thus the market loses potential for development, and in turn affects incentive development.

To avoid this cycle of inconvenience, a cost estimation strategy for off-road equipment was developed in this work which utilized component sizing to finally provide funding estimates required to deploy electric models for different types and sizes of equipment. These estimated funding amounts was then used for cost-effectiveness analysis of each type and size of equipment, considering corresponding emission reductions. Suggestions were made on the possible use of the developed cost-effectiveness analysis framework in selecting the most favorable equipment types and sizes for providing incentives. Furthermore, use of the proposed system for incentive implementation strategies for different equipment type and size was also demonstrated. Multiple assumptions were made for component sizing and cost estimation. To address the possible changes of the assumed values, a sensitivity analysis was also conducted varying 10 input parameters over 3 values each, resulting in 59,049 scenario analysis. Sample results from the sensitivity analysis was shown for select demonstration equipment type and size selections for comparison with the base case. These results recognized the possibility of the assumptions changing to certain extents, and provided information on the degree of change in funding cost-effectiveness should the input assumptions change to these extents.

5.1 Data

For the required data on different off-road equipment types, model years, horsepower (HP) bins, populations, fuel consumptions, and emissions, we used the OFFROAD2017 model [3]. It is the most comprehensive database of California statewide population and activity of off-road equipment. Even though we have collected more accurate and granular activity data from a number of equipment, and utilized the data for 17 equipment across 6 different types in the previous task of the project, the sample size is not large enough to analyze statewide funding scenarios. Because of that, OFFROAD2017 was used in this task. Figure 5-1 shows the organization of data in the OFFROAD2017 dataset. For presentation purpose, only the values used in this study are shown here; numbers are also rounded up, and examples from different calendar years are shown. Each row shows aggregated emissions in standard US tons per day (tpd), fuel consumption in gallons per year (gpy), and population data for a certain equipment type, HP bin, and model year for each calendar year. In addition to these, the database also provides data on other emission types such as reactive organic gases (ROG), particulate matter with a diameter of 10 microns or less (PM10), sulfur oxides (SO_x), ammonia (NH_3) etc.

The project duration (for the replacement of an old diesel off-road equipment with a new electric one) was assumed to be 10 years, based on the current warranties on electric vehicles (EVs) [144]. Thus, data for 10 calendar years (2021-2030) were obtained from the OFFROAD2017 database. The compiled data were cleaned to remove entries having no HP bin data or having zero population.

Calendar Year	Equipment Type	Model Year	HP Bin	NO_X (tpd)	CO_2 (tpd)	PM2.5 (tpd)	Fuel (gpy)	Total Population
2021	A/C Tug Narrow Body	1969	50	0.0003	0.0213	0.0000	689.7398	2
2021	A/C Tug Narrow Body	1969	100	0.0008	0.0275	0.0001	891.1598	1
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
2023	Excavators	1963	100	0.0005	0.0183	0.0000	594.4117	2
2023	Excavators	1969	50	0.0004	0.0325	0.0001	1054.3765	5
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
2025	Port Yard Tractor	2009	600	0.0000	0.0020	0.0000	64.2467	0
2025	Port Yard Tractor	2010	175	0.0017	0.8067	0.0000	26173.3418	4
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .

Figure 5-1. Data organization in the OFFROAD2017 model.

5.2 Component-Based Funding Amount Estimation Model

The funding amount was considered to be the cost difference between a diesel equipment and an equivalent battery electric equipment. As battery electric equivalents for the majority of the off-road equipment types were not commercially available, and as most of the available ones were in prototype stage and/or without any pricing information, a component-based cost estimation methodology was formulated. This approach estimates the costs of BEV components (electric motor, battery, additional electric vehicle systems), and the component costs of the internal combustion engine (ICE) powertrain they would replace (diesel engine and fuel tank) in a pre-transmission drop-in replacement strategy, as shown in Figure 5-2. The motor would be supplying the exact same power demands previously provided by the engine. This approach was adopted on multiple occasions as a primary step to electrify construction equipment [145], achieves electrification of both drivetrain and hydraulics, and serves well to conduct preliminary feasibility analysis such as battery sizing. The charging infrastructure cost was not considered in the primary analysis of this study, as the charging mechanism for off-road equipment is still not clearly defined. Unlike on-road electric vehicles, off-road electric equipment might need creative charging solutions such as mobile chargers. But as any established charging strategy for these equipment is yet to materialize and more research is needed, the equipment charging infrastructure related costs were not included in this analysis.

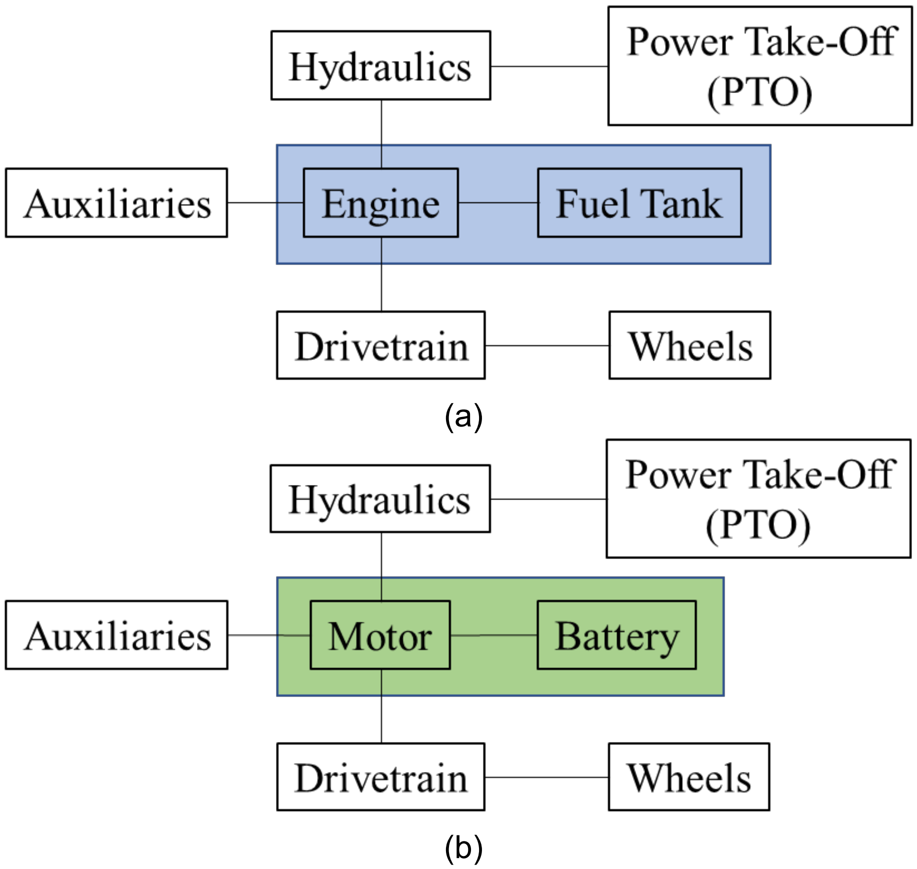


Figure 5-2. (a) General architecture of construction equipment (adapted from [146]); (b) Single-motor pre-transmission drop-in replacement considered in this study. A motor powered from a battery pack was considered to replace the engine and the fuel tank, keeping everything else the same.

Available per-unit costs of the components were gathered from literature. For each equipment type and HP bin, components were sized according to corresponding calendar and model years. The sizes were then used in conjunction with the per-unit costs to estimate the component costs. The component sizing and cost estimation methods are detailed in the next few subsections.

5.2.1 BEV Components

5.2.1.1Battery

From OFFROAD2017 data, it was observed that equipment were typically used less as they get older (their fuel consumption decreases as calendar year progresses). Therefore, it can be construed that the newly purchased equipment under any funding program will be the most used, and will not necessarily be used at the same level as the old equipment it will replace. The proposed method thus assumes that the new replacement equipment to be used the most, contrary to the assumptions used in existing funding programs such as Congestion Mitigation and Air Quality (CMAQ) Improvement Program and Funding Agricultural Replacement Measures for Emission

Reductions (FARMER) Program [147] [148]. Based on this assumption, the following methodology was formulated.

Battery size was derived from the daily energy needs of the corresponding equipment. For the energy needs of each equipment type in each calendar year, HP bin, and model year, the fuel consumption data from OFFROAD2017 was used. OFFROAD2017 provides this data in gallons per year (gpy), for the entire model year population. Gallons per day (gpd) fuel consumption for a single piece of equipment was derived from this data for each equipment type in each calendar year, HP bin, and model year. Then, the maximum of daily fuel consumption values was taken to determine the maximum energy consumption of that bin. Now, the diesel engines converted a fraction of the consumed fuel energy to meet the energy demands of the equipment. This fraction is the engine efficiency. For battery electric equipment, this fraction of energy needs to be delivered by the battery, and thus this is taken as the standard battery size for each bin. The battery sizing procedure is described in the following.

$$fuel\_gpd\_per\_equipment = \frac{fuel\_gpy}{population \times number\ of\ operating\ days\ in\ a\ year} \quad (1)$$

The OFFROAD2017 dataset is based on survey activity data, reported on an annual basis. This is a key limitation of this data to use it in such exercises. Therefore, it is needed to seek supplemental instrumented data. Reference [149] appears useful here, by providing information on data collection process of 70 pieces of off-road equipment across 12 different types. It lists the duration of data collection period, and the number of days each equipment operated in that duration. For each equipment, the percentage of operating days within the data collection duration can thus be calculated from equation (2):

$$\text{percentage of operating days} = \frac{\text{number of operating days within data collection duration}}{\text{data collection duration}} \times 100\% \quad (2)$$

This gives the percentage for each piece of equipment. However, to use this percentage in the large dataset of OFFROAD2017, where far more equipment types exist, a general percentage value is needed; which can be achieved by summing up the number of operating days within data collection duration as well as the data collection duration over all equipment pieces irrespective of type, and then using those values in Equation (2). With more data, it is possible to further increase the accuracy of this result. The researchers at the University of California, Riverside (UCR) have previously collected data from 35 off-road construction equipment. Using data from those equipment along with [149] gives the percentage of operating days as 51%. Data used for this calculation, and the changing percentage of operating days with increase in data in shown in Appendix H. The number of operating days in a year can now be calculated using this value, using equation (3):

$$\text{number of operating days in a year} = \text{number of days in a year} \times \text{percentage of operating days} \quad (3)$$

Considering 365 days in a year, the number of operation days finally comes out as $365 \times 51\% = 186$ days. With per-day fuel consumption now determined, battery sizing can now proceed as follows: The maximum grams per day (gpd) fuel consumption was taken as the fuel consumption data (Equation (4)). The energy content of the consumed fuel in kWh was then calculated using Equation (5) [150]. The required battery size (energy capacity) to provide this energy was calculated using this energy consumption value, considering the diesel engine efficiency, and electric motor efficiency (Equation (6)). Equation (6) takes into account the fact that the engine produces less energy than the fuel it consumes (determined by engine efficiency), thus the first part of the equation provides the energy delivered by the engine to the drivetrain. Also, the motor in a battery electric equipment need to consume more energy from the battery to provide the energy to the drivetrain (determined by motor efficiency). The second part of the equation involving the motor efficiency takes this consideration into account.

$$fuel\_gpd\_per\_equipment = \max(fuel\_gpd\_per\_equipment) \tag{4}$$

$$\text{energy of consumed fuel (kWh)} = fuel\_gpd\_per\_equipment \times 40.7 \tag{5}$$

$$\text{battery size (kWh)} = (\text{energy of consumed fuel (kWh)} \times \text{engine efficiency}) \div \text{motor efficiency} \tag{6}$$

For the base case analysis, engine efficiency was taken as 35%. This value was chosen as a conservative baseline; existing literature on off-road engine efficiency suggested values as low as 39% [151]. Motor efficiency was obtained from the motor efficiency map of UQM PowerPhase 145 heavy-duty electric motor, sourced from the powertrain simulation software Autonomie [122]. The motor can operate at different efficiencies based on different operating conditions. For the base case analysis, the minimum efficiency value, which is 72%, was considered.

To calculate the battery cost, per-unit battery cost ($/kWh) was obtained from literature [152]. As shown in Figure 5-3(a), it is projected to decrease over the next several years. Using the best trendline equation (with the best R^2), per-unit battery cost in each calendar year in the analysis window (2021-2030) was obtained, and all the corresponding battery costs were calculated from the battery size determined by equation (6) using the following formula:

$$\text{battery cost (\$)} = \text{battery size (kWh)} \times \text{per-unit battery cost (\$/kWh)} \tag{7}$$

5.2.1.2Motor

The replacement battery electric equipment were specified to have motor power similar to the corresponding HP bins listed in OFFROAD2017. Motor ratings in kW were obtained from the HP bin values from the following equation [153]:

$$\text{motor rating (kW)} = \text{HP bin}/1.341 \tag{8}$$

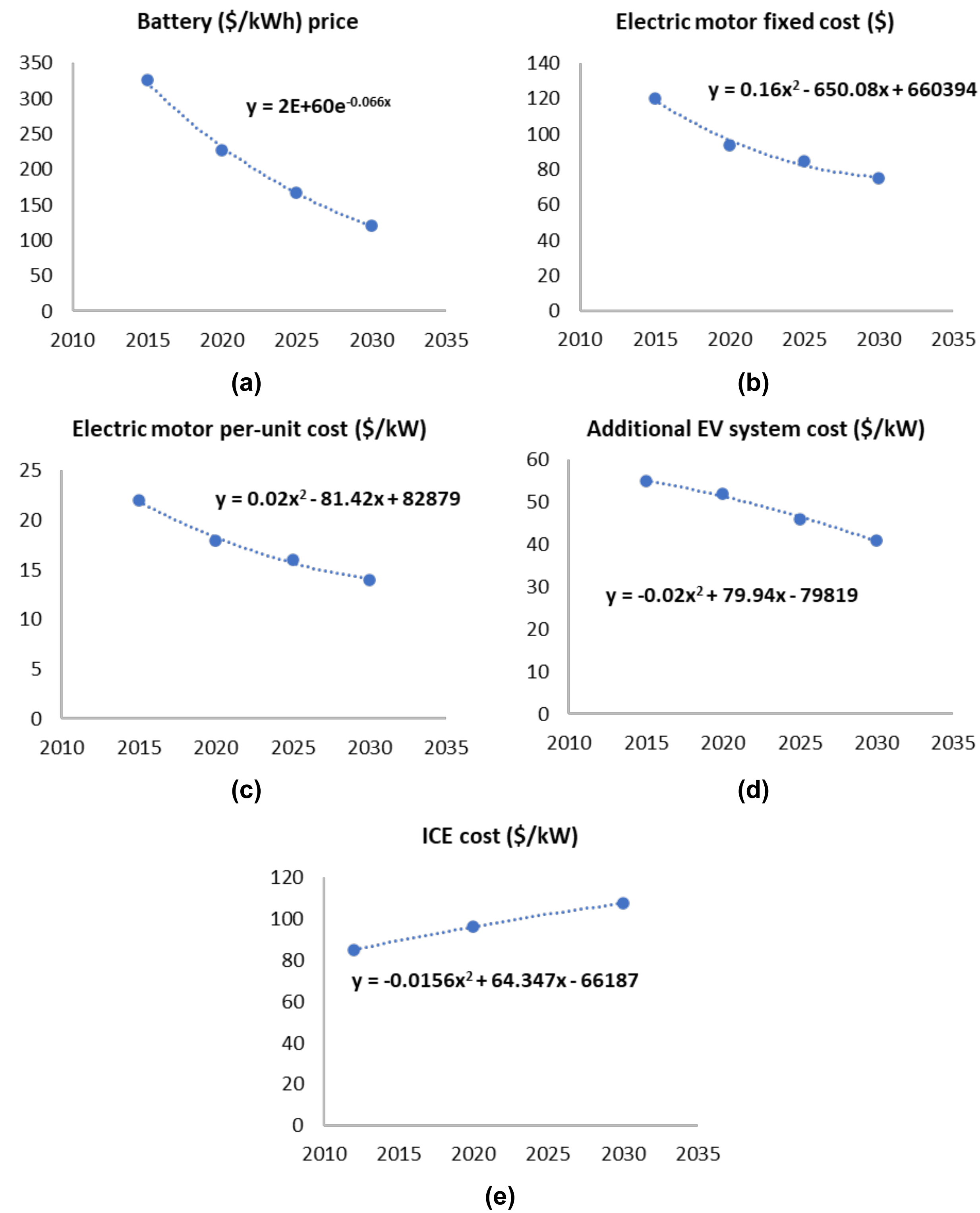


Figure 5-3. Component cost projections [152] [154] and their trendline equations.

Two components of motor cost were found in literature [152]: fixed cost and per-unit cost. Both were dependent on the calendar year, and went down with advancing years

(Figure 5-3(b), Figure 5-3(c)). The best trendline equations were used here as well to get the costs for each calendar year. The following equation then gave motor cost based on the motor size:

$$\text{motor cost (\$)} = \text{motor fixed cost (\$)} + (\text{motor rating (kW)} \times \text{per-unit motor cost (\$/kW)} \tag{9}$$

5.2.1.3 Additional EV Systems

The costs of additional EV systems such as controllers and converters are dependent on the kW ratings [155], which were taken from the determined motor ratings. The literature provided a calendar year dependent per-unit cost (Figure 5-3(d)), which was used to get the additional EV system cost using the following equation:

$$\text{additional EV system cost (\$)} = \text{motor rating (kW)} \times \text{per-unit additional system cost (\$/kW)} \tag{10}$$

5.2.1.4 Advanced Engineering Cost

The BEV component costs were based on on-road vehicles. It was assumed that for implementing these components in off-road equipment, additional engineering efforts would be required. These efforts could be needed for adapting the components to different vehicle structures, weatherproofing, enhancing ruggedness, etc. There could also be some research and development costs to manufacture EV components fully capable of serving off-road equipment. Integrating power take-off (PTO) components could also increase the cost. Because of these, an advanced engineering cost was added to incorporate these additional considerations into the cost estimation.

$$\text{advanced engineering cost} = \eta_{eng} \times (\text{battery cost} + \text{motor cost} + \text{additional system cost}) \tag{11}$$

η_{eng} is the fraction of the aggregate component cost needed for advanced engineering. For the base case analysis, it was taken as 10% [156].

5.2.1.5 Total EV Component Cost

The total EV component cost was determined using all the EV-related costs, as shown in the following equation:

$$\begin{aligned} \text{EV component cost} = \; & \text{battery cost} + \text{motor cost} + \text{additional system cost} \\ & + \text{advanced engineering cost} \end{aligned} \tag{12}$$

5.2.2 ICEV Components

5.2.2.1 Internal Combustion Engine

Per-unit internal combustion engine (ICE) cost by calendar year is shown in Figure 5-3 (e). The cost was expected to increase over time because of new technology integration, primarily to meet stricter regulations on exhaust after-treatment [154]. The best trendline equation was used to obtain per-unit ICE costs for each calendar year.

The ICE ratings were obtained from the HP bin values, and the costs were derived using the calendar year-wise per-unit cost and the ratings:

$$\text{ICE rating (kW)} = \text{HP bin}/1.341 \tag{13}$$

$$\text{ICE cost (\$)} = \text{ICE rating (kW)} \times \text{per-unit ICE cost (\$/kW)} \tag{14}$$

5.2.2.2 Fuel Tank

Fuel tank cost can vary widely based on its volume and target application. Fuel tank cost data for the wide range of equipment types included in this analysis were unavailable. Also, the fuel tank prices available online are primarily for used equipment, and those vary widely based on usage, equipment type, and other factors. Thus, fuel task cost of $482 found in the literature [155] was used.

5.2.2.3 Total ICEV Component Cost

The total ICEV component cost was determined using all the ICEV-related costs, as shown in the following equation:

$$\text{ICEV component cost} = \text{ICE cost} + \text{fuel tank cost} \tag{15}$$

All the trendline equations for the different components, and their R^2 values are shown in Figure 5-3.

5.2.3 Required Funding Amount

The difference in EV and ICEV component costs was assumed to be the required funding amount. The assumption was that producing an equivalent battery electric equipment would require replacing the abovementioned ICEV components with the EV ones. Thus, the total component cost difference between the two types of powertrain is the price premium for purchasing electric equipment in lieu of diesel equipment. It is assumed that this price premium would be covered by incentive funding. Based on this assumption, the required funding amount for each piece of equipment can be calculated as follows:

$$\text{funding per equipment (\$)} = \text{EV component cost - ICEV component cost} \tag{16}$$

The price premium in reality, however, could be different as manufacturers may include research and development costs, organizational operating costs, profit, etc. Warranty and insurance costs could also affect the price. However, as these information were not available, the required funding amount obtained through the stated assumptions was used in the cost-effectiveness analysis of incentive funding.

5.3 Emission Reduction and Funding Cost-Effectiveness

5.3.1 Emissions Reduced

For each calendar year, OFFROAD2017 provides the aggregate tons per day (tpd) emissions from each equipment type, HP bin, and model year. Across calendar years, OFFROAD2017 emissions account for the changing equipment population of different model years, changes in the level of activity (operating hours) for equipment of different model years, higher emission factors (gram per operating hour) for older equipment, and increases in emission factors as equipment get older.

For the cost-effectiveness analysis, emission values are required in tons per year (year), which were calculated from the tpd values using the following equation:

$$\text{emission (tons per year)} = \text{emission (tons per day)} \times \text{number of operating days in a year} \tag{17}$$

where, $\text{number of operating days in a year} = 186$

Emissions were calculated for three pollutants: CO_2, NO_X, and PM2.5. These emission values were considered to be the amount of emissions reduced as a result of replacing a diesel equipment with a battery electric equivalent.

5.3.2 Cost-Effectiveness of Incentive Funding

Cost-effectiveness of incentive funding can be derived from the following equations:

$$cost\ effectiveness\ of\ funding\ dollars = \frac{Capital\ Recovery\ Factor \times Funding}{emission\ (tons\ per\ year)} \tag{18}$$

where,

$$Capital\ Recovery\ Factor\ (CRF) = \frac{(1 + discount\ rate)^{project\ duration} \times (discount\ rate)}{(1 + discount\ rate)^{project\ duration} - 1}$$

and

$discount\ rate = 0.01$ [139]

Using the three emission reduction values (CO_2, NO_X, and PM2.5) resulted in three different cost-effectiveness measures, one for each of CO_2, NO_X, and PM2.5, respectively. This provides the opportunity to determine the effectiveness of incentive funding in reducing specific pollutants.

5.4 Results

The cost-effectiveness results are compiled and provided in Appendix I. In this section, heat maps were created to aid the visualization of results obtained in this analysis. Using these heat maps, it is possible to quickly compare emissions and funding cost-effectiveness across multiple parameters, including equipment type, HP bin, calendar year, and model year. The heat maps can be generated for:

- Each equipment type
- Each model year in each calendar year
- Individual emissions of CO_2, NO_X, and PM2.5
- Replacing a single piece of equipment as well as the whole equipment population

Examples of heat maps of emissions and funding cost-effectiveness are shown and discussed in the following subsections.

5.4.1 Emissions

For an example case of replacing excavators in the 175 HP bin from calendar year 2021 to 2030, heat maps of the three emission types are shown in the following two figures. Figure 5-4 shows emissions from a single piece of equipment across the 10 calendar years, broken down by model year. Figure 5-5 shows emissions from the whole population of excavators in the 175 HP bin. There are multiple model years of equipment for a certain type and HP bin, in a certain calendar year. This is shown for the calendar year 2021 in Figure 5-1. The figures below are essentially matrices where calendar years are placed along the Y-axis and model years along the X-axis. The color in each cell of these matrices represents the amount of emissions caused by the equipment of that model year in that calendar year. For certain cells, the emission values are not present in the OFFROAD2017 database. These cells are colored white. For example, there is a series of white cells on the upper right of every heat map. This is because the latest model year available in calendar year 2021 is model year 2022. Similarly, the latest model year available in calendar year 2030 is model year 2031.

It can be observed from Figure 5-4 that for each calendar year, the newer model year equipment generate a higher amount of CO_2. This is due to the higher usage of new equipment, and thus, fuel consumption and CO_2 emission. On the other hand, the newer model year equipment produce less NO_X and PM2.5 emissions as they comply with stricter emission standards. Among the three emission types shown here, CO_2 outweighs the other two in quantity.

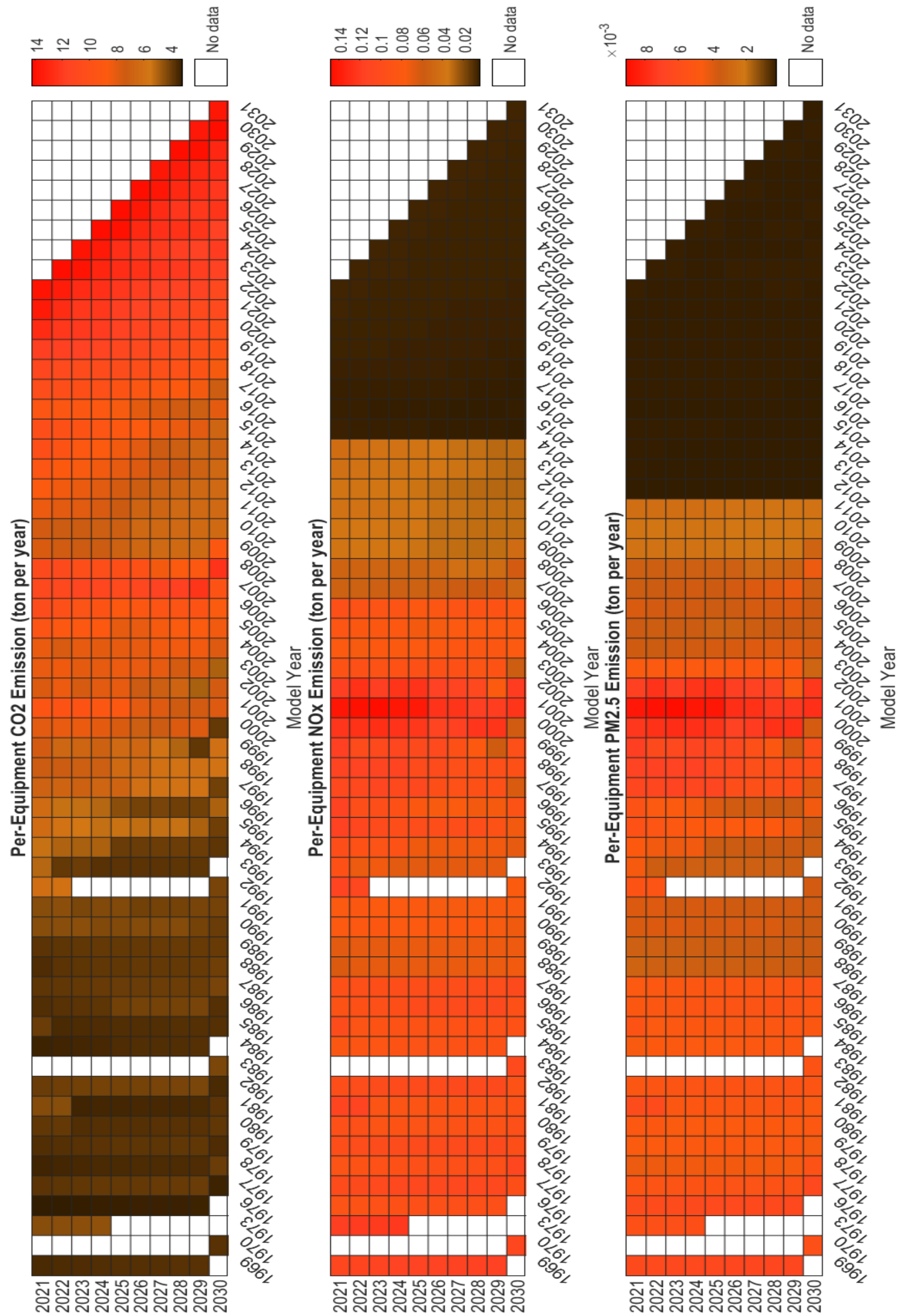


Figure 5-4. Per-equipment emissions produced by Excavators in the 175 HP bin.

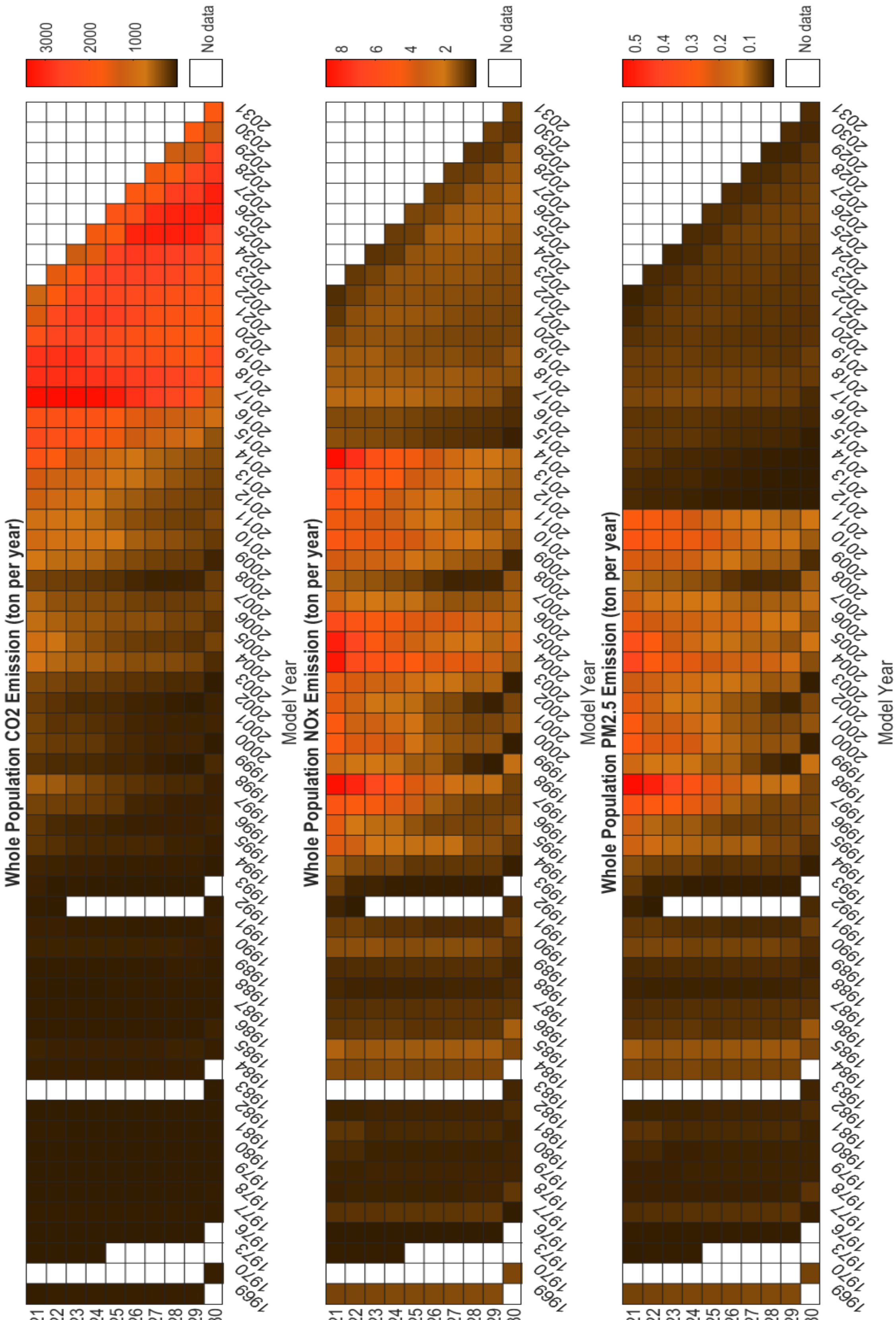


Figure 5-5. Whole population emission produced by Excavators in the 175 HP bin.

As the equipment population of different model years are different in each calendar year, the whole population emissions shown in Figure 5-5 are different from the per-equipment emissions in Figure 5-4. The latest model years in each calendar year (e.g., model years 2021 and 2022 in calendar year 2021) tend to have smaller population than the slightly older model years (e.g., model years 2017, 2018, 2019, 2020 in calendar year 2021). Thus, the newer model year population produce less pollution as a whole for all three emission types (CO_2, NO_X, and PM2.5).

Figure 5-4 and Figure 5-5 can be utilized in different decision-making processes. As Figure 5-4 shows per-equipment emissions, it can be used to determine the amount of certain types of pollution (CO_2, NO_X, and PM2.5) caused by certain equipment types and model years in certain calendar years. This can be useful to determine the efficacy of funding a specific number of certain equipment, or to determine the impact of approving certain grant applications. Figure 5-5, on the other hand, shows the emissions of whole model year populations. Thus, it is useful while deciding on regulations to remove certain type and model year equipment from operation, invoked from certain calendar years.

5.4.2 Funding Cost-Effectiveness

The results of funding cost-effectiveness are presented in the same way. From the funding agency's perspective, in developing an incentive funding program with a fixed amount of available funding, it would be necessary to focus on certain equipment types, HP bins, and model years. Additionally, the program timeline would also need to be decided. In a figure format similar to Figure 5-4 and Figure 5-5, it would be possible to determine the targeted model years and the program timeline, but only if the specific equipment types and HP bins have already been decided. To support the decisions on the equipment types and HP bins to target, an additional layer of heat map was created for funding cost-effectiveness values, which shows the average funding cost-effectiveness for different equipment types and their HP bins. An example is shown in Figure 5-6.

In the compiled 10-year OFFROAD2017 database, there were 170 equipment types even after the data cleaning, and each had multiple HP bins. Showing all of them in a single figure is not possible. Thus, in Figure 5-6, the five equipment types that were recommended for battery electrification in Section 4 of this report are shown. Also, HP bins above 600 are not included as the off-highway tractors studied in this project--a type deemed infeasible for full electrification at this time--had HP rating of 558. Therefore, only the equipment types and the HP bins determined to be feasible for full electrification according to the current knowledge are shown. Moreover, as equipment in the 25 HP and lower bin are out of the scope for heavy-duty equipment, 25 HP was not included in this heat map as well.

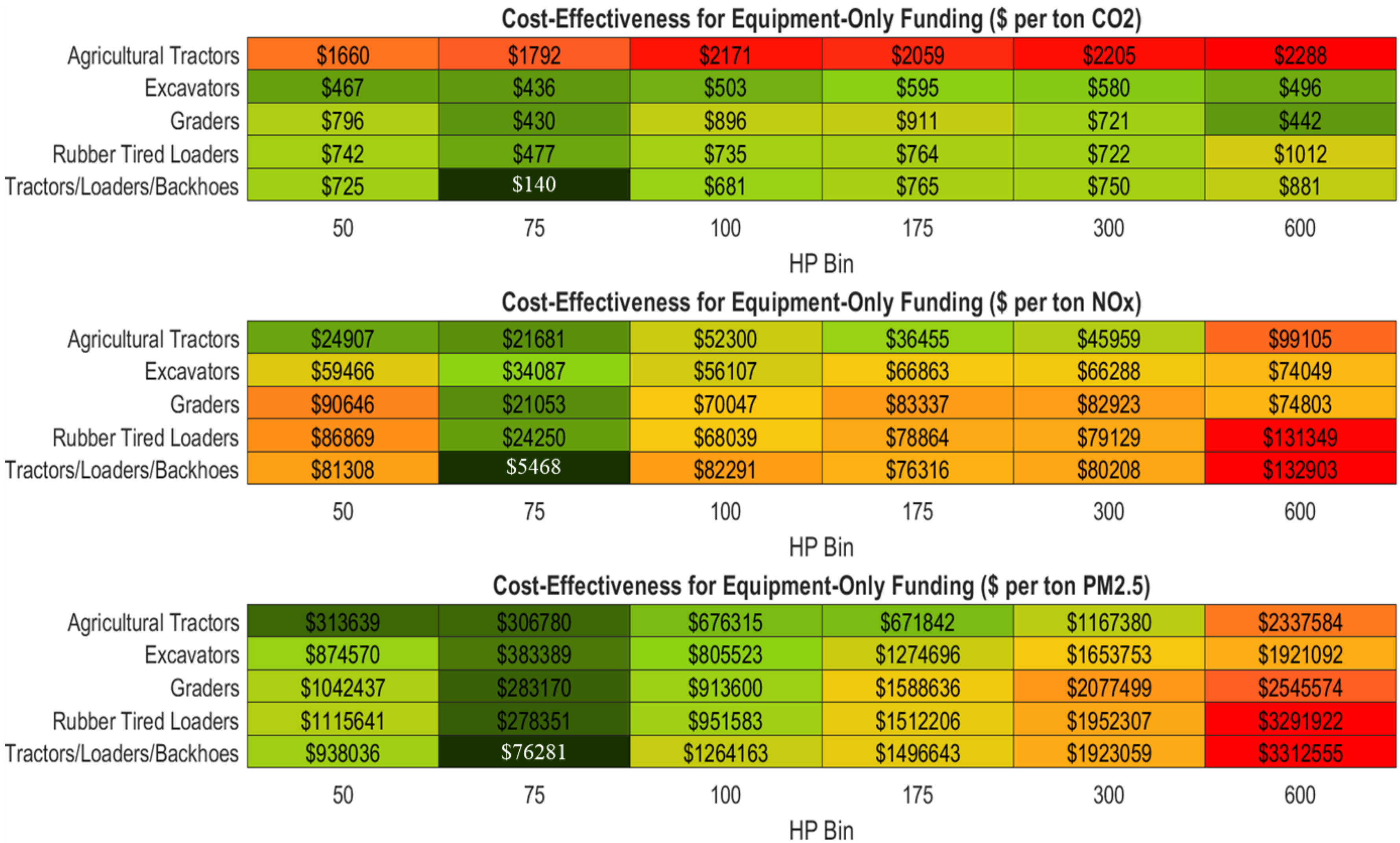


Figure 5-6. Average funding cost-effectiveness for selected equipment types and HP bins. HP bin 75 contains all equipment sizes from 51 horsepower to 75 horsepower, and so on.

From Figure 5-6, it can be seen that targeting certain equipment types and HP bins would be more cost-effective than others, based on their dollars-per-ton values for the different emission types. For example, tractors/loaders/backhoes in the 75 HP bin have the least dollars-per-ton values for all the emission types. Thus, funding battery electric replacement of this equipment type and size would be the most cost-effective on average. Now, with the equipment type and size (HP bin) selected, the heat maps of funding cost-effectiveness for by calendar year and model year can be used to further fine-tune the focus of funding on specific model years in different calendar years.

To be consistent with the emission visualization examples in Figure 5-4 and Figure 5-5, we created a heat map of funding cost-effectiveness by calendar year and model year for excavators in the 175 HP bin, as shown in Figure 5-7. A quick glance reveals that the cost-effectiveness heat maps look to be opposite to the emission heat maps in Figure 5-4 and Figure 5-5. However, the emission and the cost-effectiveness heat maps do not have a strict inverse relationship as the equipment component costs change with each calendar year rather than remaining constant. The funding amount decreases overall with progressing years, as the EV component costs come down while the ICE cost goes up as shown earlier.

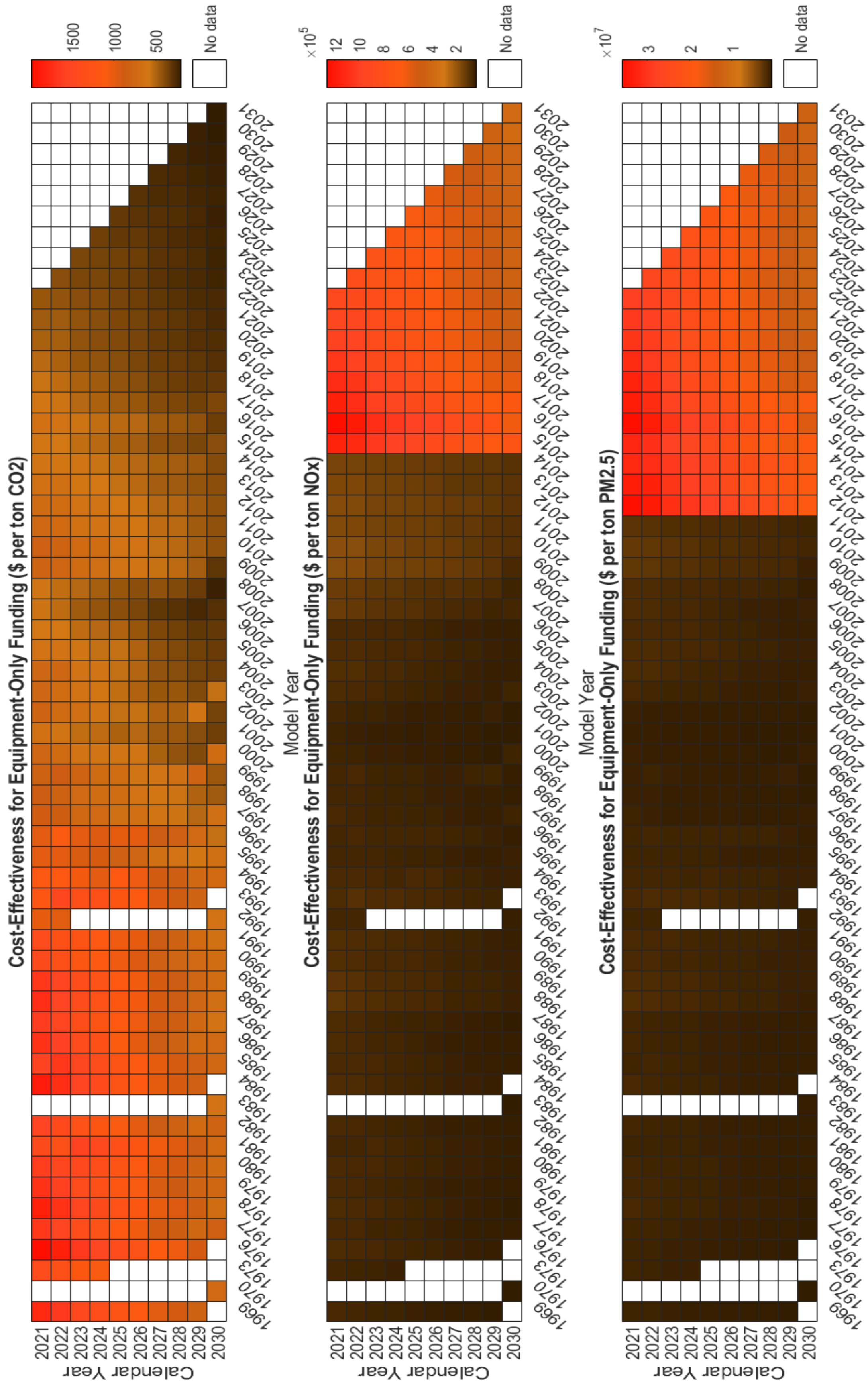


Figure 5-7. Funding cost-effectiveness breakdown by calendar year and model year for 175 HP excavators.

If NO_X and PM2.5 emission reduction is the goal, then Figure 5-7 shows that replacing the older model years in any calendar year would be an effective use of funding dollars. For CO_2 emission reduction, however, replacing newer model years would be more cost-effective as they are the main CO_2 emitters due to their high usage. It should be noted that equipment replacement considering NO_X- and PM2.5-based funding cost-effectiveness can ultimately lead to lowering CO2 emission as well. This is because the data in OFFROAD2017 shows that the newer equipment get used the most. If, following the implications of the NO_X- and PM2.5-based funding cost-effectiveness statistics, older model year equipment are replaced with electric versions, the electric equipment will become the new equipment – which are likely to be used the most. Thus, this will reduce the use of diesel equipment previously in operation, and will contribute in lowering CO_2 emissions. Following NO_X- and PM2.5-based funding cost-effectiveness thus supports the conventional wisdom of replacing older equipment, and offers the secondary benefit of reducing CO_2 emission in the process.

Also, the variations in the heat maps provide additional considerations in designing the funding strategy. For example, funding the replacement of 1969 model year equipment is more cost-effective for CO_2 emission reduction when done in calendar year 2029 instead of 2021. Similarly, the best time in terms of CO_2 emission reduction for replacing 1999 model year equipment is 2030. Using these heat maps, it is possible to develop highly focused funding strategies by selecting the most cost-effective combinations of equipment types, HP bins, model years, and calendar years.

The next two figures provide a demonstration of how the strategies can vary based on the equipment type and HP bin combinations. Figure 5-8 shows the funding cost effectiveness heat map for excavators in the 100 HP bin. As compared to the 175 HP bin in Figure 5-7, there are noticeable differences in the NO_X-based cost-effectiveness heat map. For the 100 HP bin, replacing the 2008-2014 model years are not as cost-effective as in the case of the 175 HP bin.

Figure 5-9 changes the equipment type to graders but keeps the HP bin the same as Figure 5-7 (175 HP). Funding the replacement of the 2010 model year is markedly less cost-effective here in terms of CO_2 and combined emission, compared to neighboring model years. This is not the case in Figure 5-7. These examples show how different equipment types and HP bins can benefit from different funding strategies, tailored specifically for them to achieve the maximum cost-effectiveness by considering the funding objectives and potential outcomes.

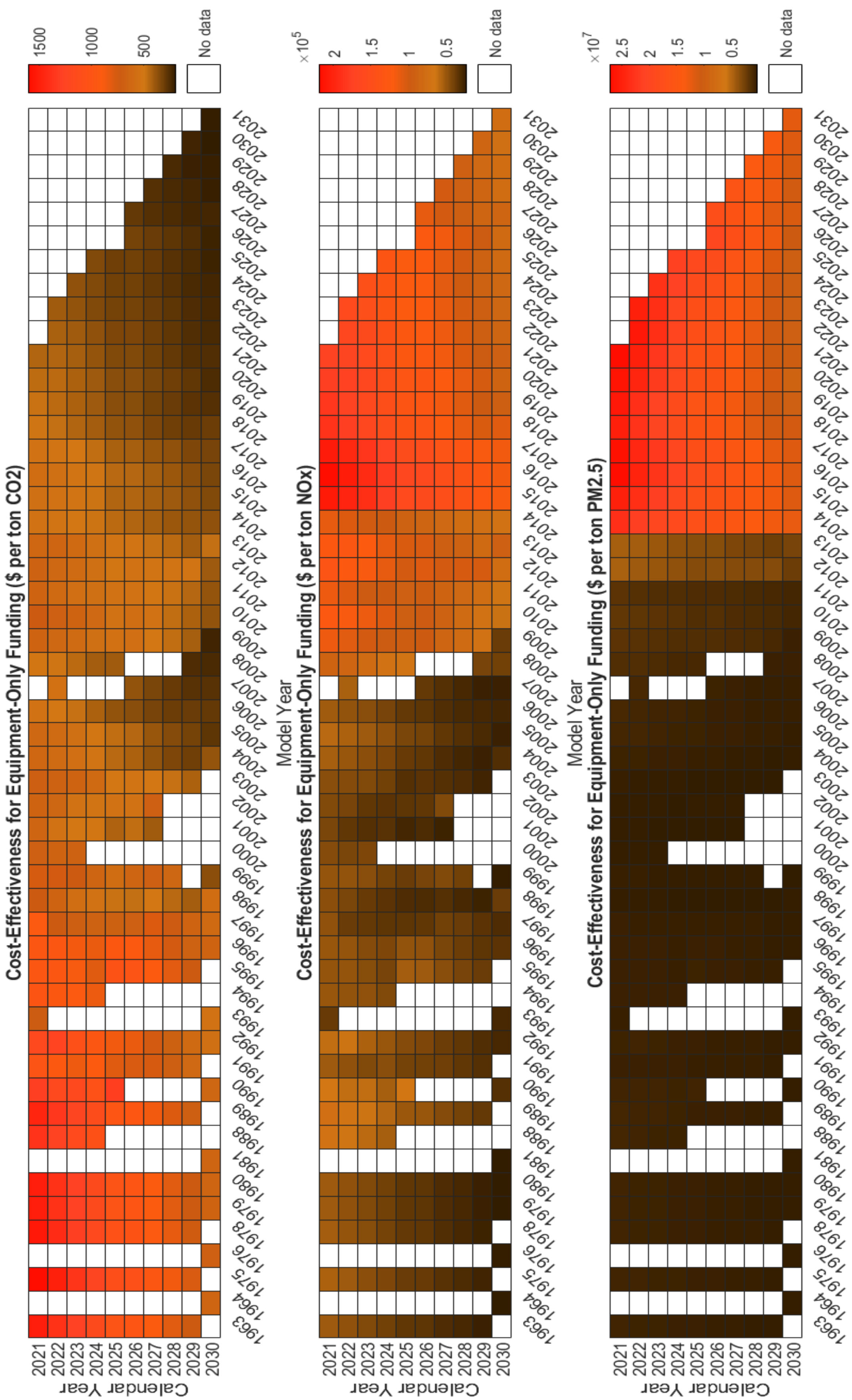


Figure 5-8. Funding cost-effectiveness breakdown by calendar year and model year for 100 HP excavators.

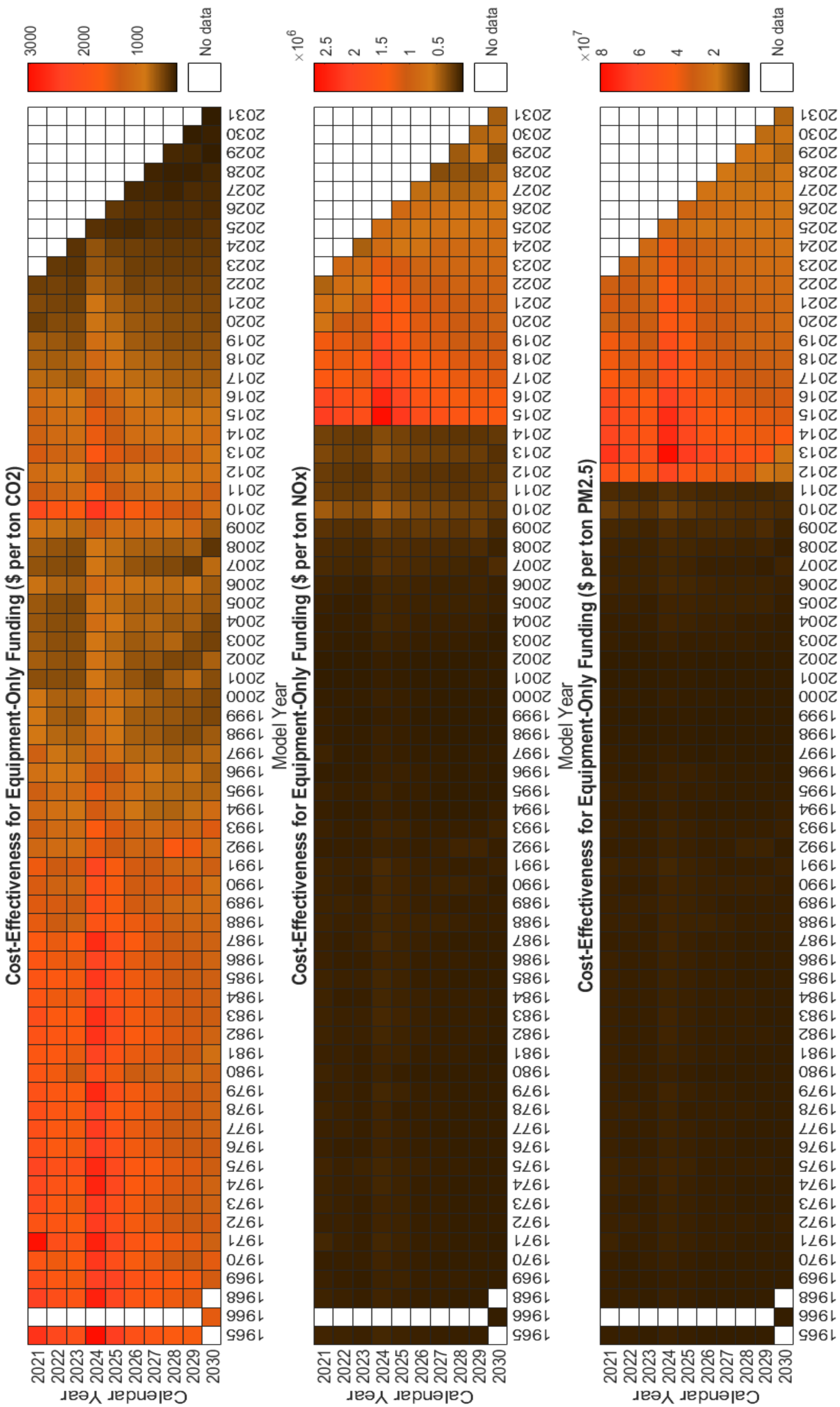


Figure 5-9. Funding cost-effectiveness breakdown by calendar year and model year for 175 HP graders.

5.5 Sensitivity Analysis

This analysis so far made several assumptions for component sizing as well as cost estimation. But the assumed values can be a bit different, and that will produce different results. In order to address all these possible changes, a sensitivity analysis was conducted by varying all these input parameters over certain ranges. 35% efficiency of diesel engine considered for battery sizing could be much lower for many equipment types and operating conditions, thus lower efficiencies were explored. Diesel engines could also be oversized in equipment, making the HP values used for motor and additional EV system cost estimation oversized as well; the input HP values were varied to address this issue. Per-unit cost of components could change due to altered manufacturing processes as well as raw-material logistics. Advanced engineering cost could vary for different equipment, PTO types, and manufacturing methods. The fuel tank cost could also be different based on factors such as equipment type and fuel tank capacity. Thus, both smaller and larger values than the base-case were considered for these parameters. Table 5-1 shows the varied parameter values against the base values. All 10 parameters had 3 different values, and the resulting 3^{10} = 59,049 scenarios were all simulated to observe the range of output variation. This analysis determined the component sizing and cost-effectiveness for each scenario considering corresponding input values.

Table 5-1. Parameter base values and variations for sensitivity analysis

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%

For each scenario, component costs were calculated using equations (1) through (15), the required funding amount was obtained by from equation (16), and funding cost-effectiveness was calculated from equation (18) using emission calculations obtained from equation (17). Each scenario simulation provided component sizes, costs, required funding amount, and funding cost-effectiveness for the emission reductions. To provide these results in a compact and meaningful way, means and standard deviations of the determined scenario outputs were calculated. These are presented in the following subsection.

Figure 5-10 shows the mean cost-effectiveness for funding electrification of excavators in the 175 HP bin. These heat maps have the same pattern as the base-case results in Figure 5-7. However, the magnitudes decreased slightly overall, as can be seen from the ranges of the scales.

The mean values showed an average of the outputs obtained through simulating all the 59,049 scenarios, and for any set of conditions, these values could be either larger or smaller than the means. In order to explore those ranges, upper and lower confidence boundaries of the mean cost-effectiveness values were obtained using the standard deviations in the following manner:

$$Upper\ confidence\ boundary = mean + standard\ deviation \quad (19)$$

$$Lower\ confidence\ boundary = mean - standard\ deviation \quad (20)$$

The mean cost-effectiveness values with these boundaries are shown for the excavators in the 175 HP bin in Figure 5-11, broken down by calendar year (marked with vertical partitions) and model year. The blue lines in each of the graphs show the mean cost-effectiveness, and the upper and lower boundaries indicate the range of variation of the cost-effectiveness values from the mean obtained at different runs of the sensitivity analysis scenarios. The data trend in consistent with the results observed in Figure 5-7: replacing the older model years in any calendar year would be an effective use of funding dollars for NO_X and PM2.5 emission reduction; replacing newer model years would be more cost-effective for CO_2 emission reduction. The range of variation is wide for high cost-effectiveness values, as seen from the areas marked by the confidence boundaries in all cases.

Similar to the 175 HP excavators, the 100 HP excavator heat maps heat maps showed the same pattern as the base-case results at Figure 5-8. However, the magnitudes decreased slightly overall, as can be seen from the ranges of the scales. The variation range for funding cost-effectiveness of 100 HP excavators are shown in Figure 5-13. The observations from Figure 5-11 apply here as well.

For the graders in 175 HP bin, mean cost-effectiveness values slightly decreased in value overall (Figure 5-14) compared to the base-case in Figure 5-9 (noticeable from the ranges of the scales). The patters are the same.

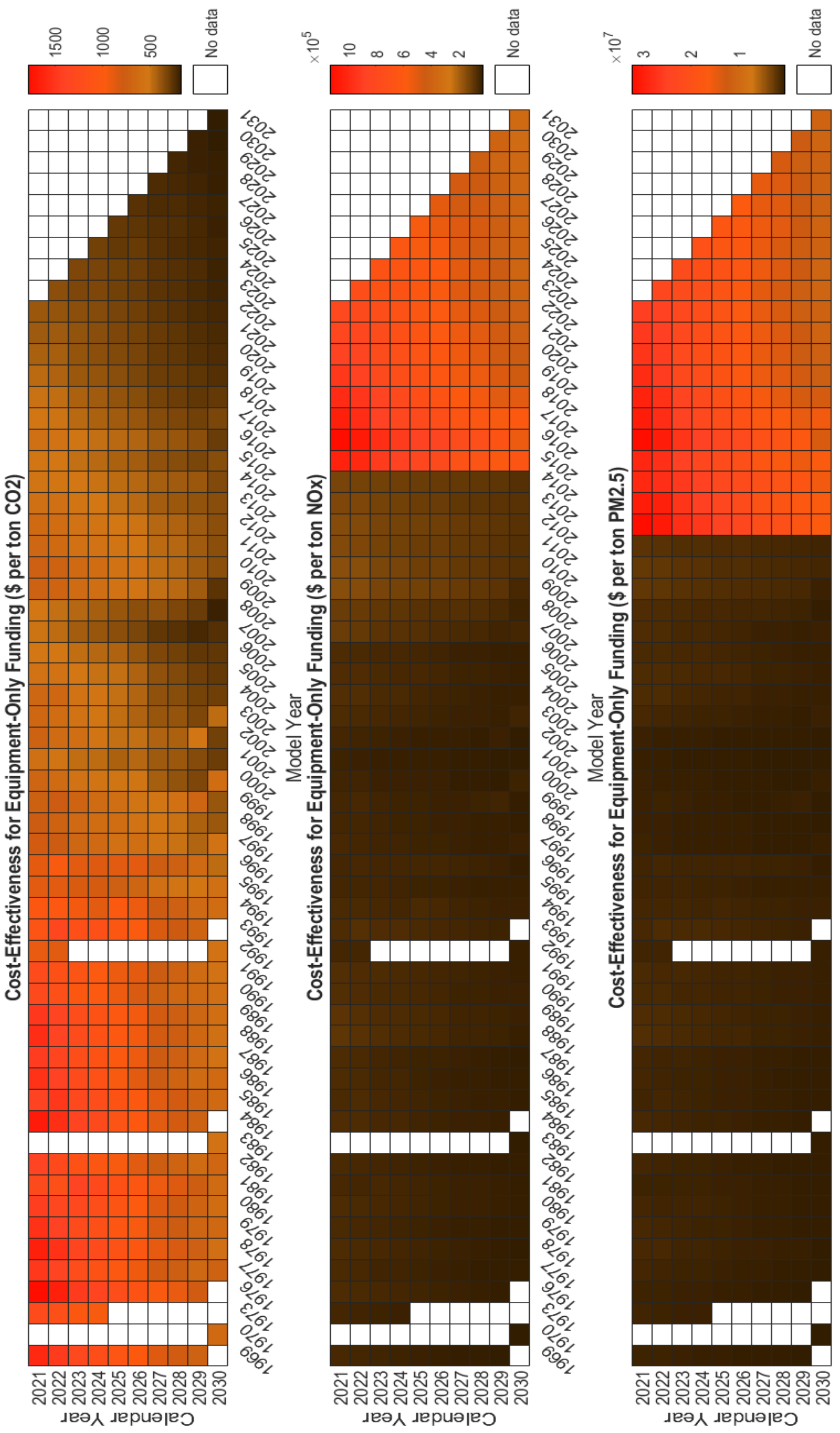


Figure 5-10. Mean funding cost-effectiveness breakdown by calendar year and model year for 175 HP excavators.

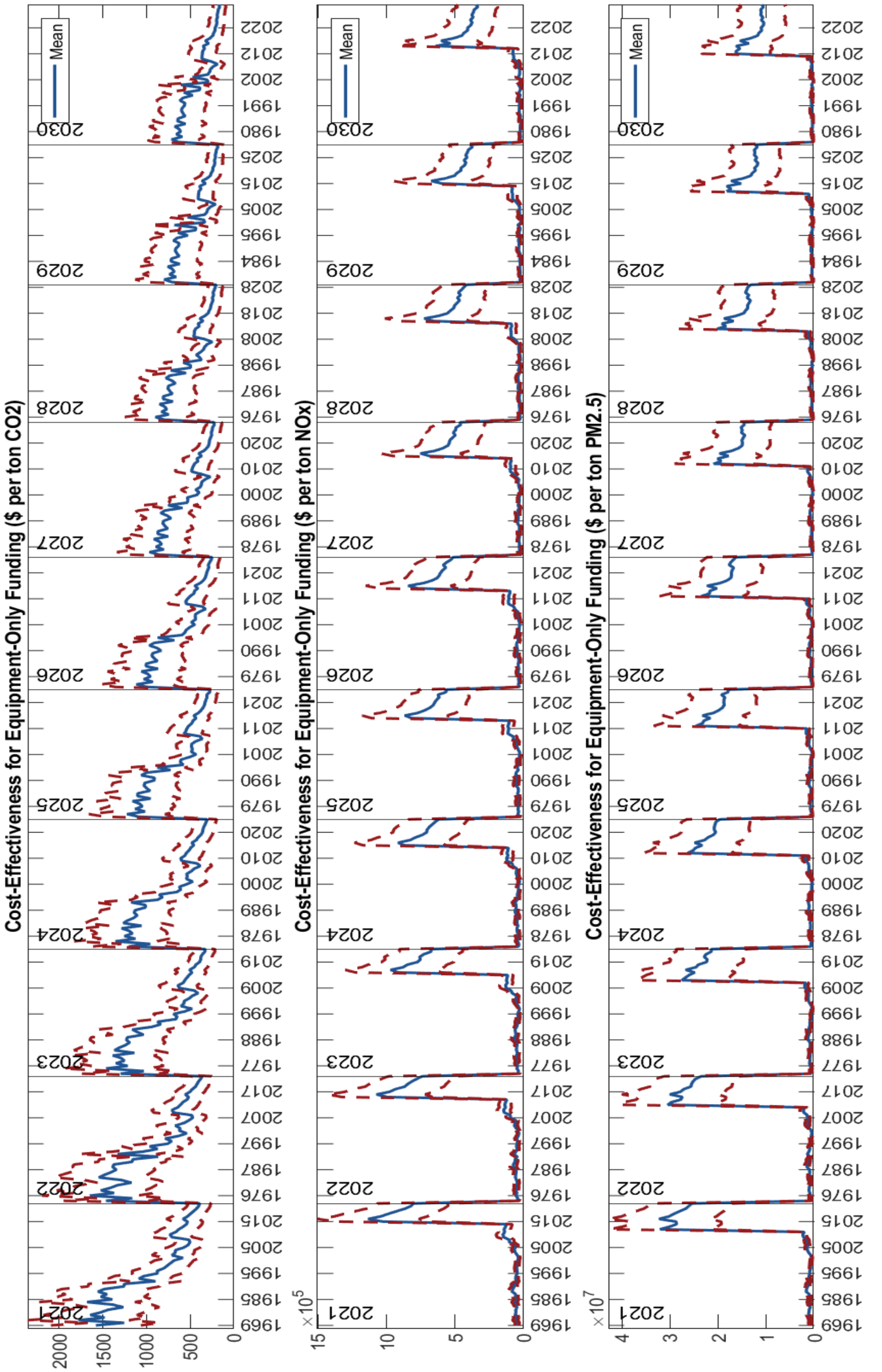


Figure 5-11. Mean funding cost-effectiveness breakdown by calendar year and model year with confidence boundaries, for 175 HP excavators.

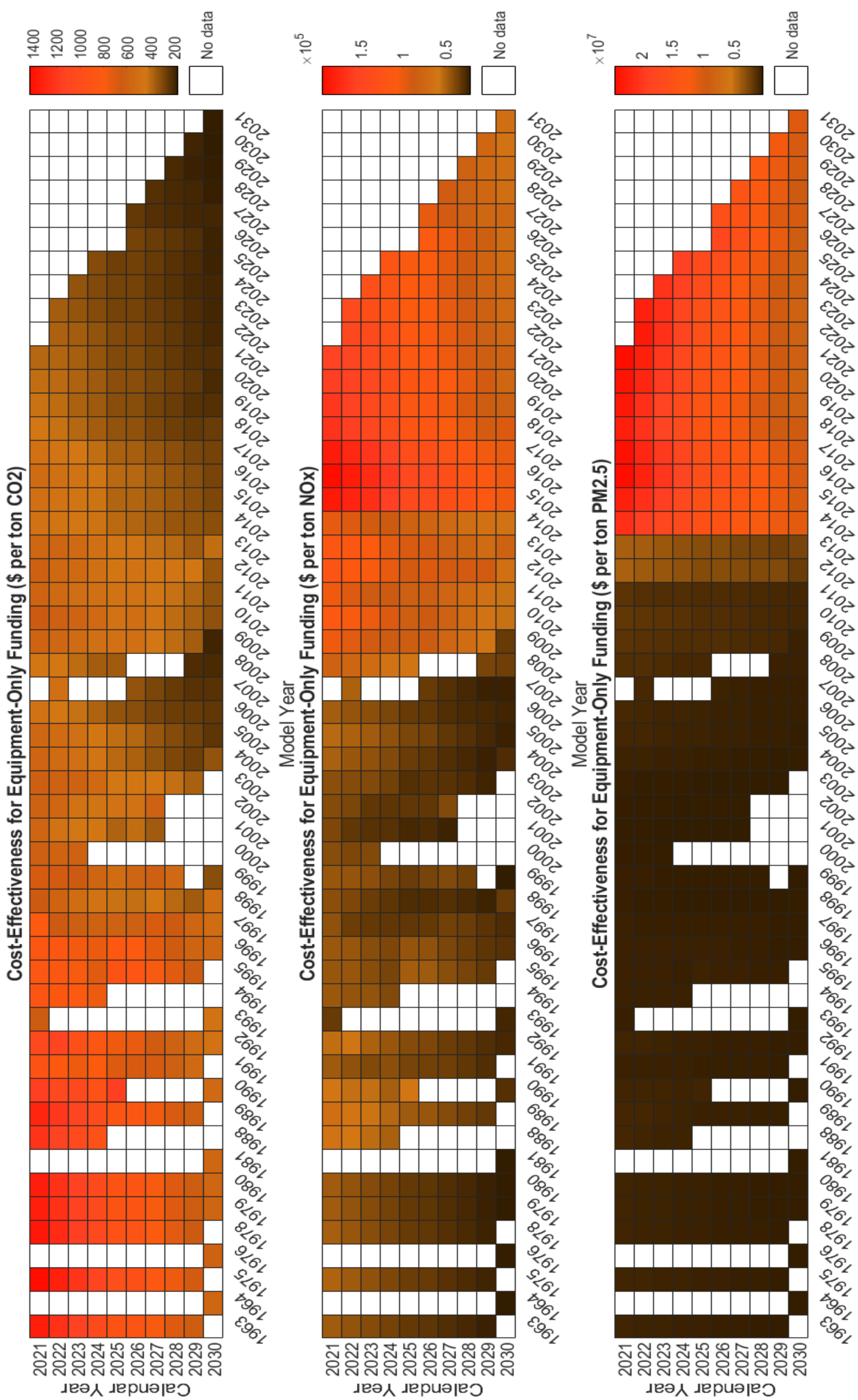


Figure 5-12. Mean funding cost-effectiveness breakdown by calendar year and model year for 100 HP excavators.

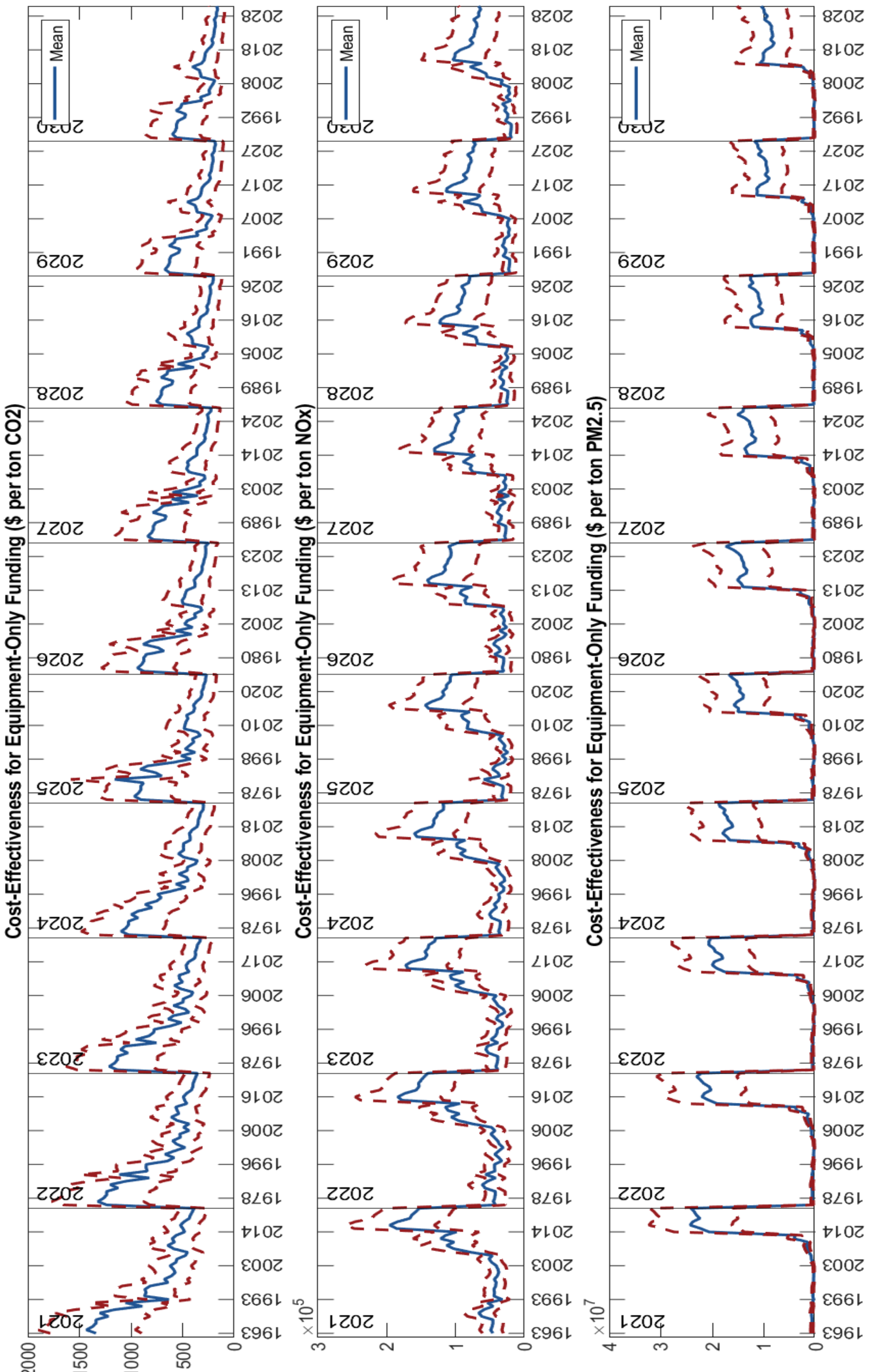


Figure 5-13. Mean funding cost-effectiveness breakdown by calendar year and model year with confidence boundaries, for 100 HP excavators.

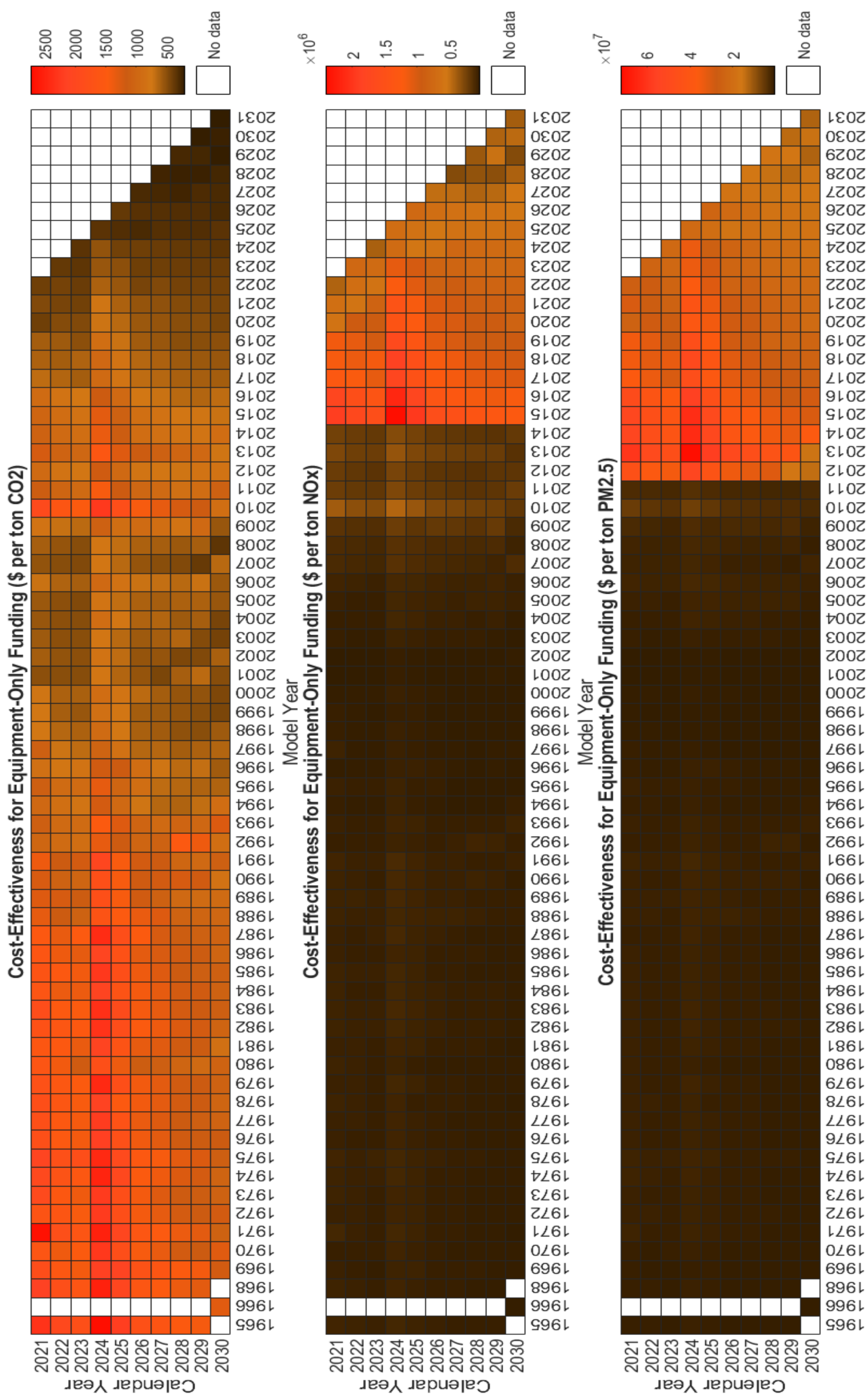


Figure 5-14. Mean funding cost-effectiveness breakdown by calendar year and model year for 175 HP graders.

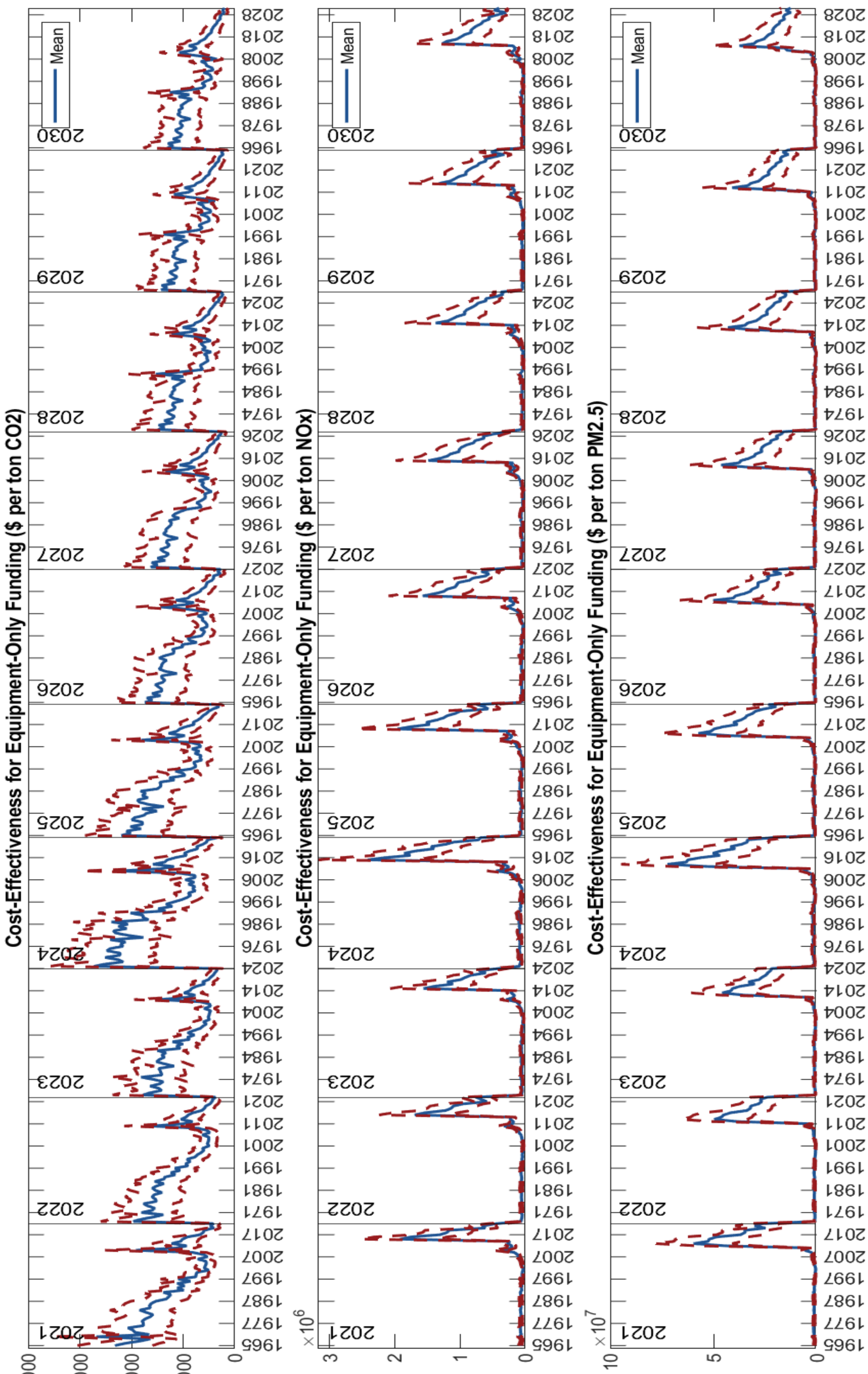


Figure 5-15. Mean funding cost-effectiveness breakdown by calendar year and model year with confidence boundaries, for 175 HP graders.

It should be pointed out that the cost of battery electric equipment, and consequently the cost effectiveness of funding these equipment, presented in this chapter depends largely on the battery price projections obtained from [152] and shown in Figure 5-3(a). However, recent data that were released after the analysis has been completed show that the real battery price has fallen faster than projected over the last few years (see Figure 5-16). For example, the real battery price in 2015 was $384 per kWh, which is 18% higher than the projected price of $326 per kWh. In 2020, however, the real battery price dropped to $137 per kWh, which is only 60% of the projected price of $228 per kWh. Since the battery cost accounts for approximately 80% of the total EV component cost in this analysis, the actual incentive funding required and the dollars per ton of emission reduction would be about half of the results presented in this chapter.

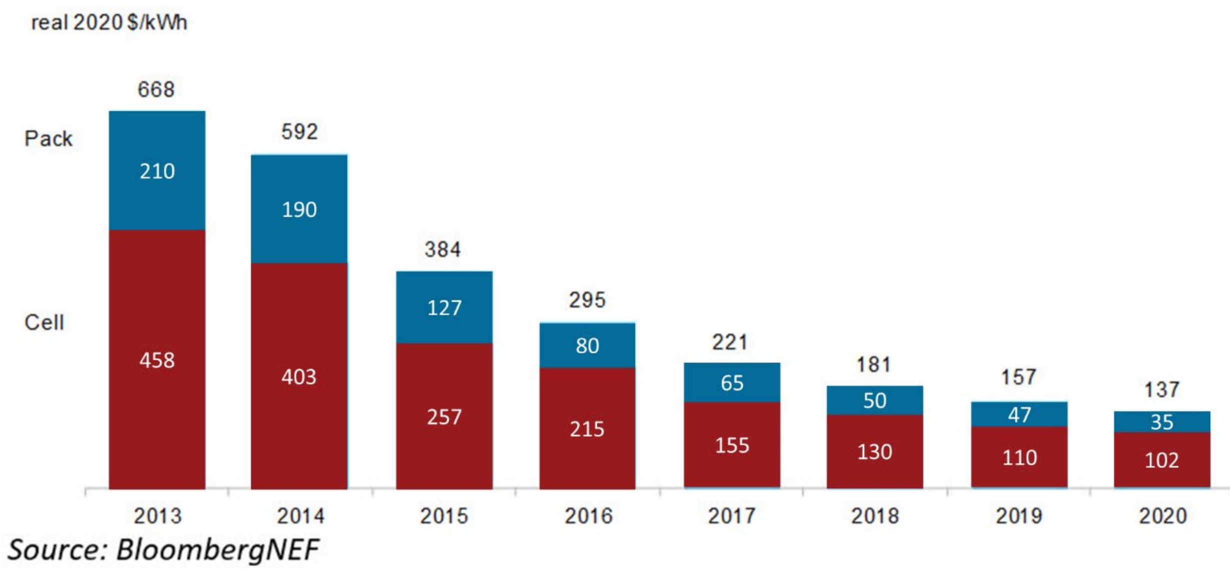


Figure 5-16. Volume-weighted average battery pack (dark blue) and battery cell (dark red) prices[1].

[1] BloombergNEF. Battery Pack Prices Cited Below $100/kWh for the First Time in 2020, While Market Average Sits at $137/kWh, December 16, 2020, https://about.bnef.com/blog/battery-pack-prices-cited-below-100-kwh-for-the-first-time-in-2020-while-market-average-sits-at-137-kwh/

6 Conclusions and Recommendations

This project has conducted a comprehensive investigation of hybridization and electrification potential for off-road applications. Heavy-duty equipment have been emphasized as the project objective; construction equipment in this area of focus have been studied to meet project objectives, while covering relevant agricultural equipment within the limits of the scope. This project started by investigating the current state of off-road equipment by studying their population and emission inventories. The state of hybrid and electric equipment both in industry as well as the research arena has been reviewed extensively afterwards to provide the status quo for equipment electrification and hybridization. Along with the analysis of readily available market data, interviews with manufacturers have been conducted to glean further insight on industry mindset and outlook on equipment electrification and hybridization. Along with descriptions of commercial and demonstration equipment models, available motors to facilitate equipment electrification have also been reported.

After this extensive literature and market study, technical analysis on equipment electrification potential has been undertaken. Real-world in-use operational data collected from a number of equipment across multiple types have been studied to extract their operational statistics – which has provided key operational insights. This study also pointed out the amount of variation seen in real-world operation, compared to standard certification cycles. Next, the operational data has been used to identify the electrification potential for different equipment types. Currently available motors suited to electrify each equipment type have been identified; required battery sizes and charging powers for electrification have been determined. This analysis also highlighted equipment type with lower potential for battery electrification at this point in time – which have been suggested for hybridization. Finally, cost-effectiveness of funding equipment replacement with battery electric versions has been calculated which utilized a component-based cost estimation model developed to overcome the lack of appropriate electric models in the market as well as the unavailability of pricing data.

6.1 Key Findings and Policy Implications

Key findings from this research and their policy implications are discussed below:

Emission Inventory

According to the statewide emission inventory for construction equipment in the OFFROAD2017 database, tractors/loaders/backhoes are the most common type by population, followed by rubber tired loaders, scrapers, off-highway trucks, crawler tractors, and excavators, respectively. These six equipment types are also the top contributors of CO_2, NO_X, and PM emissions among all types of construction equipment. Thus, they should be the primary targets for electrification within the construction equipment category. At the same time, agricultural tractors are the top emitters of the three emissions and have the second largest population in the agricultural equipment category. Therefore, they should be the primary target for electrification within this category.

State of Electrification Technology

Different EV powertrains and architectures are seen across equipment types, ranging from diesel-electric, different hybrids and plug-in hybrids all the way to battery electric and fuel cell electric vehicles. Main components of electrifying off-road equipment are already developed and rapidly penetrating into the fleet. In addition, electrification provides opportunities for new technological development in the off-road equipment sector such as novel energy regeneration methods from implements. Reduction in fuel consumption, emission, and noise as well as other benefits of electrification provide multifaceted benefits for both manufacturers and operators.

Some equipment types received more research attention than others. For example, off-highway trucks have commercial diesel-electric versions available. Excavators and agricultural tractors also received significant electrification efforts. But other types are lagging behind and need increased research. In the current off-road equipment market, there are more hybrid options available than battery electric ones. Excavator, loader, and agricultural tractor all have hybrid options. Loader, mining truck, and tractor all are available with diesel-electric powertrains. However, battery electric compact equipment are gaining momentum, with increasingly more models commercially available for agricultural tractor, dumper, excavator, loader, tandem roller, and warehouse vehicle. Battery electric as well as hybrid prototypes have also been demonstrated for multiple larger equipment types including agricultural tractor, excavator, loader, and telehandler.

Marketability Analysis

Interviews with manufacturers suggested that cost remains a strong concern for marketability of electric equipment, and their overall cost needs to be significantly lower than that of the diesel counterparts in order to persuade consumers to adopt the electric versions. Manufacturers believe that an improvement in price (through several different methods), duty cycle (operational duration per charge), or an increase in diesel vehicle regulations are the factors that will quickly and strongly improve the market share of electrified vehicles in the off-road space.

Activity Analysis

Real-world in-use operational data collected and analyzed from 22 pieces of equipment across 8 types shows that there are significant differences in engine torque and engine speed between in-use activity data and the certification cycles, suggesting that the certification cycles are not likely to be representative of how the engines of these equipment types operate in real world. Energy demands of these equipment types estimated using the certification cycles may not accurately reflect their real-world energy demands, and should not be used as a basis for assessing whether and how these equipment types can be electrified. Thus, the assessment of energy demand and electrification feasibility should be conducted on an equipment type and size basis as was done in this study.

Technical Feasibility Analysis

Technical analysis of 19 pieces of equipment from seven types that have sufficient data reveals that with the exception of off-highway tractor, all types are suitable for a single motor battery electric setup utilizing currently available commercial electric motors. Among these six, five types have multiple motor choices. Equipment type requiring torque and power exceeding the capabilities of a single motor may utilize hybrid powertrains, or more powerful motors designed for such usage.

Technical analysis also reveals that the battery requirements of five of these seven types (agricultural tractor, excavator, grader, rubber-tired loader, and tractor/loader/backhoe) are feasible, compared to the largest battery size currently in operation. All these five types are rechargeable with 50 kW chargers, verified by simulating their recorded activity demands with modeled battery electric versions. On the other hand, the two equipment types deemed infeasible for battery electrification at this time, off-highway tractor and scraper, can be partially electrified with diesel-electric or series hybrid technologies as an immediate electrification step.

Funding Cost-Effectiveness Analysis

For funding cost-effectiveness estimation, statewide equipment data is essential. The OFFROAD2017 database is the most suitable one available right now, despite its limitations. The two major components required for funding cost-effectiveness estimation: funding amount and emission reduction, can be derived using data from OFFROAD2017, other literature, and equipment operational data collection efforts. With many equipment types not having commercial electric versions, specification-based estimation is the viable way to assess the cost of electric equipment, based on component costs. However, the price of the electric equipment can change depending on the manufacturers. Thus, it is necessary to run sensitivity analysis on the equipment cost to provide results with sufficient confidence boundaries, as the base assumptions and data are prone to change.

The cost-effectiveness study shows that replacing older equipment is generally more cost-effective considering NO_X and PM2.5 emissions, due to older equipment not complying with newer, more stringent emission standards. However, this can also be cost-effective for CO_2 emission reduction if the new electric equipment will be used more than the old equipment it replaces. Funding strategy can be uniquely tailored for different equipment type and size, by analyzing the funding cost-effectiveness in different calendar years, across different model years, and considering different emission reduction objectives. For example, funding a turnover of equipment smaller than 100 horsepower was found to be more cost-effective, in terms of dollars per ton of emission reduction, than larger equipment at this time.

It should be pointed out that recent data released after the cost-effectiveness analysis has been completed show that the real battery price in 2020 was only 60% of the projected battery price used in the analysis. Since the battery cost accounts for approximately 80% of the total electric vehicle component cost in the analysis, the actual incentive funding required and the dollars per ton of emission reduction would be about half of the results presented in this report.

6.2 Recommendations for Future Research

The following recommendations for future research are made based on the findings in this project:

- Real-world in-use equipment and engine activity data, such as the ones used in this research, should be collected from more equipment types and from a larger sample size. The data should be used to update the current inventories in OFFROAD2017, and if possible, to further disaggregate information such as operating hours, load factor, energy use, and emissions into finer spatial and temporal scales. The data should also be used to develop new certification cycles for individual equipment types that are more representative of their operating conditions in the real world. In addition, such detailed operational data is essential for a robust analysis of electrification potential in off-road applications as demonstrated in this research. New data can be used to augment the analysis of the equipment types included in this research and to perform a similar analysis for other equipment types.

- The OFFROAD2017 model can also be enhanced to assume different numbers of operational days per year for different equipment types. In addition, fuel consumption estimates can incorporate the effect of engine deterioration similar to the effect of engine deterioration on pollutant emissions.

- This research is focused on the potential of electrifying the equipment. However, the technical, logistical, and economic feasibility of different strategies for charging these electric equipment, especially those in construction, remains to be studied. Construction equipment are often used in remote job sites where electrical grid infrastructure may not be readily in place. In addition, construction equipment are utilized primarily during the construction project period, after which they may be moved to different job sites. Therefore, different charging options (e.g., stationary charging stations, mobile chargers), operational tactics (e.g., adjusting operation schedule, employing both electric and conventional equipment), or even powertrain technologies (e.g., hybrid, hydrogen fuel cell) will need to be considered.

- The effectiveness of tailored funding strategies for different equipment types and sizes can be investigated. Calculation of cost-effectiveness based on life-cycle emissions is also worth exploring.

- Total cost of ownership (TCO) is a crucial factor for equipment uptake. Thus, TCO for electric equipment should be studied in greater detail and compared to that for conventional diesel equipment to provide a clearer picture on long-term prospects of electric equipment adoption.

- Technical feasibility analysis on larger equipment populations can be pursued to obtain further understanding on electrification prospects by equipment types and duty cycles. In addition, real-world demonstration and evaluation of electric equipment with respect to their performance, duty cycles, charging needs, maintenance and repairs, costs, etc. should be conducted.

- Studies of real-world emission and air quality impacts, along with their equity and environmental justice consideration, from the deployment of battery electric equipment and zero emission equipment in general will be important as well.

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Appendix A: Industry Survey

Informational Interviews Overview

The information gathering process was shaped by the gaps in market viability rather than technology viability. However, there is a lack of information available through research to help understand these gaps in market viability. To remedy this lack of understanding, a list of seven talking points was formulated and discussed with manufacturers in the market. It was requested that the identities of the manufacturers who took part in the interviews would be kept anonymous. The interviews were conducted in a conversational manner in order to get a clear understanding of the market from the point of view of the manufacturer. Provided below is each of the questions and some of the most informative responses gathered.

Oral Interview Questions and Results

Is the market for electrification/hybridization of off-road equipment growing faster, slower, or on par with expectations from 2010?

Answers to this question were mixed. Projections specifically from 2010 were very bullish due to stimulus money in the sector, and skyrocketing oil prices, and those bullish projections have not been met. However, several of the entities who participated had more conservative projections, and those projections have been greatly exceeded. The picture becomes clearer if looking at 2014 as the milestone year rather than 2010. In 2014 “not a lot was happening” regarding electrified vehicle industry progress. However, several factors have led to the market really picking up in recent years. The prospect of zero emission zones and cities, CO2 limits and noise restrictions on construction in cities have led to new levels of growth in the industry. Large progressive cities have a very large influence on the market and the idea that some of them are moving towards legislation that would require electric vehicles is incentivizing the growth of the industry.

What’s the one area to improve on that would spur the most growth of electrified vehicles in the industry?

Despite rapid advancements in recent years, “battery technology still has a way to go”. In the off-road market the durability and charge capacity required is very high in order to make the vehicles cost effective. A lower cost, higher durability, higher charge capacity battery would create great progress towards making the electric off-road vehicle more market viable.

User acceptance also needs to increase. There is still a feeling of uncertainty around the use of electric vehicles in this field. A cornerstone of this industry is reliability. Work can be lost if equipment doesn’t function correctly on a consistent basis, and people are hesitant to switch from a proven technology to a less proven technology because of this. However, after use, electrified vehicles have a very high approval rate among workers.

The decrease in noise and vibration leads to a smoother, more pleasant more enjoyable ride, and the instantaneous acceleration leads to increased ease of use.

What could government do to help spur the growth of the electrification/hybridization market for your company?

There are several routes government could take to spur growth in this industry. Regulations of different sorts will help increase market share. Zero-emission zones and noise free zones were mentioned and brought up in other parts of the interview as catalysts for the growth of the electrification markets. “Regulations will make the market shares increase more quickly, however there is the issue of technology not being ready.” An issue that was brought up regarding this point was the potential of forcing a technology that is not yet applicable for certain duty cycles or applications into use. If the vehicle is not ready for use in a capacity but is forced into use, it can lead to complications that could be dangerous, or harm the improving reputation of electrified vehicles.

Expanding incentive programs will help drive sales and therefore user acceptance. Sales on manufacturers’ ZEV and hybrid vehicles are much higher when Moyer and other programs have money to give out. There is a considerable drop in sales once the programs run out of yearly funding. Incentive programs are fantastic at lowering the incidental cost of the vehicles, which is one of the largest barriers to entry for the technology.

Funding research to “help drive down component costs and battery costs” will help overcome the incremental costs and make batteries more effective. The technology is still undergoing major improvements, and funding research will help reduce the incremental cost and improve the efficiency and productivity of hybrid and electric vehicles. However, there was no clear consensus on whether it would be more useful to fund research to make the parts less expensive and higher quality, or to fund programs that would drive demand which would lead to more demand for research on its own.

What traits are customers looking for that electric vehicles could offer?

Electric vehicles tend to have a very positive user experience due to added features that fundamentally change the user experience, factors that are unique to electric vehicles. These factors include instantaneous acceleration and low noise (which helps with fatigue). These positive impacts on working conditions may help companies lure in more workers, in a field where there is a shortage of experienced workers. However, the people purchasing the equipment will likely not be the ones operating the equipment. On a base level, the bosses want to increase productivity, and there is evidence that electrified vehicles will increase productivity. Factors that will increase productivity are: lowered fatigue, instantaneous acceleration, shorter repair downtimes. Added features like improved ease of use (to reduce training time) and E-Stop also factor into improving productivity of the vehicles. All of these benefits add on to the reduction in operations cost.

Electrification allows for enhanced company brand building. Companies are able to offer products that increase efficiency due to running on electric power, which is good for their brand. An example is using an electric seeder (an addon that plants seeds). The electrified version of this technology gives you more control and reduces error. Companies are moving into the space of being "Solution providers that aren't tied by one type of technology, but rather are focused on maximizing intelligence." Electrification will help push this image and business model.

Is tech transferability a relevant part of your business models?

This question was answered with a resounding yes. A large part of companies' business models is scaling of applications. The higher the volume of production is for the parts for electric vehicles, the lower the price of the parts can become, and the lower the incremental cost will be. So "finding ways to make technology transferable is a large part of our (several companies) business models." The adaptability of this technology is very promising, which can lead to increased market shares for parts, which will drive down production costs.

However, the issue with relying on tech transferability is that you end up with a lower quality part on average. "Easily transferable parts aren't as efficient as specialized parts". So, while the parts will be cheaper, the parts will end up being a less efficient fit for each of the applications they are used in. This dichotomy ends up being something of a tightrope, but companies are planning on using transferable parts as a key strategy to fight the higher prices of electrified vehicles. This is a solution that will continue to provide greater yields as the market for electrified vehicles in all sectors continues to increase.

Are there improvements that electrification will open the doors to? Will they help drive sales?

The major direct impacts outside of lower operations costs are the following. Improved ease of operation (leads to lower required training time), reduced noise (leads to longer hours of operation and less stress on the operator), reduced pollution (for compliance with city regulations) and instantaneous acceleration (which leads to higher productivity). The argument can be made that these vehicles will improve a project's efficiency and increase the scope of projects that one would be qualified to work for. These factors will drive sales.

"Electrification will help with automation efforts, automation will help the completion of tasks be smarter and more efficient." It's widely known that once automation can be implemented in a safe and effective way, it will reduce costs and improve efficiency of jobs. The previously mentioned Row Seeder is a prime example of automation improving efficiency and yields. The space for this type of automated efficiency enhancing technology will increase as automation improves and becomes more widely used. This has the potential to drive sales as the technology becomes more fleshed out.

Anything else you would like to share that you think is important for us to know.

- "User experience is very positive for electrification, we just need to find ways to increase exposure, options like rental fleets may help."

- "Agriculture is lagging construction likely because of the differences in duty cycles. Agriculture equipment is stagnant for much longer periods of time. Electric machines make their incremental costs back while running, so the TCO is much worse for agriculture equipment."

- "Electrification has become something of a buzz word, and a brand enhancer. But the incremental costs need to come down before it becomes a household technology. "

- "The market share of electric vehicles will increase, but not at a rapid rate until government regulations or incentives impact the market. Electrification needs to become cheaper before this will happen."

- "Hybrid technology makes sense for in city applications. One could potentially use a diesel engine to drive to the city and battery for the rest of the trip. Then plug into the grid during use, this would be very efficient in terms of cost and emissions. There's a lot of room for hybrids, depending on duty cycles, more complex duty cycles may have a part in the rise of electric off-road equipment.

Follow up Survey Questions and Results

We received survey results from two companies, the surveys received comprised of the options of 10 people. The aggregated results will be presented below, but due to a desire for anonymity from the manufacturers who responded, the individual reports will be included.

Question 1:
The consensus was that the market is slightly behind where projections from 2014 assumed it would be. This answer matches the consensus interview portion where the results were mixed. The score was a 4 out of 10, 10 being exceeding projections and 0 being lagging behind.

Question 2:
Question 2 asks which improvements would accelerate the market. The three highly rated answers were:

- Improving Battery Technology (9)
- Achieving Economies of Scale (8.5)
- Decrease Incremental Cost (7)

The rest of the answers were significantly lower. Improving battery technology will improve the total cost of ownership in the vehicle, the vehicle's duty cycle, and the incremental cost. Achieving economies of scale will lower the price of vehicles and can be achieved by increasing market share of electrified vehicles. And decreasing incremental cost is self-explanatory and can be achieved through several methods, including the two other answers discussed in this section. All the favored answers for this section were economic with some duty cycle considerations. These seem to be the most impactful factors toward increasing market share.

Question 3:
Question 3 asks what government can do to improve the market share of these vehicles. All of the answers received relatively good scores, but the clear front runner was Government Regulation. These regulations are meant to decrease viability of diesel alternatives and range from increased taxes on diesel vehicles to the adoption of zero emission zones.

Question 4:
Question 4 asks what aspects of these electrified off-road vehicles are more appealing than their diesel alternatives. All answers scored within 1.5 points of each other, but the highest rated score was “compliance with regulations”. This again shows the manufacturer opinion that the most impactful way to increase market share of electrified off-road vehicles in the short term is government regulation.

Question 5:
Question 5 asks if technology transferability (the use of the same components across different technology applications) is a major aspect of the company’s business model. At 8.5, and overwhelming yes was the answer to this question. This reflects accurately what was discussed in the interviews. Technology transferability is a major part of manufacturers’ business models.

These responses are summarized in Table A-1.

Table A-1 Aggregated Survey Results

1. Is the market for electrified vehicles exceeding or lagging previous market projections from around 2014?		Exceeding Projections. (10)	Lagging behind projections. (0)			
Q1 Answers:	4					
2. What's the one area to improve on that would spur the most growth of electrified vehicles in the industry?		Battery technology needs to improve, in terms of cost and durability.	User acceptance needs to improve, if people become more familiar with the benefits of electrified tech, market share will improve.	We need to become better at designing electrified vehicles. Improving design could help lower costs and increase usability.	We need to achieve economies of scale for the electric components, this will drive down the costs.	Decrease incremental costs.
Q2 Answers:		9	5	5	8.5	7
3. What could government do to help spur the growth of the electrification/hybridization market for your company?		Government Regulations: (Zero Emission Zones, Increased Taxes on Diesel, etc.)	Incentive Programs (Carl Moyer, etc.)	Subsidize research into improving batteries.		
Q3 Answers:		8.5	5.5	6		
4. What traits are most impactful to the electric vehicle market?		Better user experience and ease of use.	Reduced Operational Cost.	Brand enhancement.	Compliance with regulations.	
Q4 Answers:		5.5	6.5	5.5	7	
5. Is tech transferability a relevant part of your business model?		Largely Relevant. (10)	Not Relevant. (0)			
Q5 Answers:	8.5					

The sixth question was asked but not included in the survey results above in order to improve the readability of the chart. The question was:

6. Is there anything you would like us to communicate to CARB that is not covered in another question? (Optional)

And the results are below:

1. In general the combination of TCO and features that improve off road vehicle productivity are key.
2. One consideration may be to subsidize/provide grants to manufacturers to complete system designs to commercialize more vehicle forms. This allows fleets to move towards hybridization that can drive economy of scale and broaden user experience with electrification.
3. For many off road machines, the hydraulic circuit is the main consumer of engine power for significant periods of the duty cycle. Improvements in hydraulic efficiency can decrease the loading on the engine and help reduce emissions. Credits for improving hydraulic efficiency of the machine could help with adoption of more efficient hydraulic systems.
4. Fuel cell applications and hydrogen infrastructure development can enable longer run time in high power vehicles and should be considered as a primary energy source for off road vehicles.
5. Consider incremental powertrain electrification as a realistic commercial path towards driving adoption and acceptance of electrification. Off road vehicles have significant peak loading and auxiliary work functions that can take advantage of electrification beyond what you see in automotive powertrain.

This question was proposed to fill in any gaps in the full picture that the 5 proposed questions missed. There are several points brought up that are advise from manufacturers on how to help grow the market with regard to addressing the weaknesses of the current market. Several of the points brought up here were addressed in the interview.

One of the undiscussed points in the interviews was point 4, discussing the hydrogen fuel as a potential flagship technology for the off-road industry. While there are positive aspects to the hydrogen technology, there are currently no off-road vehicles examined in this report that utilize hydrogen. Beyond that there are a limited number of vehicles in any market ready space that use hydrogen. More research may be needed to examine the potential benefits of hydrogen vehicles in a mature market.

Appendix B: Off-Road Beachhead Market Analysis

CALSTART was tasked with mapping the current market for electrified vehicles in the industrial off-road and agriculture sectors. A list was derived of the industry leaders in each respective field, specifically looking at the top 5-10 leaders in market share in the United States. After the research on the industry leaders was exhausted, a search for electrification innovations achieved by smaller players in the market was conducted to understand the full breadth of electrification innovations. Further research was conducted on each of the industry leaders to identify the electrified models that either: are currently available, are not available but have an availability date, or are being worked on without a release date. The initial goal of the product data mining was not just to discover what electrified products are available and are being developed, but also to figure out the strengths and weaknesses of the products and glean information into why electrified vehicles have the market share that they have. While this information may still be uncovered by interviews with industry leaders, the comparative information was not available online to develop a good understanding of the strengths and weaknesses of electrified vehicles compared to their fossil fuel counterparts.

Off-Road Mining and Construction

Caterpillar (33% Market Share)

Caterpillar is the largest construction vehicle manufacturer in the United States. They have several models of electrified vehicles, both currently available and in the prototype stage.

Caterpillar D6E

The D6E is a traditional diesel Cat C9.3B engine powered electric drive train. The electric motor can operate at all ground speeds, ensuring the dozer is always operating at the most efficient point possible. The electric drivetrain yields several advantages to its fully mechanical counterpart: a fuel reduction of up to 35%, better instantaneous acceleration, an improvement in maintenance costs up to 12% and allows a high degree of technology to be built into the vehicle. The vehicle costs $350,000 new and comes with a 7-year 20000 hour warranty.

Caterpillar 336E/ DH/ FH

The Caterpillar 336E is part of a line of "swing hybrid" excavators, along with the DH and FH. It has a traditional hybrid set up of a diesel engine and electric motor. The Excavator uses hydraulics to recapture the energy from the swing of the excavator arm. The captured energy is stored on an electric battery. Caterpillar asserts that the hybrid excavator will reduce fuel consumption between 25 and 50%. The excavator also creates significantly less noise and will typically repay the added costs of the hybrid model in 18 months. The 336E has a 5 year 7000 hour warranty.

Caterpillar 988K XE

The Caterpillar 988K XE is a diesel dozer with an electric drive converter system. The dozer boasts a 25% efficiency improvement, a lower maintenance cost and an increased overall lifetime of up to 3500 hours more than its diesel counterpart. The vehicle has a 3 year or 5000-hour warranty.

Caterpillar 300.9D

The Caterpillar 300.9D is a less than 1 ton mini excavator. It can run on either on a diesel engine or as a plug in electric to an electric power source. The full electric mode allows it to run in building shells without creating air quality issues. The vehicle has a power output of 13 horsepower.

Pon Catterpillar 323 Z-Line

The Pon Catterpillar 323 Z-Line is an electrified conversion of a Caterpillar 323 F by the Dutch company Pon. The vehicle was a prototype used on construction projects in Norway. This is one of the few examples of a full-sized ZEV vehicle. The vehicle can operate 5-7 hours and has fast charging capability to fully charge in 1-2 hours. The vehicle was a one-off alteration and does not have plans to be made commercially available in the near future.

Caterpillar R1300G LHD

The Caterpillar R13000G LHD is a fully electric underground mining loader. The vehicle is a fully electric version of the diesel version that CAT has offered in the past. The proof of concept was used in a live mining operation in Canada in 2018. However, this concept vehicle is still years away from full market availability. Along with the traditional benefits of electric vehicles, this vehicle also has the added benefit of improving air quality in the confined spaces where it operates.

Caterpillar Summary

Caterpillar's electrified products are a reasonable representation of the current market for electrified off road construction technologies. They offer several models of their traditional diesel vehicles with hybrid electric converters and electric powertrains. However, the offerings of fully electric models are limited. Caterpillar has stated that full electric models are currently in the works, but there is little information on release dates or specifics.

John Deere (17% Market Share)

John Deere is the second largest construction vehicle manufacturer in the United States with 17% of the market share. Their selection of electrified vehicles is limited to hybrids and electrification kits.

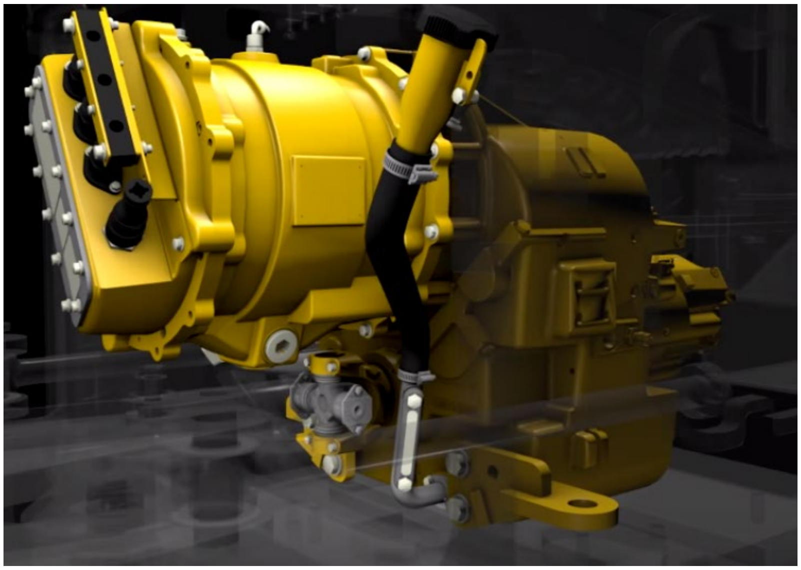
944K Hybrid Loader

The 944K and 644K are hybrid loaders. The hybrid motor converts mechanical energy into electric energy when the vehicle operator stops accelerating. This system works similarly to a traditional breaking system but instead of dispersing the energy from slowing down, it converts it into electrical energy. The loader boasts a reduction in fuel consumption of between 9 and 14% and it warrantied for 8 years or 20,000 hours of operation. The vehicle also boasts a maximum power output of 536 horse power.

TE 4x2 Electric

The TE4x2 Electric is a fully electric warehouse vehicle offered by John Deere. It has a top speed of 15 mph on 6 horsepower. It boasts benefits of being completely quiet and having zero emissions. The primary use for this vehicle is indoor transportation of light goods and people. The vehicle is currently available and can be purchased for $12,000.

Electrification Kits



John Deere offers a wide range of customized electrification solutions, specifics about the electrification kits very based on the specifics of the vehicle and situation.

John Deere Summary

John Deere’s whole catalog of vehicle electrified solutions are limited to a hybrid model, and a full electric warehouse vehicle. The existence of electrified solutions from John Deere along with the lack of breadth of vehicles may signify that the market is not yet asking for a wide range of electrified vehicles despite John Deere having the capability to build electrified machines.

Komatsu (13% Market Share)

Komatsu is a Warehouse and Construction equipment company based out of Tokyo Japan, they occupy 13% of the Construction market in the United States. The company offers two electrified models, one hybrid and one fully electric that is still in the development stage.

Komatsu 830-1AC

The Komatsu 830-1AC is an electric drive heavy duty mining truck. The AC control system provides independent control to the back wheels to improve control in slippery conditions. Tire wear is also improved due to the electric drive train. But the majority of the power is provided by a diesel engine.

Komatsu 840E-4

The Komatsu 840-E is an electric drive heavy duty mining truck. This truck is the following generation of the 830-1AC. The AC control system provides independent control to the back wheels to improve control in slippery conditions. Tire wear is also improved due to the electric drive train. The majority of the power is provided by a 16-cylinder diesel engine.

Komatsu HB365

The Komatsu HB365 is a swing hybrid excavator similar to the Deere swing hybrid excavator. It is a traditional diesel-powered excavator that recovers mechanical energy from the swing of the crane arm and stores it as electric potential energy. The HB365 boasts an average fuel reduction of 20% compared to its full diesel counterpart. The HB365 is also an undefined amount less noisy than its diesel counterpart. It comes with a 5 year or 7000h warranty and has comparable power output to its diesel counterpart.

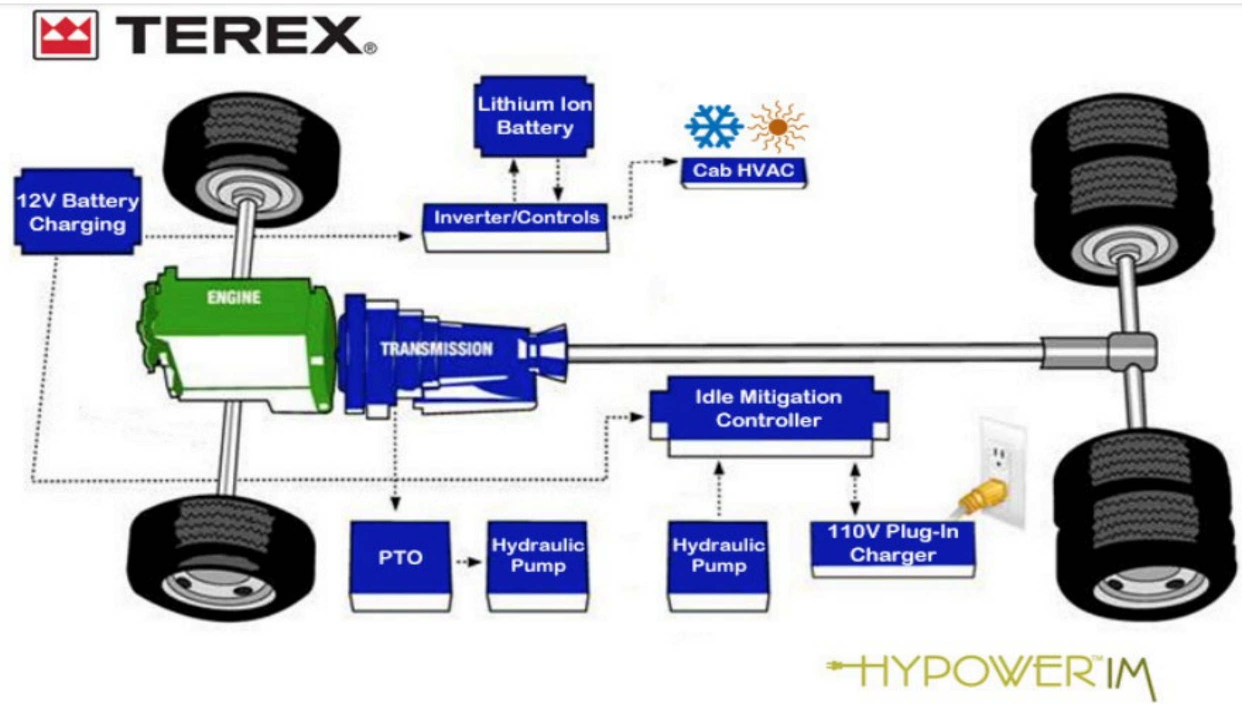
Komatsu Electric Mini Excavator

The Komatsu Electric Mini Excavator is unsurprisingly a fully electric 10,000 lb excavator with an output of 24.4 horsepower. The excavator is fully electric and is significantly less noisy than its diesel alternative. The reduction in noise and emissions makes it ideal for operations in close quarters.

Terex (7% Market Share)

Terex is a Connecticut based global material handling company that represents 7% of the off-road construction sales in the US. While Terex has a large market share their electrified solutions are limited to a hybrid conversion system.

Terex HyPower Hybrid System



The Terex Hypower is a plug-in hybrid conversion system. The Hypower is designed to limit the idle time gasoline usage of utility trucks. The apparatus powers all electric applications of the vehicle, from the atmosphere control systems to boom arms. The hybrid system is reported to reduce fuel consumption between 600-1000 gallons per year, reduce noise pollution by 12-15% and displace between 6 and 10 metric tons of CO_2 a year.

Case New Holland (5% Market Share)

Case New Holland has no market available or in research electrified off road solutions. They previewed a hybrid hauler in 2007, but the product was never brought to market. They are instead focusing on different types of alternative fuel vehicles. They recently previewed a methane powered loader at Bauma 2019.

Volvo Construction (5% Market Share)

Volvo is a multinational Sweden based company that manufactures on-road, off-road mining and power solutions. Volvo has five announced or available electrified off road vehicles, in production stages ranging from prototype to market available. Volvo has made electrified solutions a major part of its business moving into the 2020s. Volvo's solutions range from hybrid to full electric vehicles, however the bulk of their solutions are still in production.

Volvo 300 E Hybrid Excavator

The Volvo EC300E is a swing hybrid excavator similar to the Cat and Komatsu swing hybrid excavators. The EC300E features Volvo Construction Equipment's hydraulic hybrid technology, which utilizes the boom down motion to support the hydraulic pump. The result is 12-17% better fuel efficiency and reduction in CO_2, compared with the diesel (EC300) model. Volvo claims that due to the average fuel savings brought on by the hybrid motor, the EC300E will pay back its incremental costs in 12 months assuming the 17% fuel reduction. The vehicle is currently still in development and is not yet market available.

Volvo L25

The Volvo L25 is a fully electric Loader. The vehicle is projected to have an 8-hour battery life. The L25 projected to recharge in 12 hours but will recharge 80% of its battery life in 2 hours. Along with fuel, maintenance and emissions benefits associated with zero emission vehicles, the vehicle is also significantly less noisy than its diesel counterpart. The product is still in development, but has a 2020 release date.

Volvo EC 25

The Volvo EC25 is a full electric mini loader similar to the Komatsu and Caterpillar electric mini loaders. Like the Volvo L25, the vehicle has an estimated run time of 8 hours and recharges in 8 hours, but can recharge 80% of its battery in 2 hours. The EC25 boasts all of the ZEV benefits, lower maintenance costs, no noise pollution, faster acceleration and reduce noise. The vehicle is still in development, and will be available for the first time in 2020.

Volvo X Models

The Volvo X line were prototypes that likely lead to the previously discussed. They were created as research products looking to examine the viability of light weight electric vehicles in the construction sector. Volvo projected the vehicles would reduce the lifetime cost of ownership by 25% on average.

Volvo HX2

The Volvo HX2 is a fully electric, autonomous load carrier, with four wheel steering and four wheel drive. The vehicle is the first fully autonomous load carrier to be used in a functional quarry. Eliminating the need for a driver has increased the efficiency of the vehicle immensely. The vehicle is still being developed, and is not currently available for purchase. But 8 HX2s have been deployed to various mining sites for a sort of beta testing.

Volvo Summary

Volvo is currently looking to roll out a full line of light and medium electric construction vehicles in the 2020s and eventually plans to move away from diesel. However, Volvo notes that it currently has no plans for a similar move to electric among its larger excavators and loaders as diesel remains “the most appropriate power source” for these larger machines.

Other (7% Market Share)

This section will examine electrification advancements beyond the top producers in the US. The companies that are covered here are: Multi-Tool Trac, Wacker Neuson, Manitou, Takeuchi, Hidromek, Liebherr and Mecalac. The companies listed here range from startups, to large market contributors in markets outside of the United States. Many of the products listed in this section are prototypes, meaning they are not yet market available.

Wacker Neuson WL20e

The WL20e is the first fully electric wheel loader from the German manufacturer. The wheel loader can operate up to 5 hours on a full charge of 8 hours. The WL20e offers the traditional benefits of a full electric vehicle: lower maintenance costs, lower fuel costs, lower noise pollution and instantaneous acceleration. Beyond that it has a 40% lower operating cost than its diesel equivalent would. This vehicle is currently available for purchase, but an MSRP was not found.

Wacker Neuson EZ17e

The EZ17e is a fully electric compact excavator with the same weight and performance abilities as its diesel counterpart. However, unlike its diesel counterpart it has zero emissions, no noise and significantly lower maintenance costs. It is projected to have an MSRP that is 20-25% higher than its diesel counterpart and will be available in the US by the end of 2019.

Wacker Neuson EZ26e

The EZ26e is a full electric version of 2.6 ton EZ26. This fully electric excavator is a heavier duty version of the EX17e, however it is currently just a technology study and there is no timeline for its market availability.

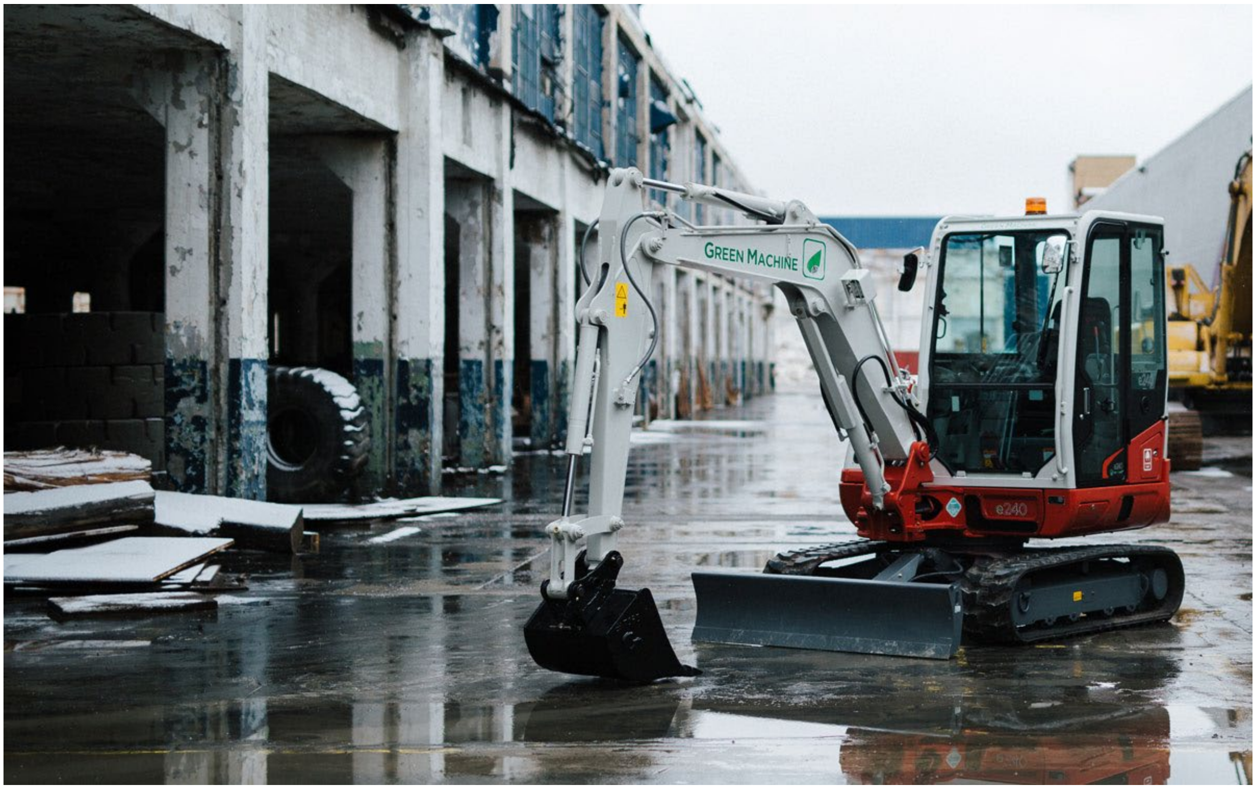
Wacker Neuson DW15e

The DW15e is a fully electric wheel dumper that incorporates an all-wheel drivetrain as a lead-acid battery, which yields similar performance to its diesel equivalent. The payload goes up to 1.5 metric tons and has an electric motor that transfers energy lost to breaking into electric potential energy for the battery. Its size and lack of emissions makes it ideal for use in tight quarters. It is currently available, but no MSRP was found.

Deutz/ Manitou MT 1135 Telehandler

This is a standard diesel Manitou MT 1135 that is fitted with a Deutz TCD 3.6 electric motor that produces 60 kW. The vehicle boasts all of the benefits of a full electric model: Lower maintenance and operating costs, no noise, and zero emissions. The vehicle is still currently in the development phase, but Manitou has given the vehicle a release date of 2022. Beyond that Manitou has claimed that there will be a sizeable market for the vehicle and that the full electric version will make up 5-10% of its total sales upon release.

Takeuchi e240



The Takeuchi e240 is a fully electric mini excavator. The excavator takes 10 hours to recharge a 9-hour runtime. The e240 has a lifetime warranty of 2000 charge cycles or 12 years. The vehicle is also 90% less expensive to operate, 50% less noisy, and produces zero emissions. The vehicle is currently on the market, but no purchase price for a new vehicle was found.

Hidromek H4 Series

The Hidromek H4 is a fully electric excavator that was just premiered at Bauma 2019. The machine is one of the few full sized fully electric excavators in production. The full electric engine brings all of the traditional benefits of electric powered technology discussed throughout the paper. Added features include added safety sensors, and visual safety laser lit parameter marker for surrounding site workers. The vehicle was just previewed at Bauma 2019 and is not currently market available.

Liebherr R 9200 E

The Libherr R 9200 E is a fully electric full sized (210 ton) Excavator, that produces 850 kW. The electric motor yields all of the traditional benefits of electric motors already discussed. However, this model has the added benefit of being able to start more easily in cold weather which can be an issue for this vehicle’s diesel siblings. This is one of the few full sized electric excavators in development. The vehicle was first reviled at Bauma 2019 and is not yet market available.

Liebherr T236

The Liebherr T236 is a diesel-powered electric drive 100 ton mining truck. It boasts a payload class of 110 tons and 1200 horsepower. It runs on a Cummins QST 30-C and the electric drive provides a reduction in fuel costs and maintenance costs. The main draw for electrifying this model is the improved acceleration, the ability to climb steeper inclines, and the lack of gears which leads to lower maintenance costs.

Mecalac E12

The Mecalac E12 is a fully electric prototype of its 12MTX excavator that is being targeted for use by building sites in urban areas. The E12 has a 146 KWh capacity for 8 hours before a recharge of 6-7 hours is required. Trials state that the E12 will have a lower maximum travel speed than its diesel counterpart but will have the same duty cycle capabilities and the same digging and lifting capabilities. The E12 was set for release in mid-2019 but is not yet currently available.

JBC 19C-1E

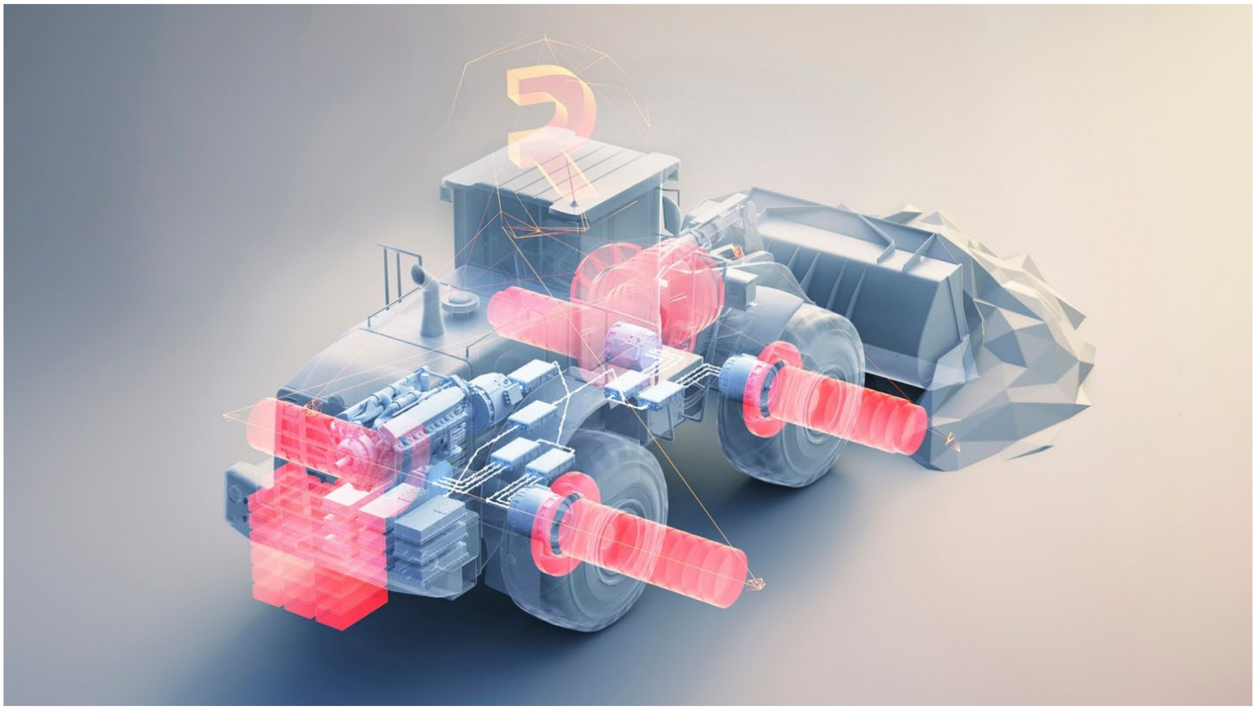
The JCB 19C-1E is a fully electric mini excavator. The vehicle weighs just two tons and is optimal for use in confined spaces. The vehicle can fast charge in just two hours and recharges in 8 hours on a traditional 230 V source. The vehicle boasts the same benefits of fully electric vehicles: quieter operation, lower operating and maintenance costs and reduced emissions. However, the zero emissions motor also allows this vehicle to be used in confined spaces, an attribute that is conducive to its size.

BOMAG BW 120 AD-5 E

This battery electric tandem roller is offered alongside its diesel and liquid petroleum gas (LPG) variants, the electric one aimed at operations in enclosed spaces. It has a

24.8 HP electric motor and maintenance-free batteries. The electric drivetrain is advertised to provide operational cost savings of up to 40%, with simpler and faster maintenance due to simpler construction compared to conventional ones.

Danfoss Editron Fully Electric Wheel Loader System



The Danfoss Editron battery electric wheel loader system includes a synchronous reluctance-assisted permanent magnet motor capable to operate at up to 4000 rpm. It's 650V battery runs the motor through DC/AC converter; other subsystems are operated by the DC link voltage, fed through DC/DC converter from the battery.

Agriculture

The agriculture sector is lagging behind the mining and construction sectors by a significant amount in terms of producing market ready models for electrified vehicles. Of the six manufacturers with the top market share in the US, only 2 have electrified products and none of the products are currently available for purchase. Two smaller players had electric tractors in the prototype phase as well. Due to the lack of options per manufacturer, this section will not be broken down as the previous section was.

John Deere SESAM

The John Deere SESAM is a fully electric tractor prototype, previewed by John Deere in 2016. The vehicle will likely last for 3100 charging cycles at 4 hours of operation per cycle. The SESAM has the traditional benefits of full electric vehicles including being totally silent, emitting no onsite CO_2 and having lower operations costs. But a large bonus this tractor has over other tractors is no idle fuel costs, a trait that Deere believes is a large benefit this prototype has over other tractors. This vehicle is a prototype and does not have a release date or price yet.

John Deere Gridcon Electric Tractor

The John Deere is a prototype fully electric tractor with a unique battery free cockpit free design. The tractor is controlled autonomously and is given the data about where and how to run by computer. The tractor eschews a traditional battery by fitting the tractor with a 1km long power chord that uncoils as the tractor moves away from its initial location, and recoils as it moves back, in an effort to reduce cable ware. This is the only tractor of its type in the prototype phase. The tractor boasts all of the traditional benefits of a fully electric vehicle, and is also guided by computer mapping, leading to autonomous run time options for the vehicle. The vehicle is a prototype and is not currently available.

AGCO Fendt e100 Vario

The AGCO Fendt e100 Vario is a fully electric compact tractor. It produces 50 kW for a 5-hour charge and recharges 80% of its battery in 40 minutes. It also boasts an energy recovery system found in some hybrids. The vehicle has lower operations costs, maintenance costs and makes less noise than its diesel siblings. The tractor is marketed toward use in cities. The tractor also makes use of sensors and heat pumps to make a point to manage heat and atmosphere in the vehicle. Stats on the efficiency of the vehicle can be analyzed on computers. This vehicle is available in select areas, but no price is available.

Carraro Ibrido

The Carraro Ibrido is a plug-in hybrid electric tractor. The tractor has three run modes: Full electric, full diesel and hybrid. It can run purely on electricity for uses inside of enclosed structures like greenhouses, stables and municipal applications. It can run on purely diesel when hauling heavy loads or when being driven long distances. Or it can run as a hybrid which is ideal for short distance transportation or for towing medium loads. Carraro claims the CO2 reduction improves the health of the crops it will be servicing, as does the vehicle’s reduction in vibrations. The Ibrido was first reviled at Bauma 2019 and is not yet avalible for purchase nor does it have a sales price.

Multi-Tool Trac

The Multi-Tool Trac is a plug in hybrid tractor that boasts 210 horse power and a top speed of 40 kph. The tractor can run on electric power for an hour if it is on-road, and for 30 minutes if not, but it is meant to run as a hybrid. The goal of the multi-tool-trac is to improve soil quality. The MTT was built with thin wheel with an adjustable radius from the center of the vehicle in order to increase the area of farmable land and high quality soil. The vehicle has an electric powertrain to provide higher torque, better traction and more precise driving. MTT claims their vehicle will raise farming yields up to 20%. The MTT was first built in 2015 and has been undergoing small boutes of experemental use in farms since then. The goal is to have the product market avalible by the end of 2019.

The equipment information are summarized in the following tables:

Table B - 1. Available Electrified Off-Road Vehicle

Type of Vehicle	Company	Model Name	Electrification Tech	Horsepower (HP)	Hybrid or ZEV	Available?	Major or Minor Company	Price	Lifetime Warranty	Fuel improvement (ZEV = NA)	Size	Industry
Tractor	AGCO	Fendt e100 Vario	Electric	67	ZEV	Limited Availability	Minor			NA	Compact	Agriculture
Dozer	CAT	D6E	Electric Drive Train	235	Hybrid	Available	Major	350000	7 Years	35%	Heavy	Construction
Excavator	CAT	336E	Swing Regeneration	308	Hybrid	Available	Major		5 Years	37%	Heavy	Construction
Dozer	CAT	988K	Electric Drive Train	492	Hybrid	Available	Major		3 Years	25%	Heavy	Construction
Mini Excacavator	CAT	300.9D	Plug in Electric	18	ZEV/Diesel	Available	Major	20000			Compact	Construction
Loader	Deere	944K	Hybrid Drive	536	Hybrid	Available	Major	700000		11%	Heavy	Construction
Excavator	Komatsu	HB215LC	Swing Regeneration	185	Hybrid	Available	Major	150000	5 Years	20%	Heavy	Construction
Forklift	Komatsu	AE 50	Electric	NA	ZEV	Available	Major	15000	5 Years	NA	Compact	Construction
Dozer	Wacker Neuson	WL20e	Electric	21	ZEV	Available	Minor	50000	2000 hours	NA	Compact	Construction
Mini Excavator	Wacker Neuson	EZ17e	Electric	NA	ZEV	Available	Minor	22.5% more than diesel		NA	Compact	Construction
Excavator	JCB	19C	Electric	27	ZEV	Available	Minor			NA	Compact	Construction
Mining Truck	Komatsu	830 R	Hybrid Drive	2500	Hybrid	Available	Major				Heavy	Mining
Mining Truck	Komatsu	930 E-4	Hybrid Drive	2700	Hybrid	Available	Major				Heavy	Mining
Cart	Deere	TE 4x2	Electric	NA	Electric	Available	Major	11659		NA	Compact	Miscellaneous
Electrification Kit	Deere	Electrification Kit	Hybrid Drive	NA	Hybrid	Available	Major			25% (Varies)	NA	Miscellaneous
Electrification Kit	Terex	HyPower	Hybrid Drive	NA	Hybrid	Available	Major		5 Years	10%	NA	Miscellaneous

Table B - 2. Announced Electrified Vehicles

Type of Vehicle	Company	Model Name	Electrification Tech	Horsepower (HP)	Hybrid or ZEV	Available?	Major or Minor Company	Fuel improvement (ZEV = NA)	Size	Niche Operation	Industry
Tractor	John Deere	SESAM	Electric	268	ZEV	Prototype	Major	NA	Heavy	NA	Agriculture
Tractor	John Deere	Gridcon Electric Tractor	Giant Power Cable	268	ZEV	Prototype	Major	NA	Heavy	Autonomous	Agriculture
Tractor	Carraro	Ibrido	ZEV/Diesel	27	Hybrid	No Release Date	Minor		Compact	Small for Vineyard Use	Agriculture
Tractor (Altered Design)	Multi-Tool	Multi-Tool Trac	Plug in Hybrid	60	Hybrid	Release Date	Minor		Compact	Adjustable Track Length	Agriculture
Excavator	Komatsu	Electric Mini Excavator	Electric	24	ZEV	No Release Date	Major	NA	Light	Safe Breathing in Building Shells	Construction
Excavator	Volvo	CE 300E	Swing Regeneration	213	Hybrid	No Release Date	Major	14%	Heavy	NA	Construction
Dozer	Volvo	L25	Electric	NA	ZEV	Release Date	Major	NA	Compact	Usable in ZE Zones	Construction
Excavator	Volvo	EC25	Electric	22.9	ZEV	Release Date	Major	NA	Compact	Usable in ZE Zones	Construction
Dozer	Volvo	LX2	Electric	NA	ZEV	Prototype	Major	NA	Heavy	NA	Construction
Mini Excacavator	Volvo	EX2	Electric	NA	ZEV	Prototype	Major	NA	Heavy	NA	Construction
Hauller	Volvo	HX2	Electric	NA	ZEV	No Release Date	Major	NA	Compact	Autonomous	Construction
Excavator	Wacker Neuson	EZ26e	Electric (Plug In Mode)	NA	ZEV	Prototype	Minor	NA	Compact	NA	Construction
Lifter	Manitou/ Deutz	TCD (w/BEV Engine)	Electric	80	ZEV	Release Date	Minor	NA	Compact	Usable in ZE Zones	Construction
Mini Excacavator	Takeuchi	e240	Electric	63	ZEV	No Release Date	Minor	NA	Compact	Safe Breathing in Building Shells	Construction
Excavator	Liebherr	R9200 E	Electric Drive Train	1139	Hybrid	No Release Date	Minor		Heavy	NA	Construction
Wheel Excavator Loader	Mecalac	E12	Electric	100	ZEV	No Release Date	Minor	NA	Compact	Safe Breathing in Building Shells	Construction
Excavator	CAT/Pon	323F Z-line	Electric (Conversion)	164	ZEV	Prototype	Major	NA	Heavy	NA	Construction
Excavator	Hidromek	H4	Electric	NA	ZEV	No Release Date	Minor	NA	Heavy	NA	Construction
Mining Truck	Liebherr	T236	Electric Drive Train	1200	Hybrid	No Release Date	Minor		Heavy	Safe Breathing Updergro und	Mining
Wheel Loader (Underground)	CAT	R1300G	Battery Electric	165	ZEV	Prototype	Major	NA	Heavy	Safe Breathing Updergro und	Mining

Appendix C: Review of Electric Motors for Off-Road Equipment

Manufacturers typically do not reveal the specifics of the brands, models and specs of the electric motors they use for their off-road electrified vehicles. This section seeks to remedy this lack of information. We started with a database of electric motors from medium and heavy-duty electric vehicles. We then examined the energy and torque outputs of each electric motor to decipher the specific off-road vehicles each on-road motor could potentially be used for. Provided below is a range of different max torque and kW outputs for different electrified construction and agriculture vehicles.

There is a large range of torque and kW output requirements called for by construction and agriculture equipment. All of the motors examined have the potential to fit off-road equipment. All of the non-hybrid vehicles had torque and power requirements that could be matched by motors examined here. However, the two heavy duty hybrid vehicles had power demands that exceeded the outputs of the electric motors and would likely require either multiple electric motors or a hybrid configuration to operate at the advertised power. Hybrid configurations tend to make sense for vehicles with the most extreme engine requirements. ICE engines provide more continuous power generation, while electric motors provide superior instantaneous torque which yields more acceleration. A potent configuration could be to utilize a high-powered electric motor as the primary source of torque and power, while utilizing an ICE engine to provide extra power when high amounts of continuous power are used. This strategy could focus specifically on vehicles that require high torque outputs in operation but only require high continuous power outputs in transportation from location to location.

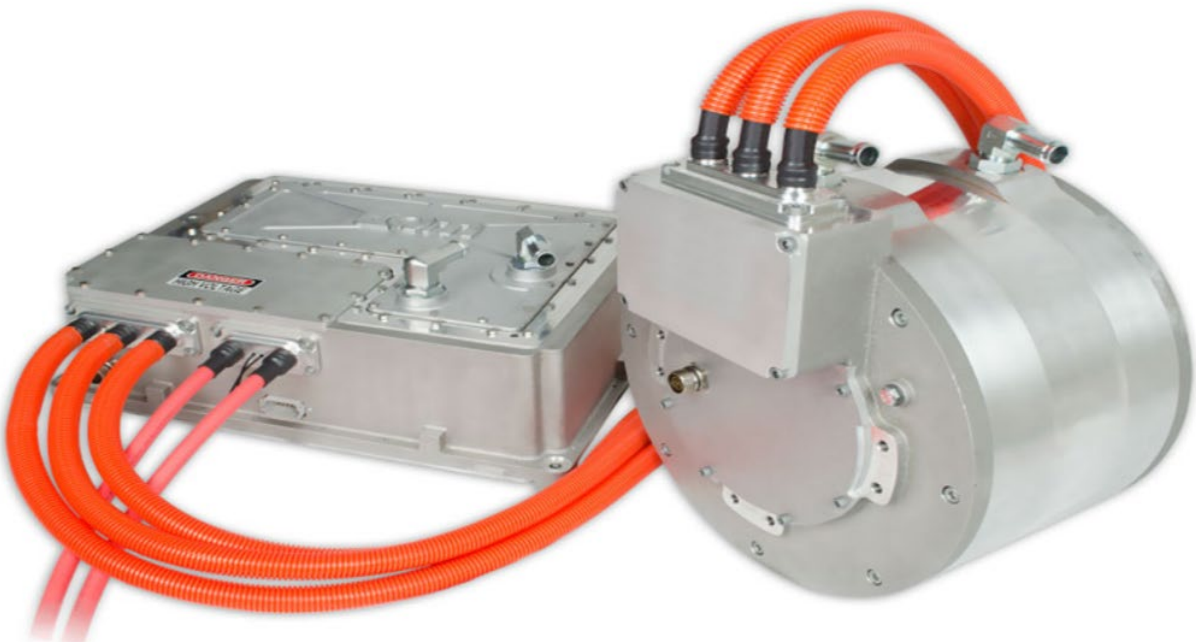
Torque and power ratings of the studied motors are presented in the following table:

	Model	**Torque and power ratings**
Construction	Volvo EC300E	1238Nm 180 kW
	Deere 944K Hybrid Wheel Loader	2530 Nm 400 kW
	CAT 988K XE	2852 Nm 432 kW
	Volvo Mini Excavator	77 Nm 38 kW
	Hidromek HMK 640WL	1600 Nm 242 kW
	Libherr TL 432-7	74kW
Agriculture	Deere 3029D	148.1 Nm 43 kW
	Deere 3029T (Turbocharged)	192 Nm 48 kW

The currently available products are listed below:

UQM HD200

https://www.uqm.com/products/propulsion/automotive/default.aspx



The UQM 200 series is a series of three electric motors specified for heavy duty vehicle fleets. The motors range of torque and power production are:

PowerPhase HD 220: 700 Nm peak, 350 Nm continuous and 220kW peak, 120 kW continuous

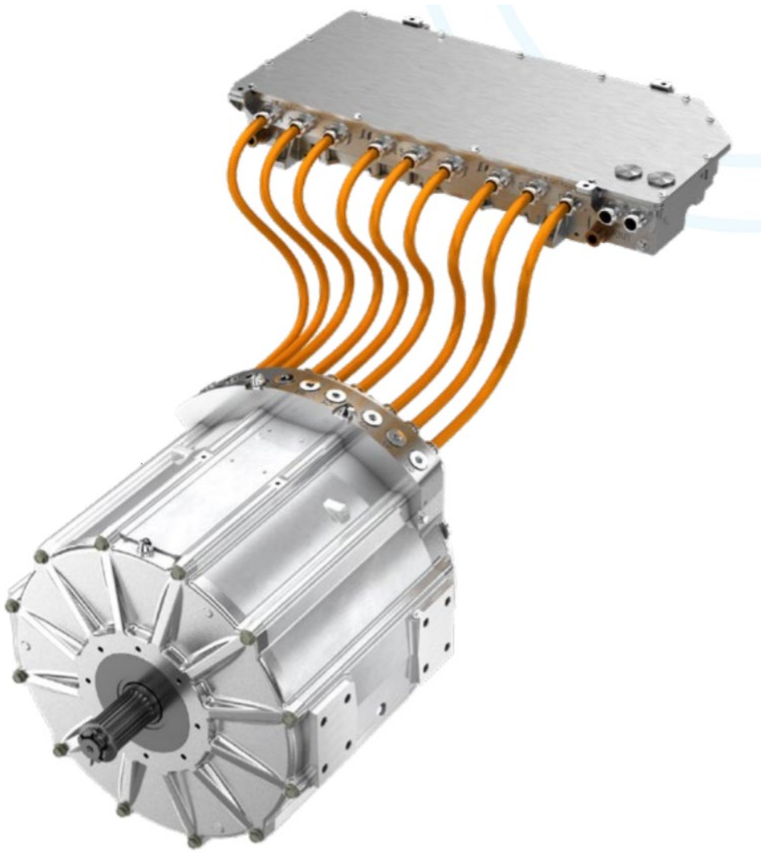
PowerPhase HD 250: 900 Nm peak, 360 Nm continuous and 250 kW peak, 150 kW continuous

PowerPhase HD 950T: 950 Nm peak, 400 Nm continuous and 145kW peak, 100 kW continuous

While not specifically indicated for use in construction or agriculture equipment, the motors have been used in airplane tug and mining vehicles. Its use in vehicles up to 18000 kg is recommended, meaning it is applicable for most construction and agriculture applications.

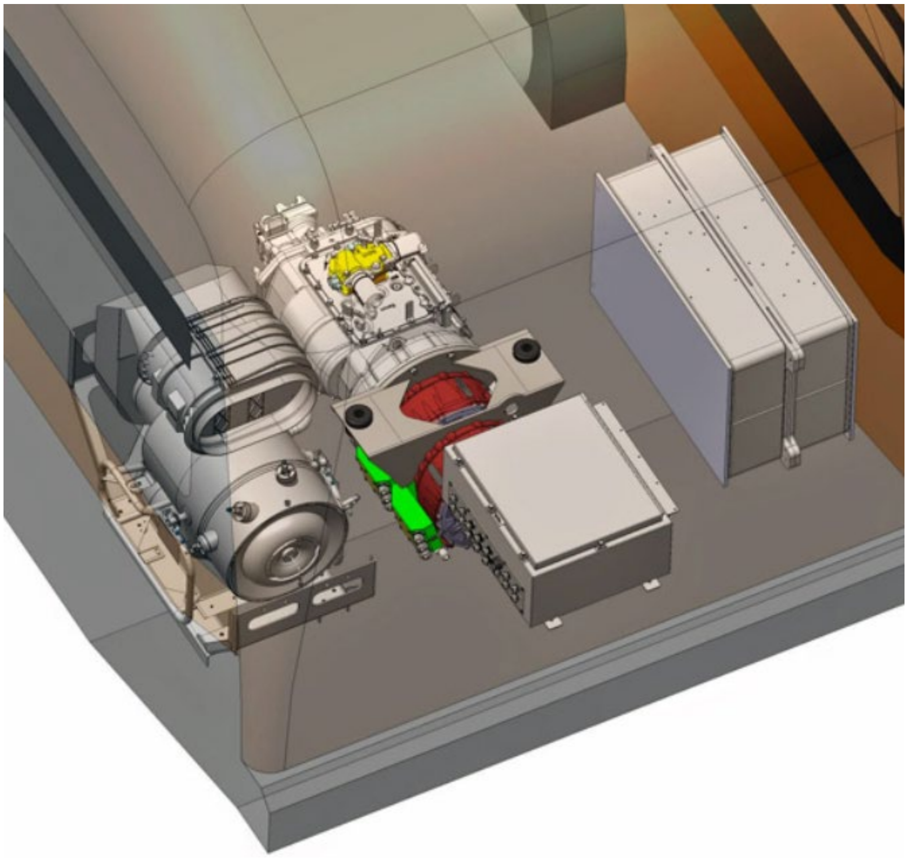
TM4 SUMO

https://www.danatm4.com/wp-content/uploads/2019/08/TM4-SUMO-HD_Dana-TM4_web.pdf



The TM4 SUMO is a series of electric motors produced by TM4. The range of torque of the three motors in the set is:
HV2700-9P: 2700 Nm peak, 2060 Nm continuous and 250 kW peak, 195 kW continuous
HV3400-9P: 3400 Nm peak, 2060 Nm continuous and 250 kW peak, 195 kW continuous
HV3500-9P: 3445 Nm peak, 1970 Nm continuous and 370 kW peak, 260 kW continuous

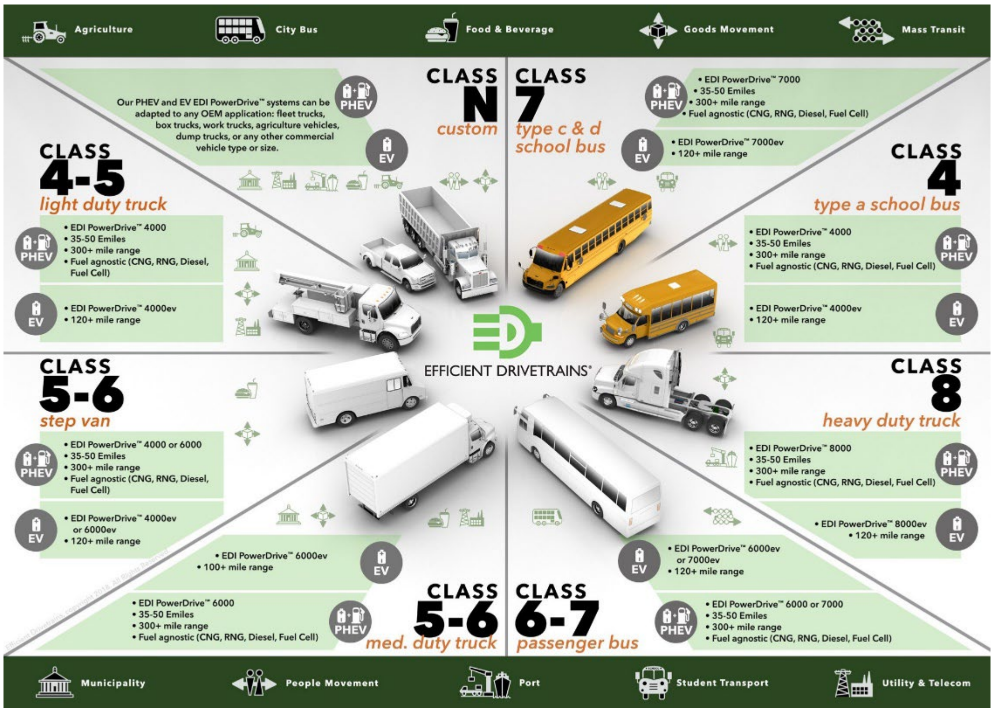
TransPower's ElecTruck™ Main Propulsion System (MPS)



The TransPower ElecTruck is an electric motor fit for light and medium duty applications requiring up to 200 horsepower (149.14 kW). Specifications on the motor were not supplied by the company, but the motor is used in several heavy duty on-road applications. And has been used for forklift applications.

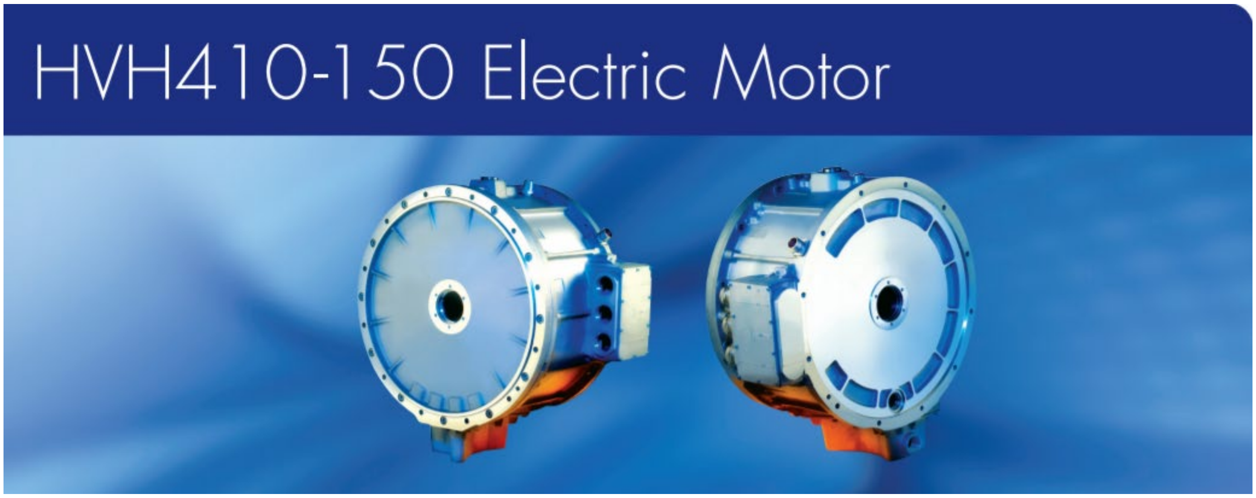
EDI Powerdrive

https://efficientdrivetrains.com/edi-powerdrive/



Efficient Drivetrains (EDI) offers a line of full powertrains targeted at all manner of on road vehicles. However, EDI claims the motors could be used in agricultural settings and are highly transferable to other heavy-duty applications. They offer both hybrid and full electric drive trains with varying mileage ranges and power outputs. All the hybrid drivetrains are fuel agnostic and come equipped with a fully electric drive mode. However, there is no information provided on the specs or power outputs of these vehicles.

Borg Warner HVH410-150 Electric Motor



The HVH410-150 Electric Motor is offered by Borg Warner and is advertised for use in on-road, off-road vehicles along with specialty high power demand applications. The motor has a max instantaneous torque of nearly 2000 Nm and a max continuous torque of nearly 1400 Nm. Also boasting power outputs of 160 instantaneous kW and 120 kW continuous kW. The two differing models of the motor, the SOM and DOM, have varying torque profiles to fit different power needs of different vehicles.
https://www.borgwarner.com/docs/default-source/default-document-library/remy-pds---hvh410-150-sheet-euro-pr-3-16.pdf?sfvrsn=a642cd3c_11

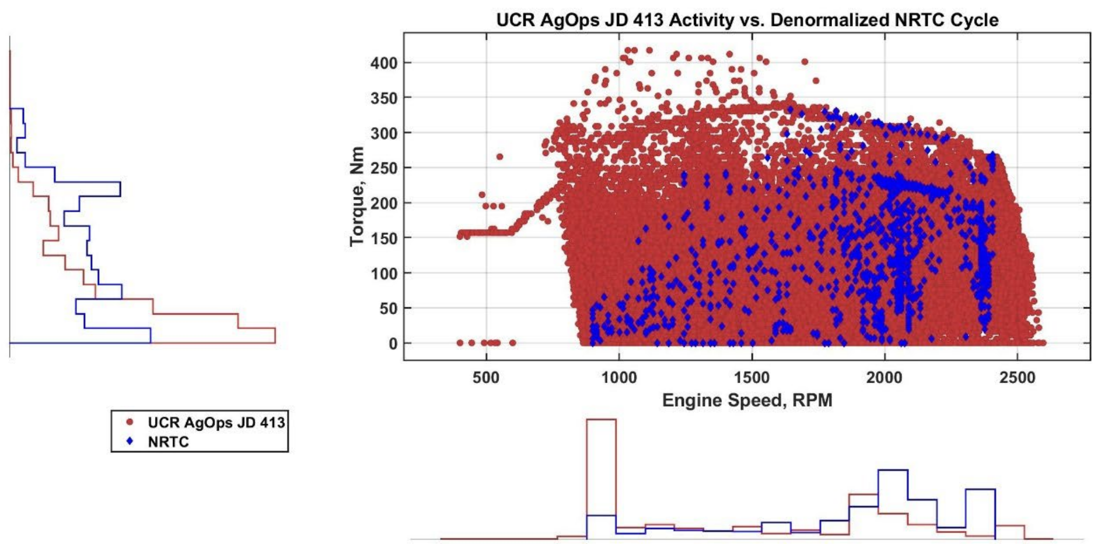
EVO Axial Flux Electric Motors

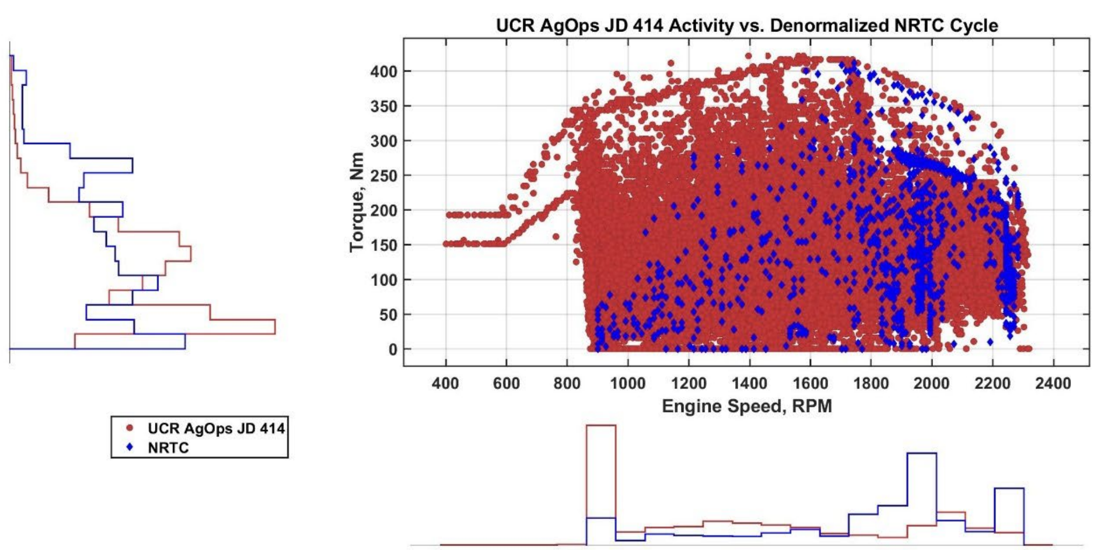
The EVO Axial Flux Motors are a line of five electric motors offered by EVO. Only three of the five have torque outputs that would potentially be applicable for construction purposes:
260 Nm continuous, 600 Nm peak and 94 kW continuous, 220 kW peak
290 Nm continuous, 700 Nm peak and 128 kW continuous, 280 kW peak
520 Nm continuous, 1200 Nm peak and 188 kW continuous, 440 kW peak.
The 145 Nm continuous 350 Nm peak, 64 kW continuous, 140 kW peak model is likely also applicable for agriculture applications. The motors are highly customizable and can be specially made to fit different applications with different torque and horsepower requirements. The motors boast a power density of 10kW/Kg and a peak efficiency of 96%.

Appendix D: Scatter Plots and Histograms of Torque and Engine Speed

This appendix presents torque and engine speed plots along with accompanying histograms, as described in Section 3.3, for the collected data and the Nonroad Transient Cycle.

Agricultural Tractor

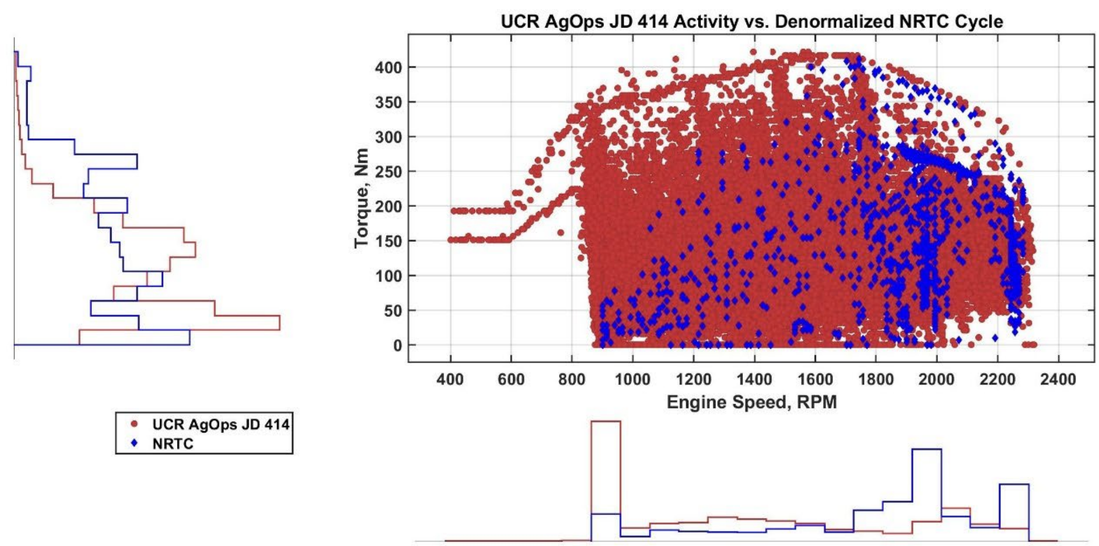




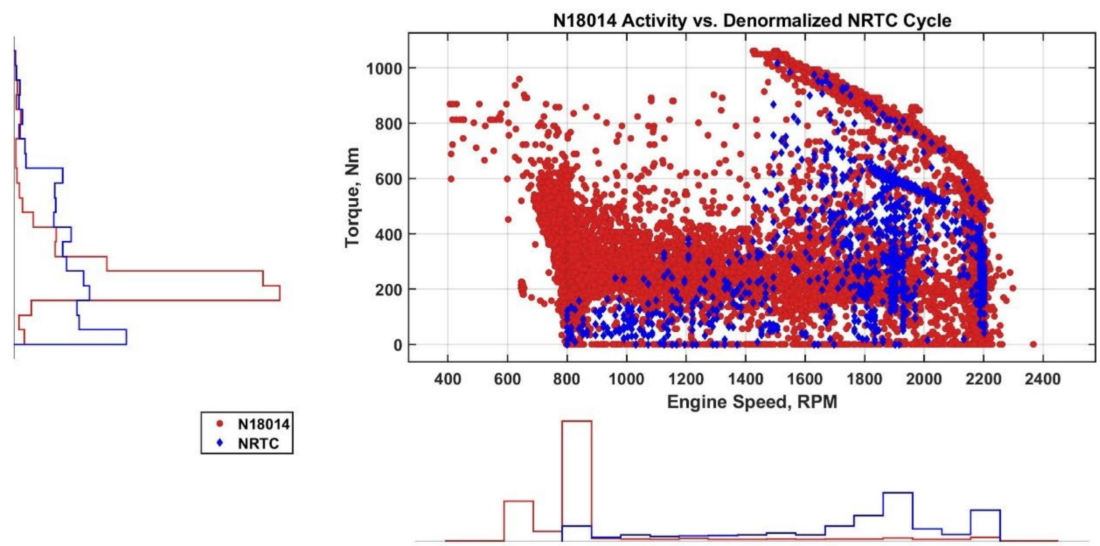
Crawler Tractors

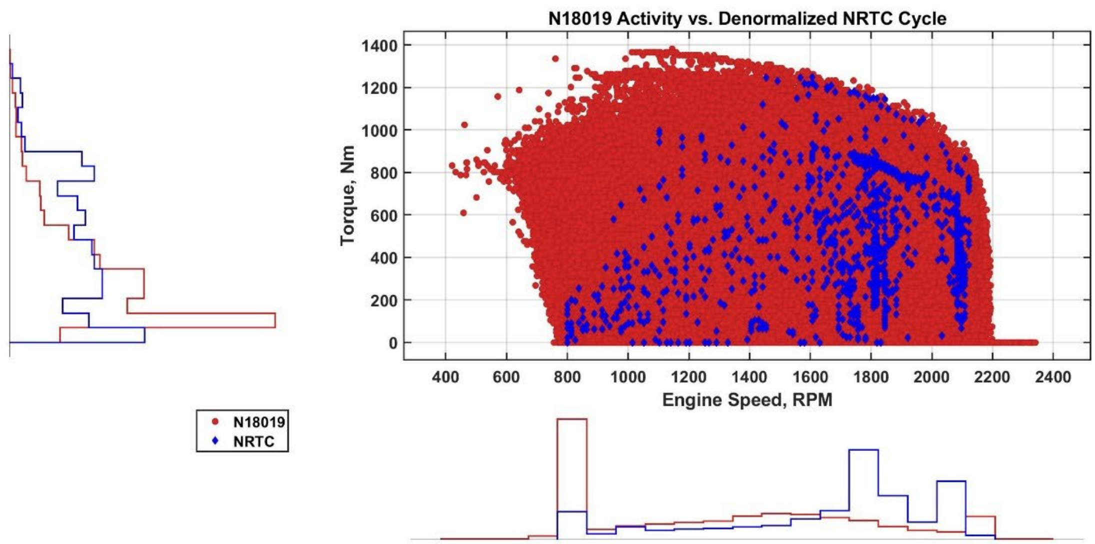
Data were collected from two crawler tractors. However, for both crawler tractors the data for engine parameters needed to calculate or estimate engine brake power were unavailable so torque cannot be determined or estimated.

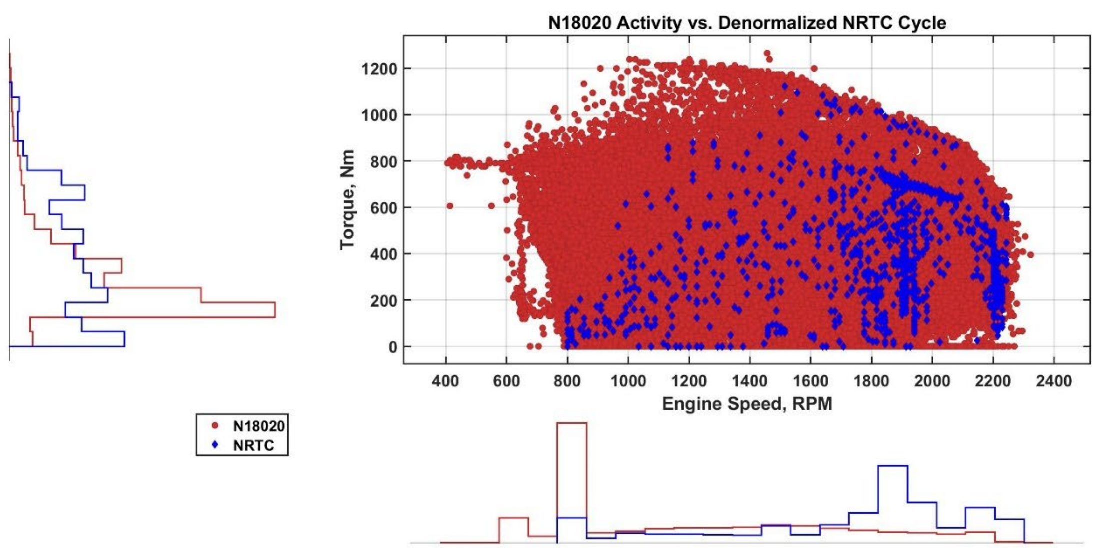
Excavator

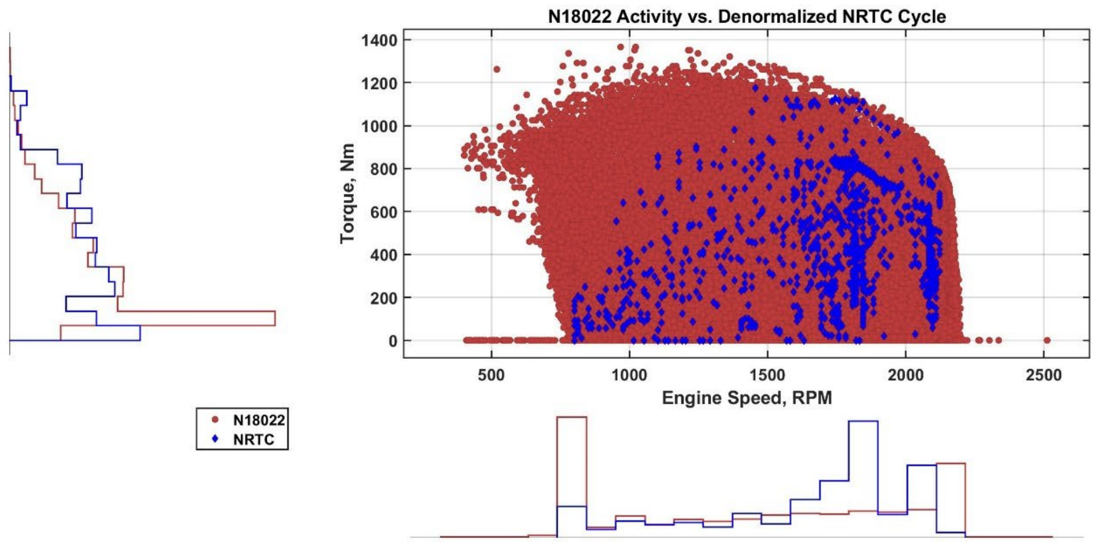


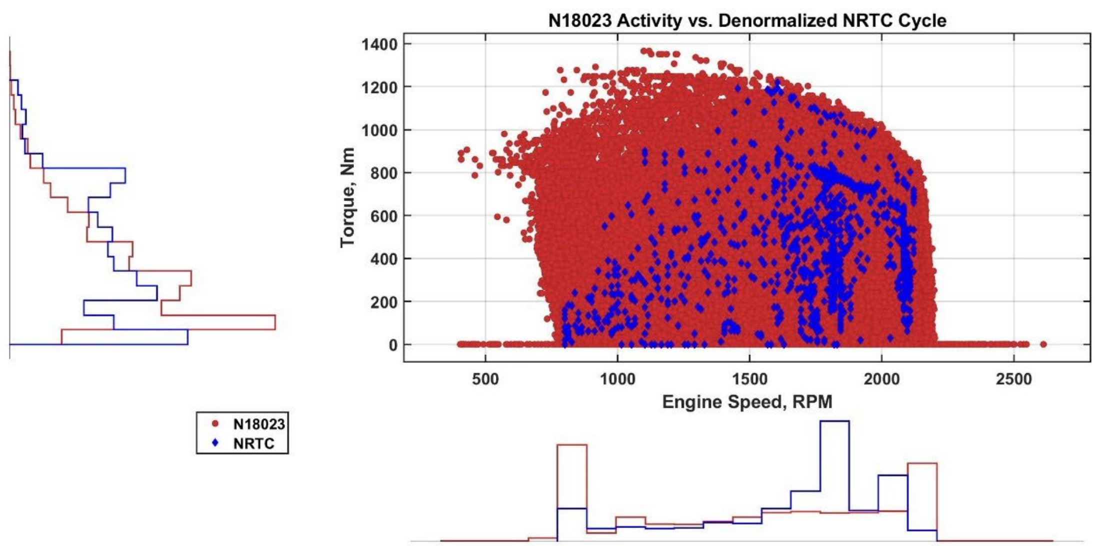
Grader



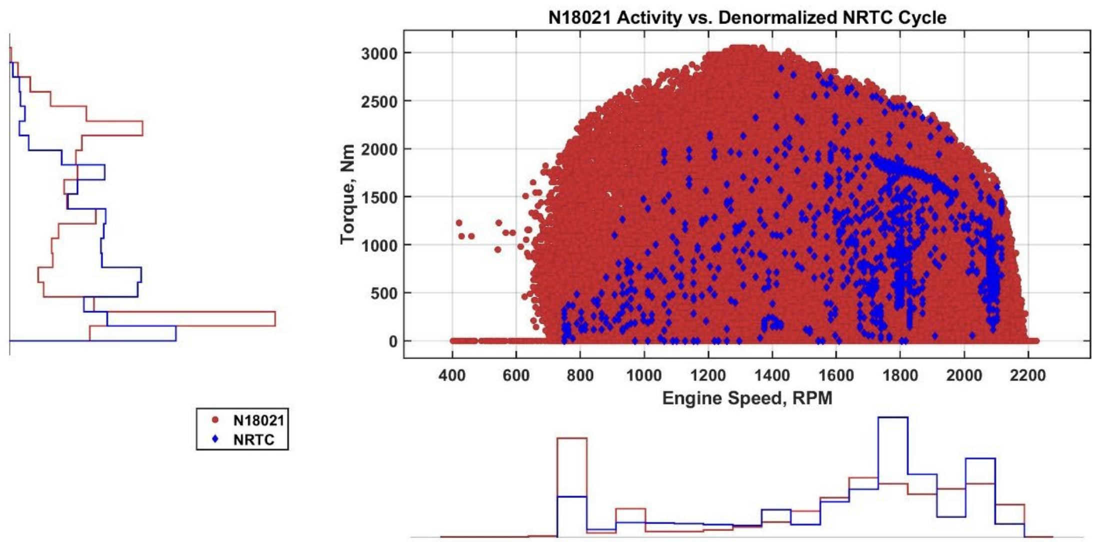

N18019 Activity vs. Denormalized NRTC Cycle
Torque, Nm
Engine Speed, RPM
N18019
NRTC

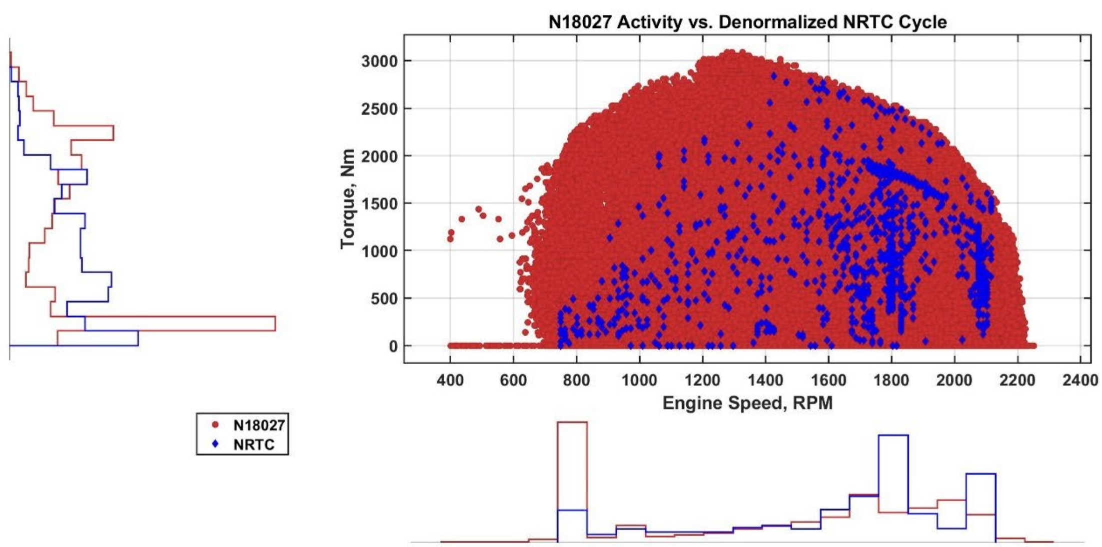

N18020 Activity vs. Denormalized NRTC Cycle
Torque, Nm
Engine Speed, RPM
N18020
NRTC


N18022 Activity vs. Denormalized NRTC Cycle
1400
1200
1000
800
600
400
200
0
Torque, Nm
500
1000
1500
2000
2500
Engine Speed, RPM
N18022
NRTC

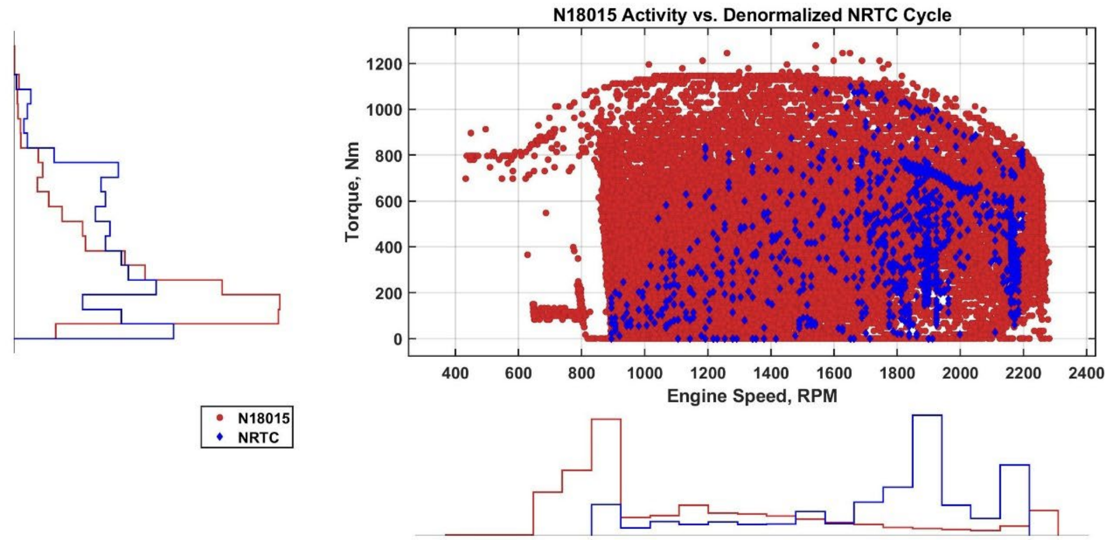

N18023 Activity vs. Denormalized NRTC Cycle
1400
1200
1000
800
600
400
200
0
Torque, Nm
500
1000
1500
2000
2500
Engine Speed, RPM
N18023
NRTC

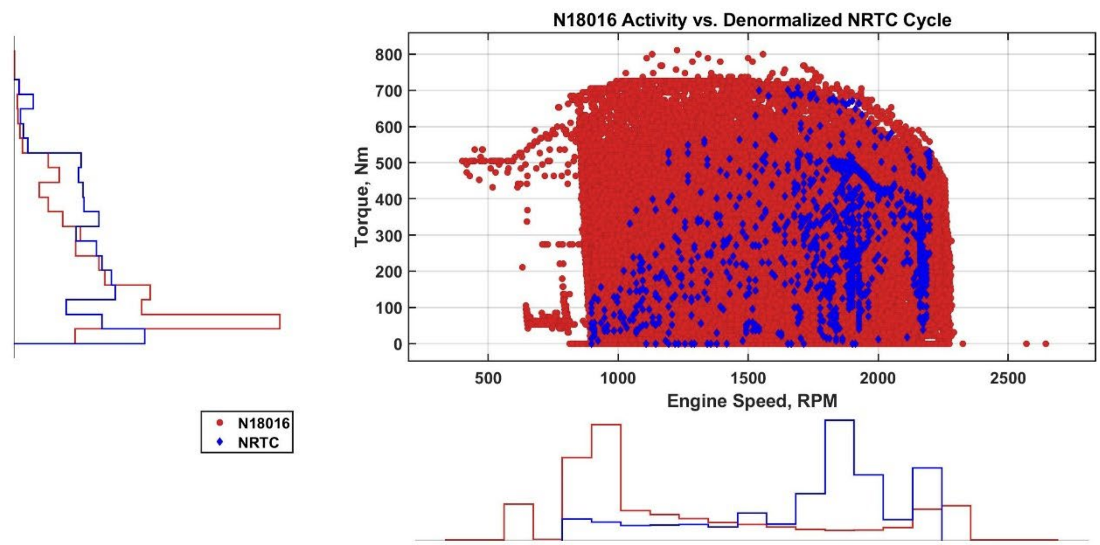
Off-Highway Tractors

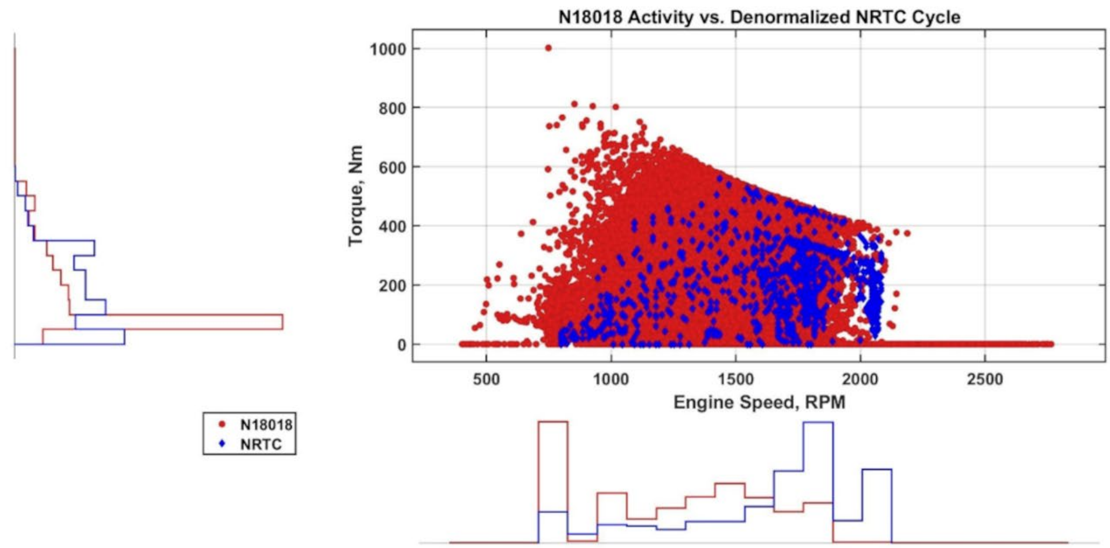


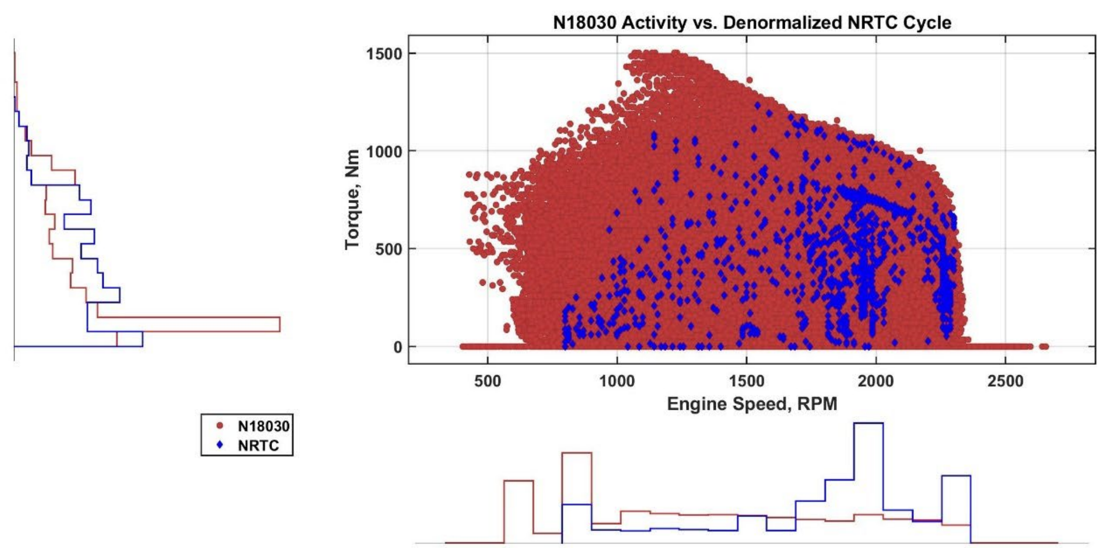


Rubber Tired Loaders

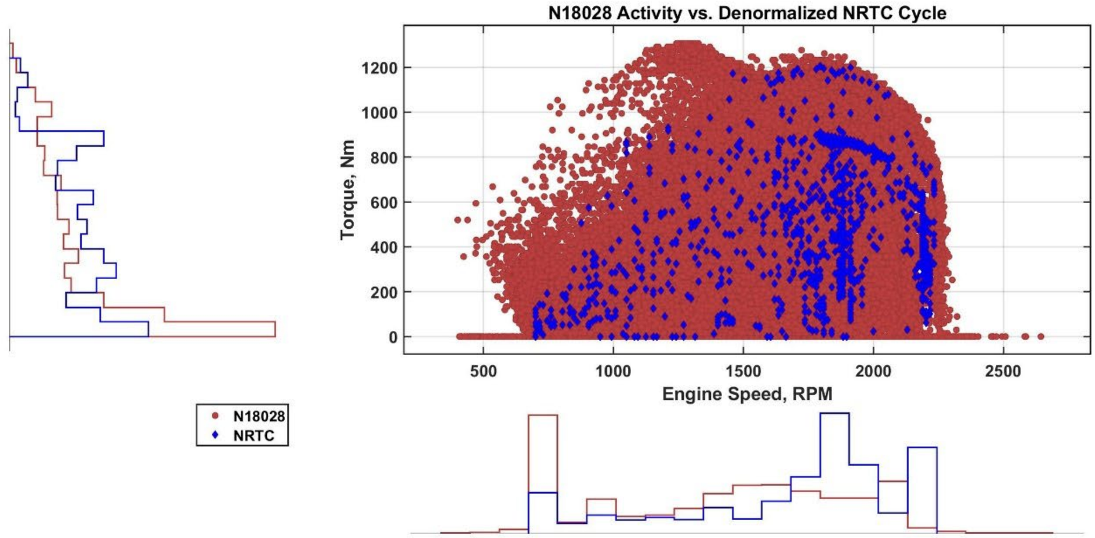


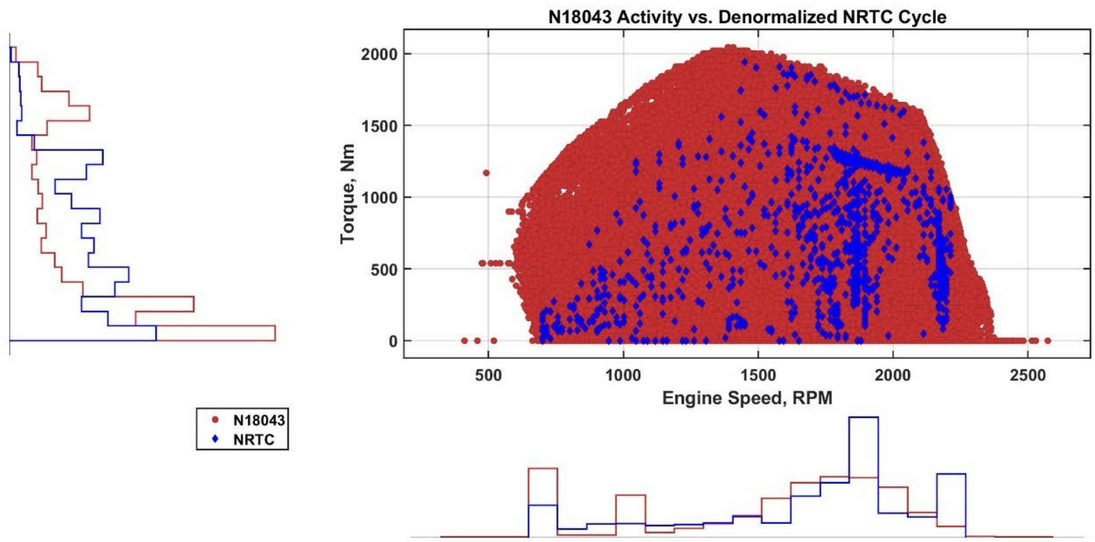



N18018 Activity vs. Denormalized NRTC Cycle
Torque, Nm
1000
800
600
400
200
0
500
1000
1500
2000
2500
Engine Speed, RPM
N18018
NRTC

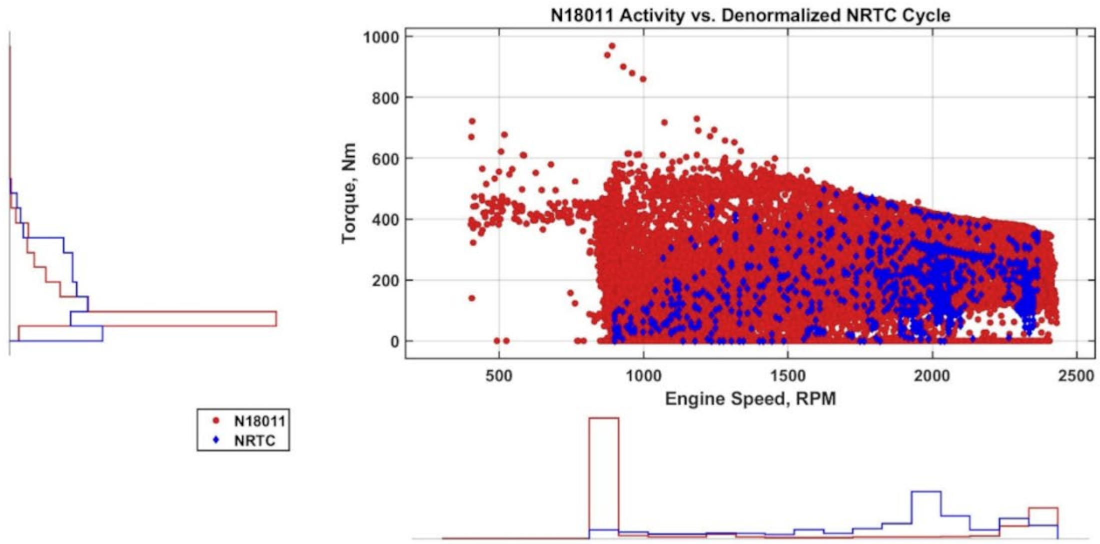

N18030 Activity vs. Denormalized NRTC Cycle
Torque, Nm
1500
1000
500
0
500
1000
1500
2000
2500
Engine Speed, RPM
N18030
NRTC

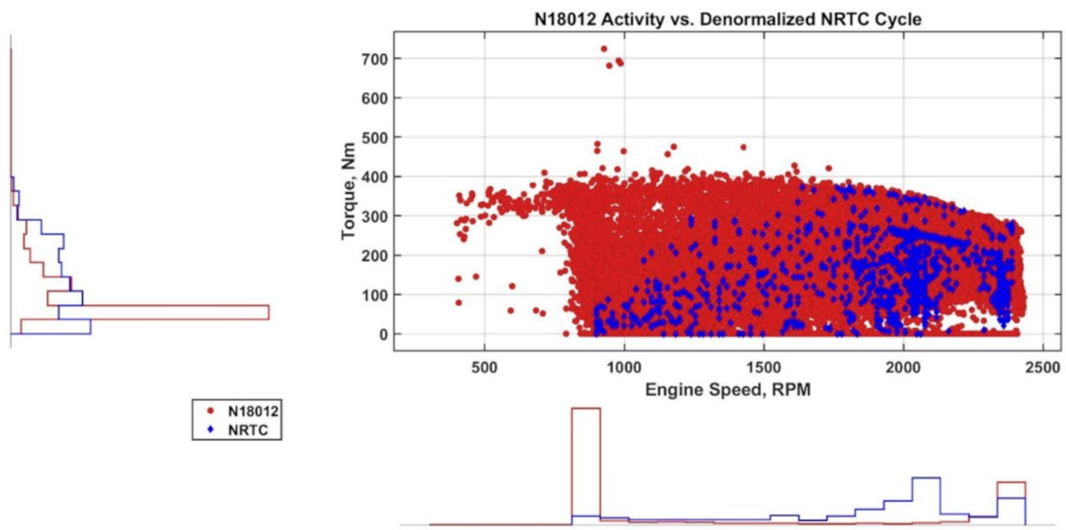
Scraper

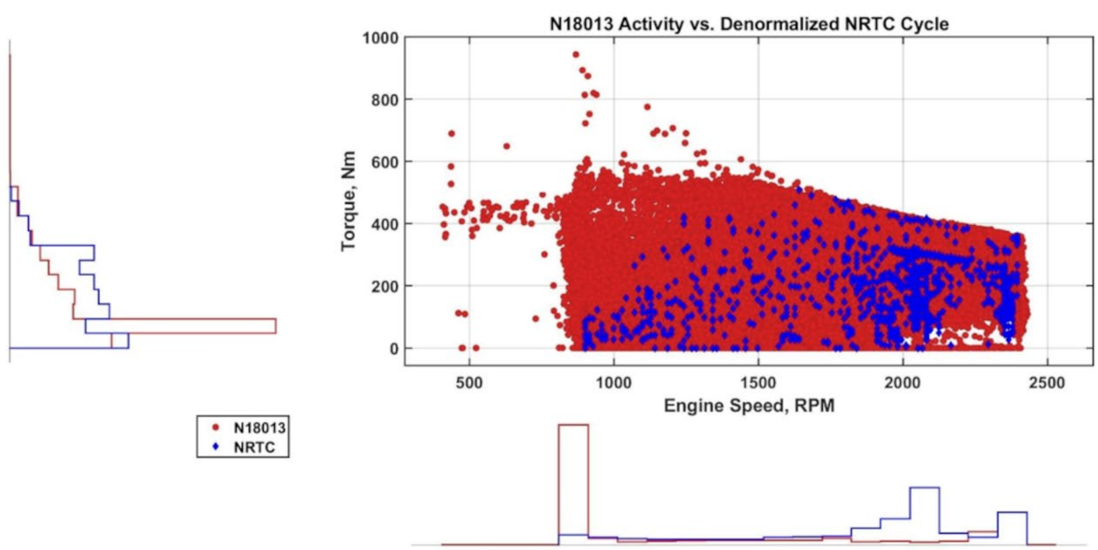

N18028 Activity vs. Denormalized NRTC Cycle
Torque, Nm
Engine Speed, RPM
N18028
NRTC


N18043 Activity vs. Denormalized NRTC Cycle
Torque, Nm
Engine Speed, RPM
N18043
NRTC

Tractor/Loader/Backhoe



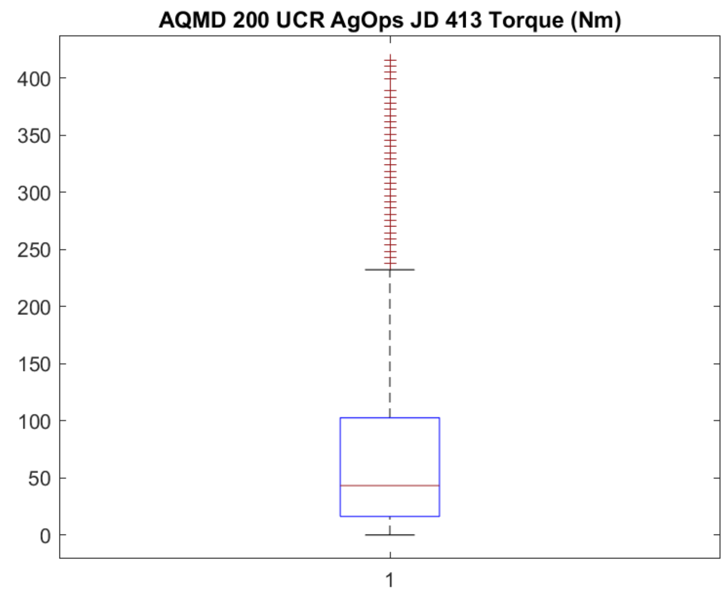


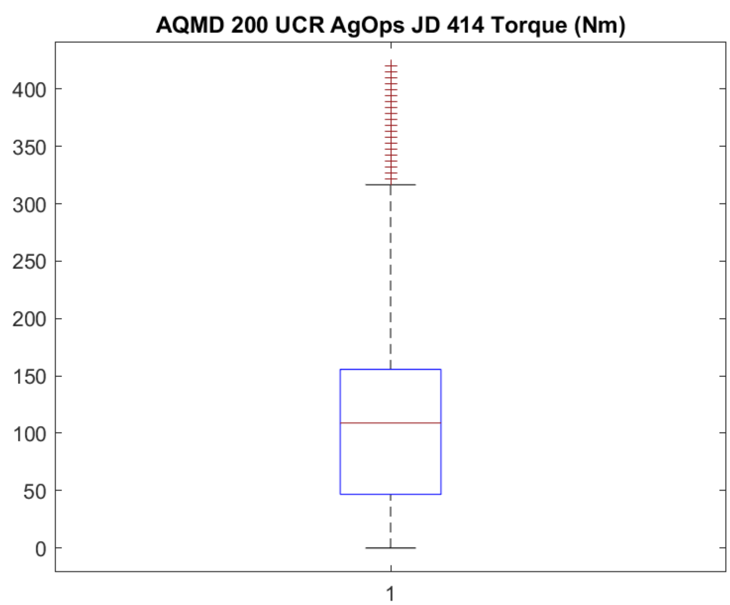


Appendix E: Box Plots of Torque Demand

This appendix presents box plots of torque demand for each piece of equipment, as described in Section 4.1.

Agricultural Tractor

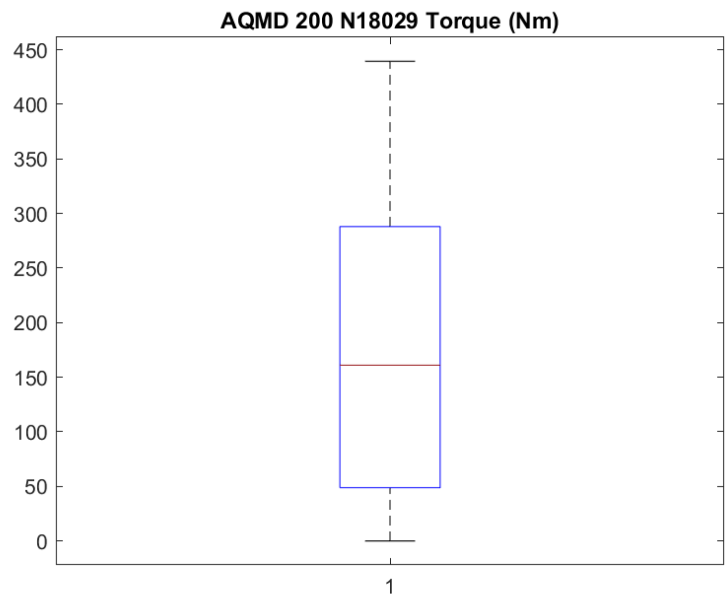




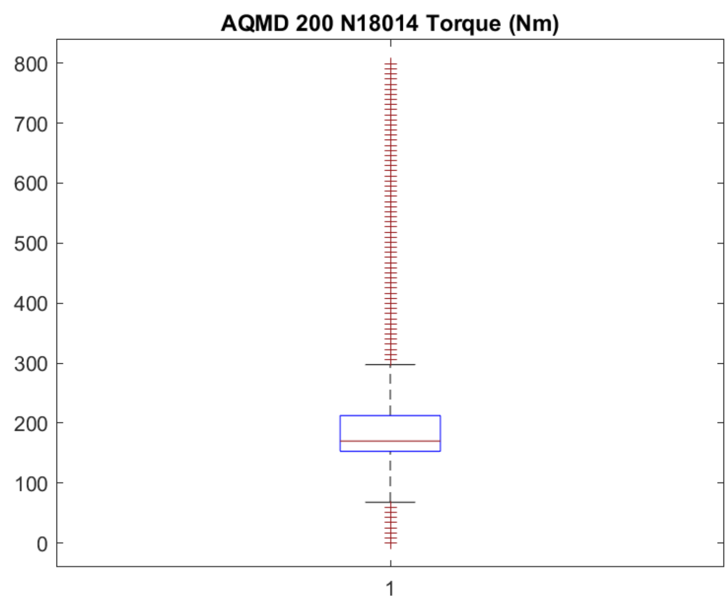
Crawler Tractors

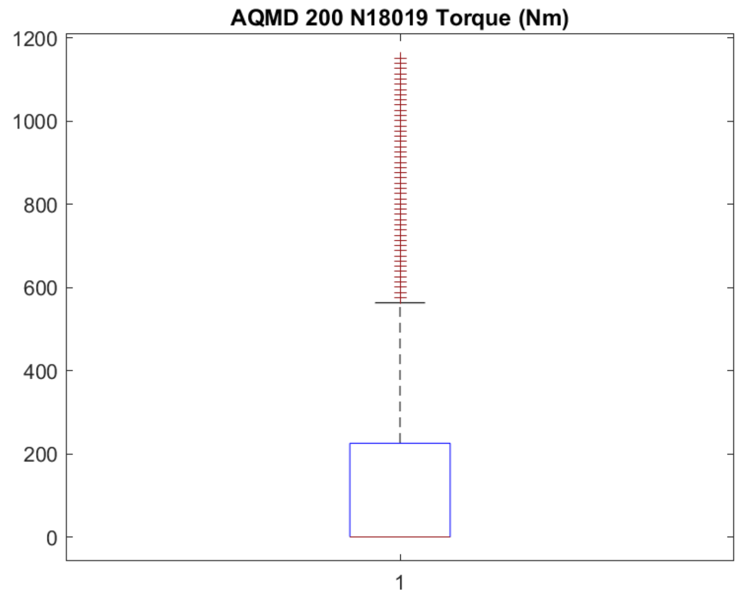
Data were collected from two crawler tractors. However, for both crawler tractors the data for engine parameters needed to calculate or estimate engine brake power were unavailable so torque cannot be determined or estimated.

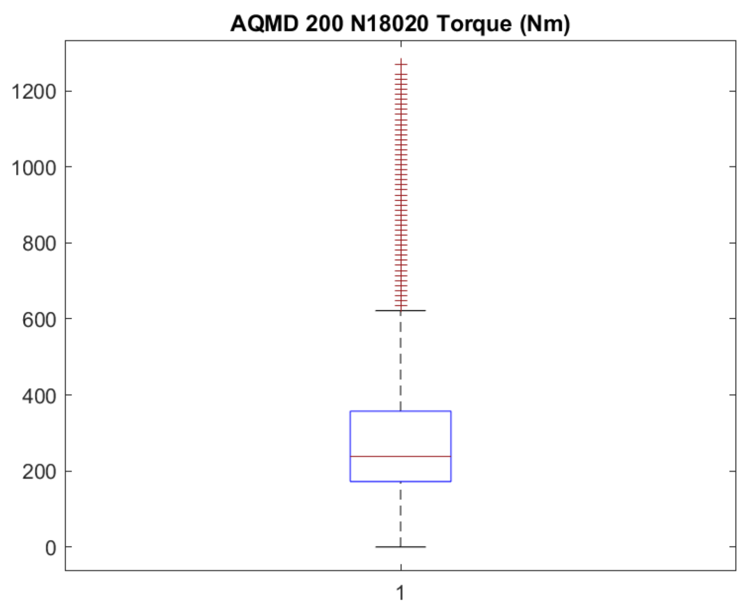
Excavator

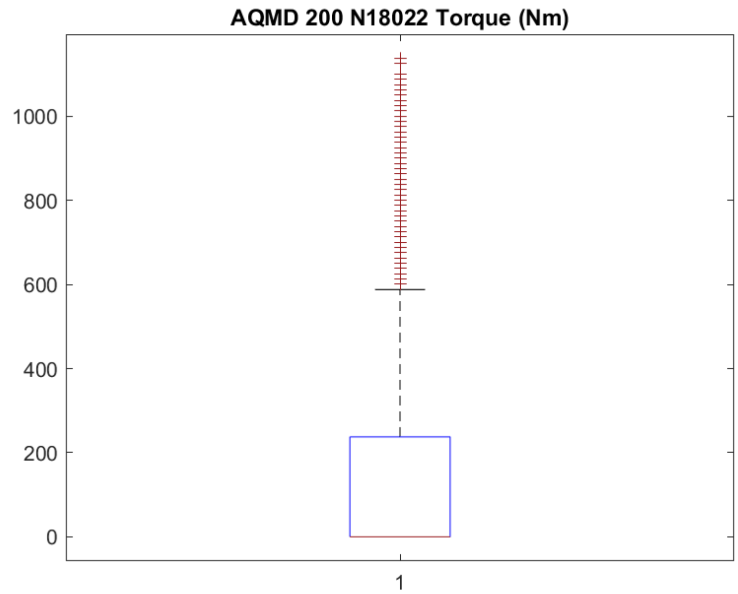


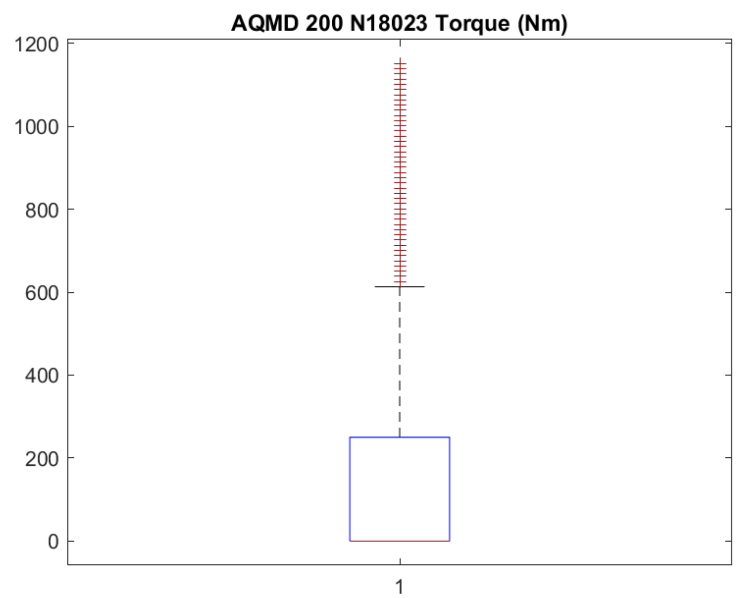
Grader



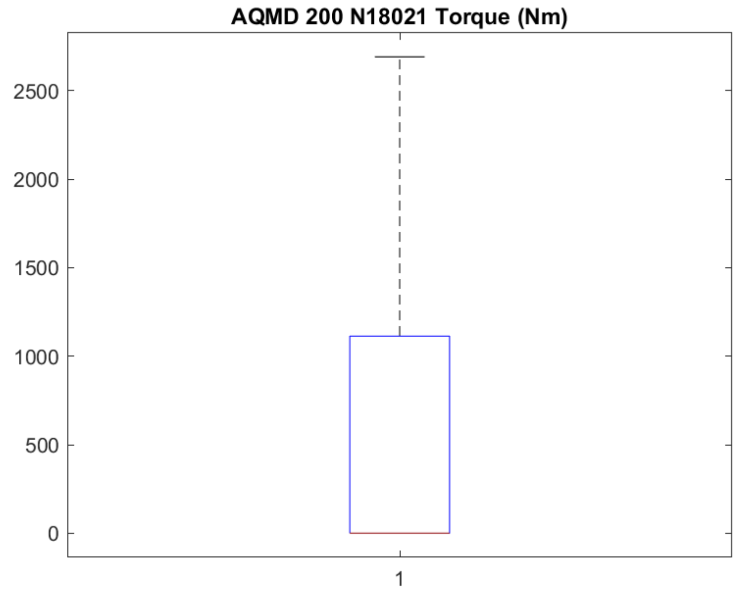

AQMD 200 N18019 Torque (Nm)
1200
1000
800
600
400
200
0
1

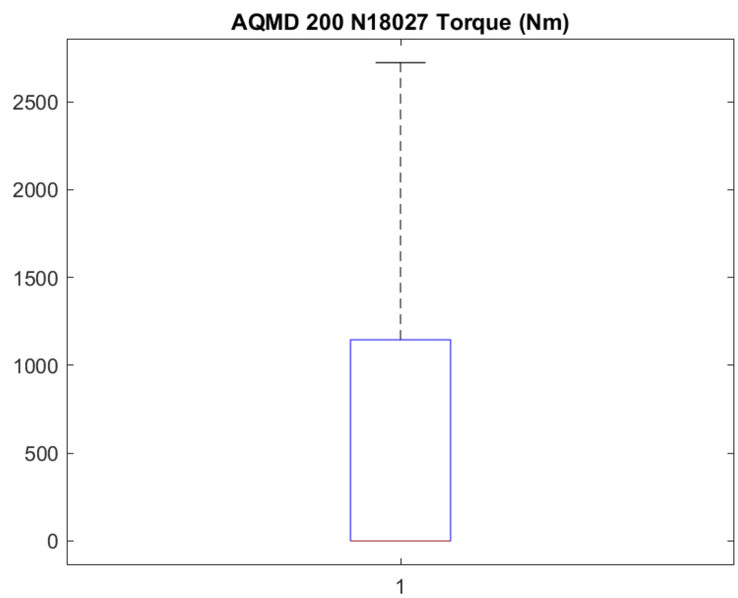

AQMD 200 N18020 Torque (Nm)
1200
1000
800
600
400
200
0
1


AQMD 200 N18022 Torque (Nm)
1000
800
600
400
200
0
1

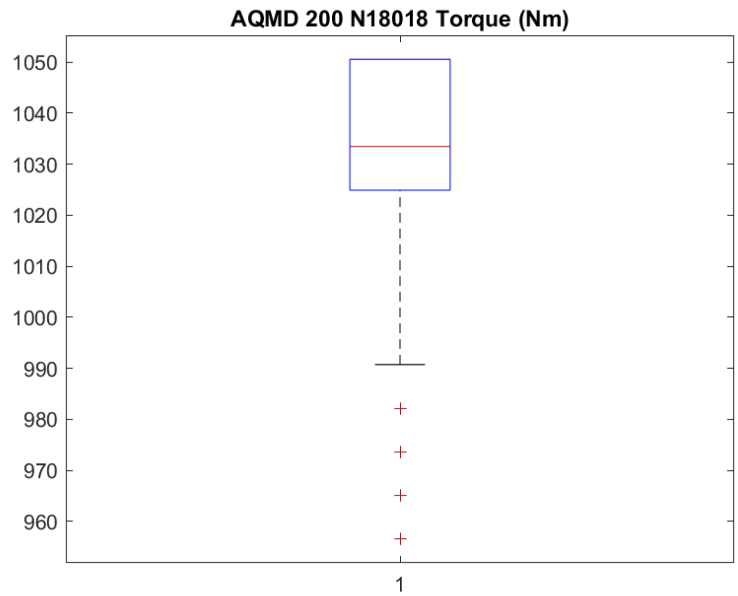

AQMD 200 N18023 Torque (Nm)
1200
1000
800
600
400
200
0
1

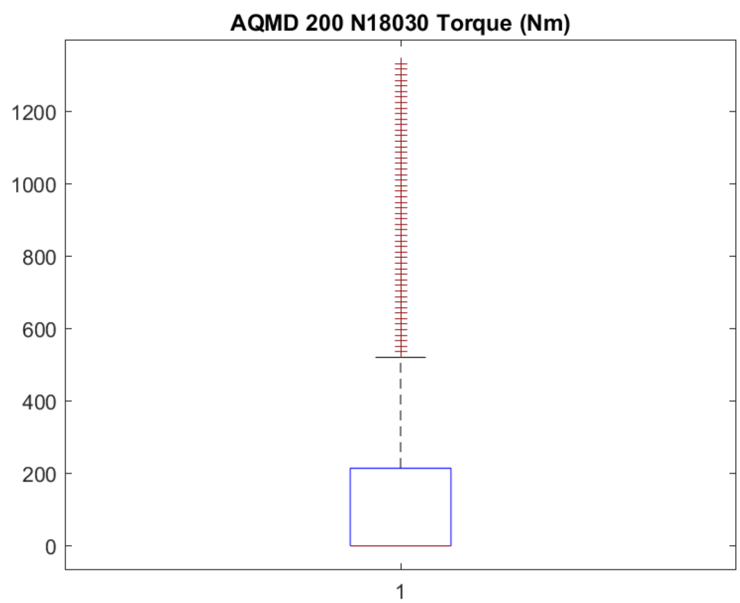
Off-Highway Tractors



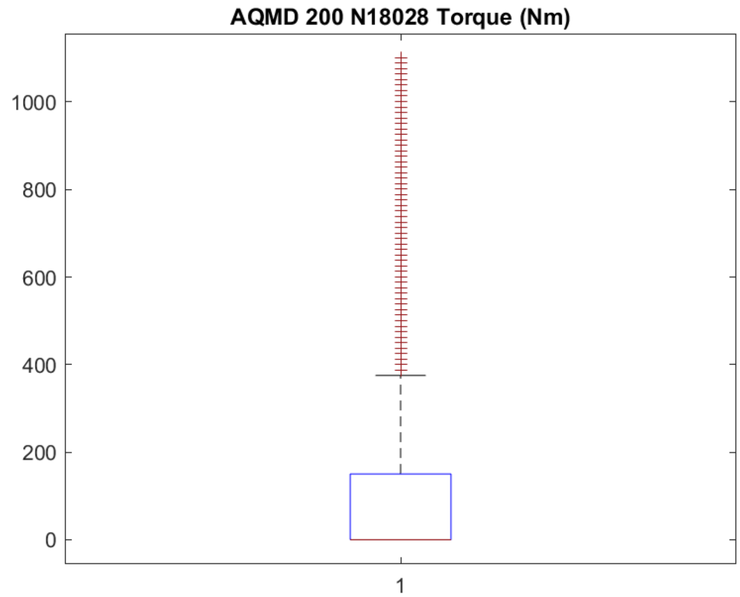


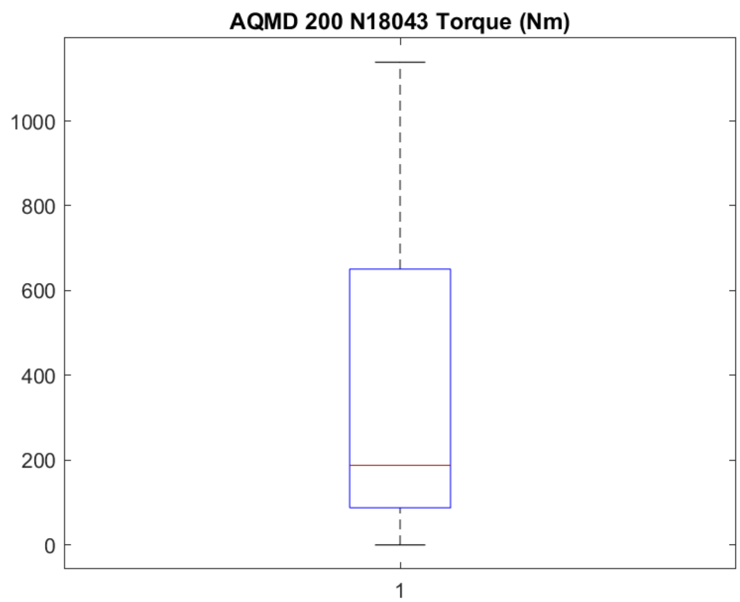
Rubber Tired Loaders



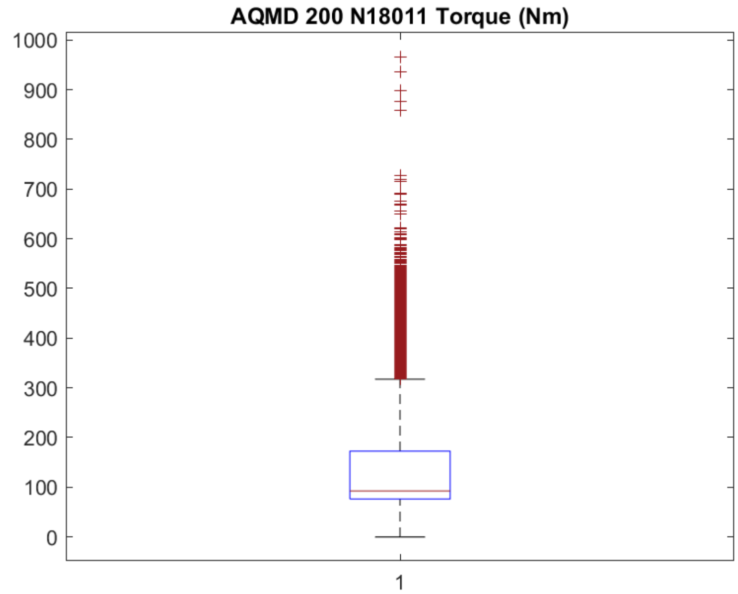


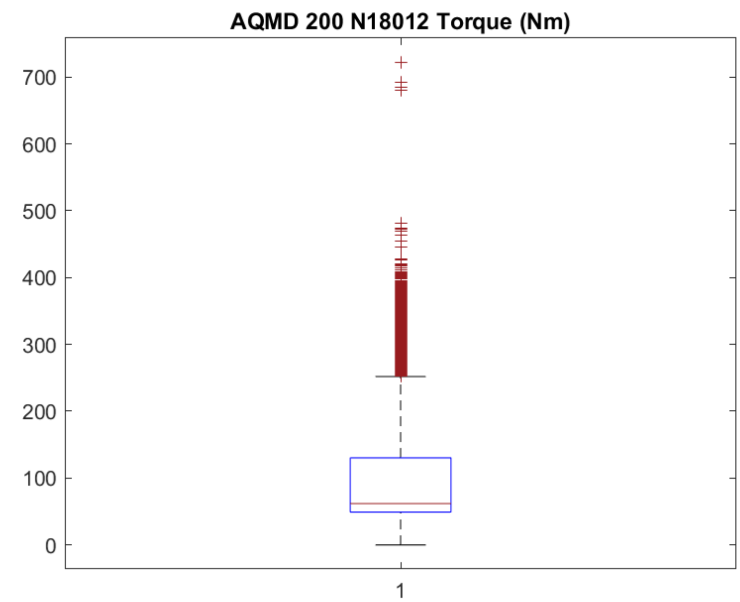
Scraper

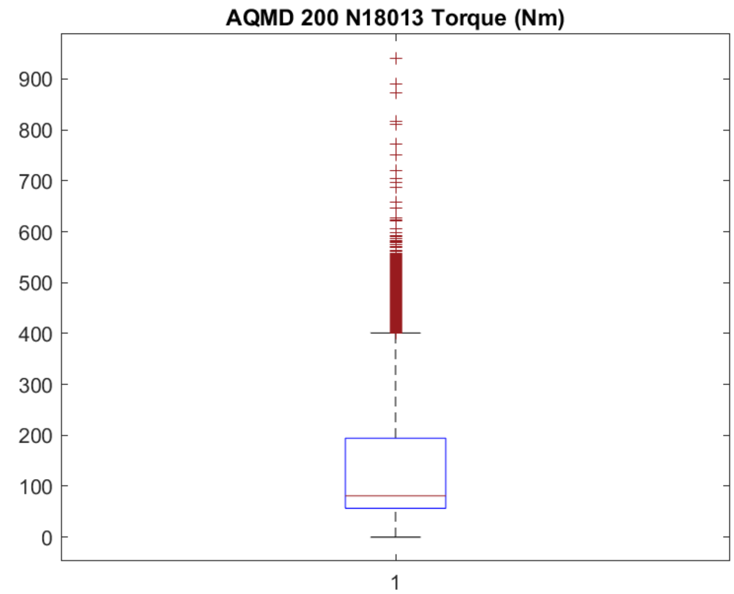

AQMD 200 N18028 Torque (Nm)
1000
800
600
400
200
0
1


AQMD 200 N18043 Torque (Nm)
1000
800
600
400
200
0
1

Tractor/Loaders/Backhoes



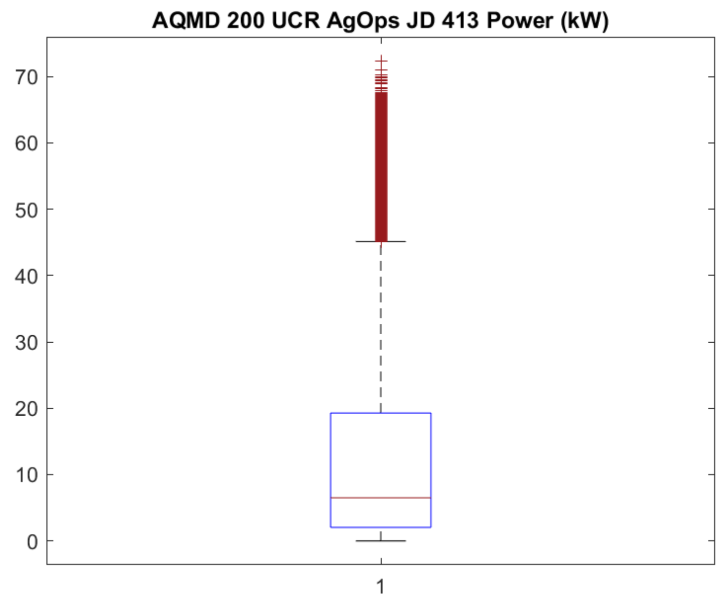


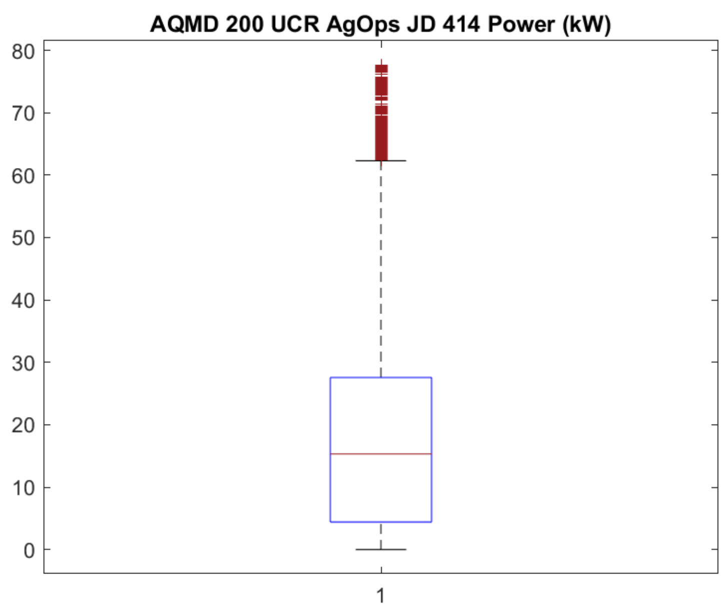

AQMD 200 N18013 Torque (Nm)
900
800
700
600
500
400
300
200
100
0
1

Appendix F: Box Plots of Power Demand

This appendix presents box plots of power demand for each piece of equipment, as described in Section 4.1.

Agricultural Tractor

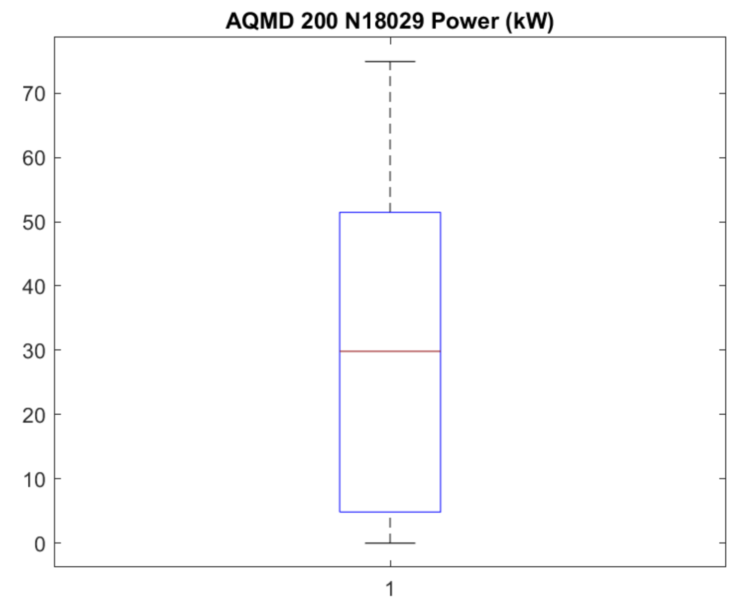




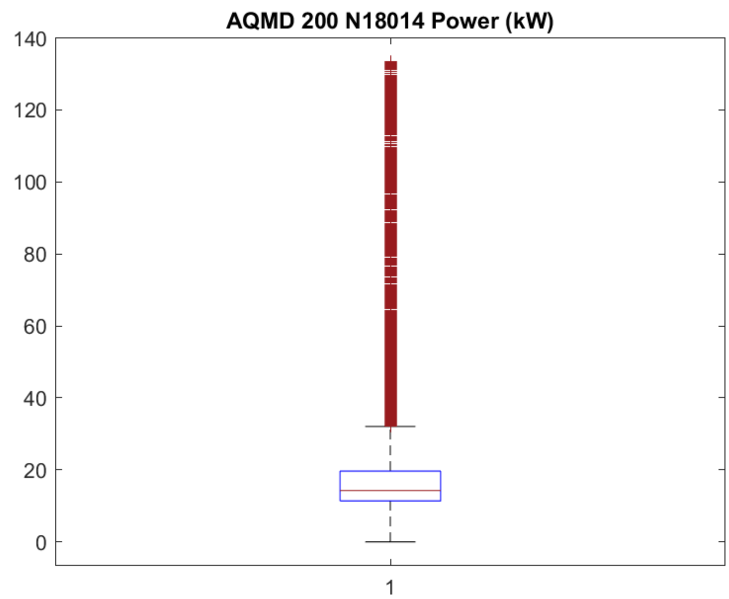
Crawler Tractors

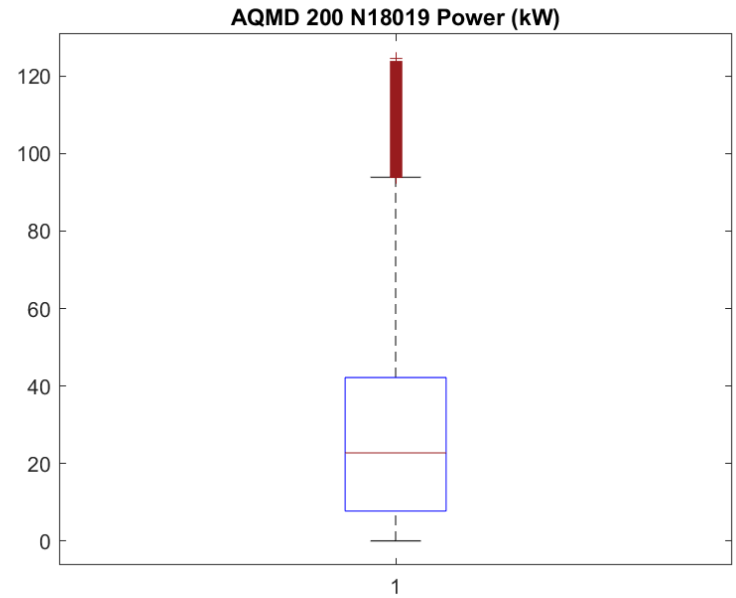
Data were collected from two crawler tractors. However, for both crawler tractors the data for engine parameters needed to calculate or estimate engine brake power were unavailable.

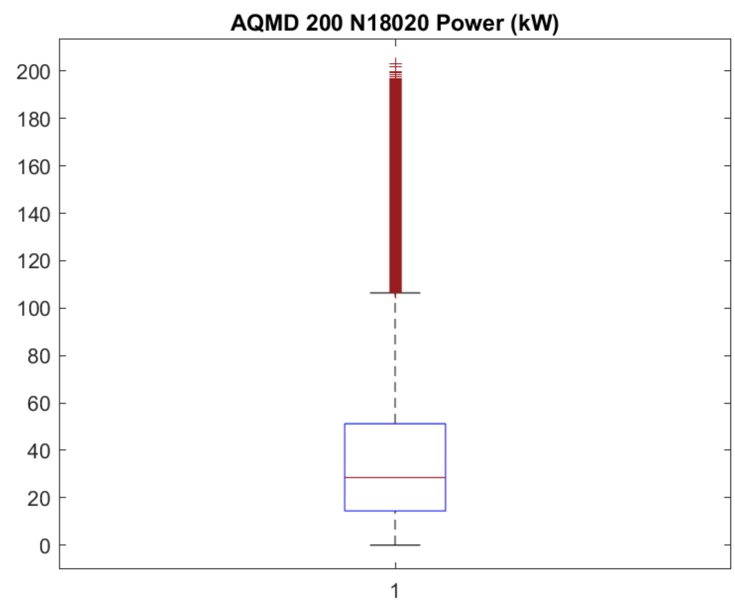
Excavator

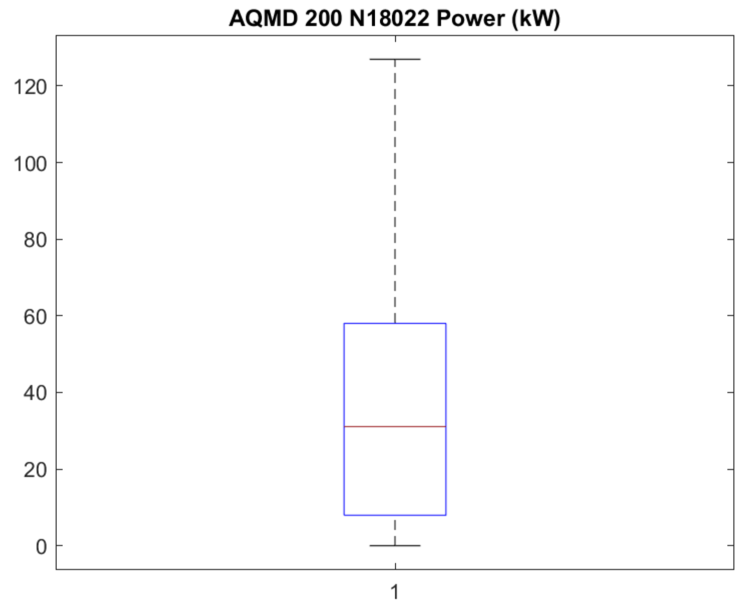


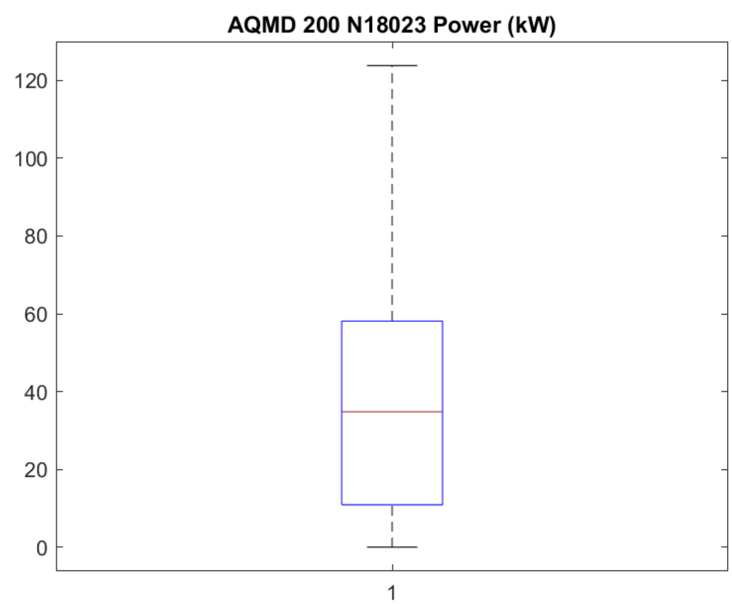
Grader



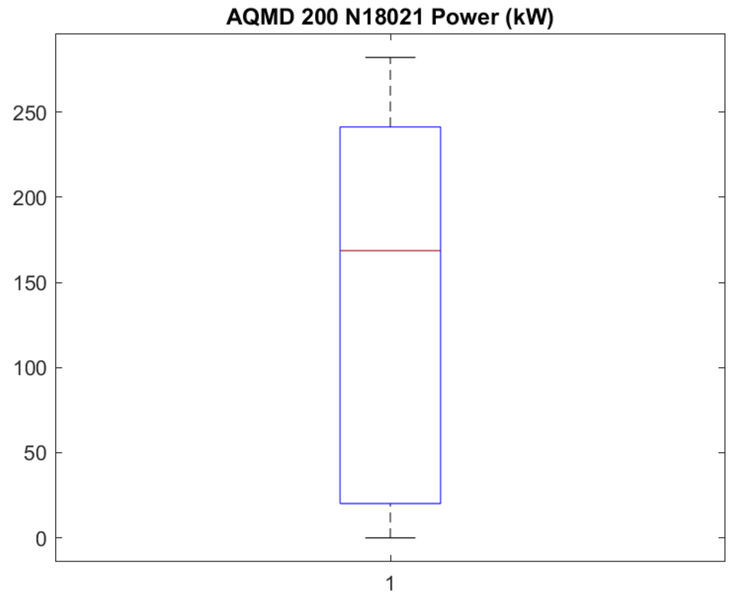

AQMD 200 N18019 Power (kW)
120
100
80
60
40
20
0
1

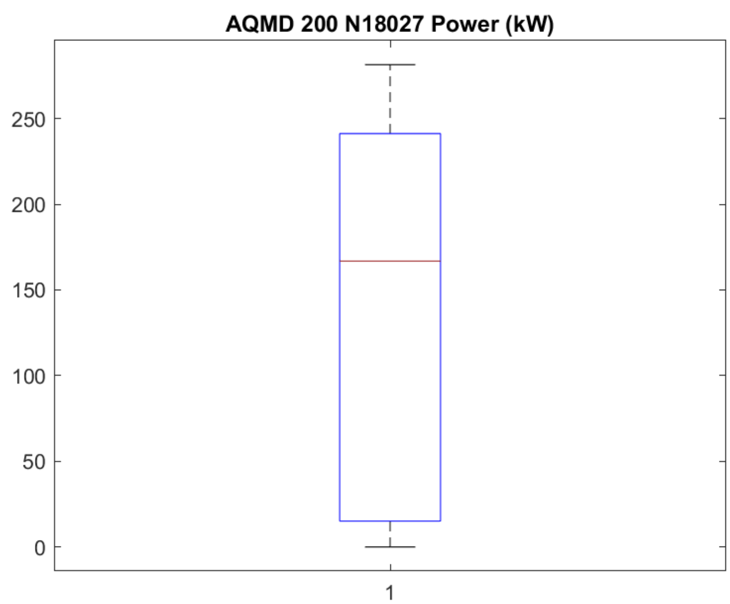

AQMD 200 N18020 Power (kW)
200
180
160
140
120
100
80
60
40
20
0
1


AQMD 200 N18022 Power (kW)
120
100
80
60
40
20
0
1

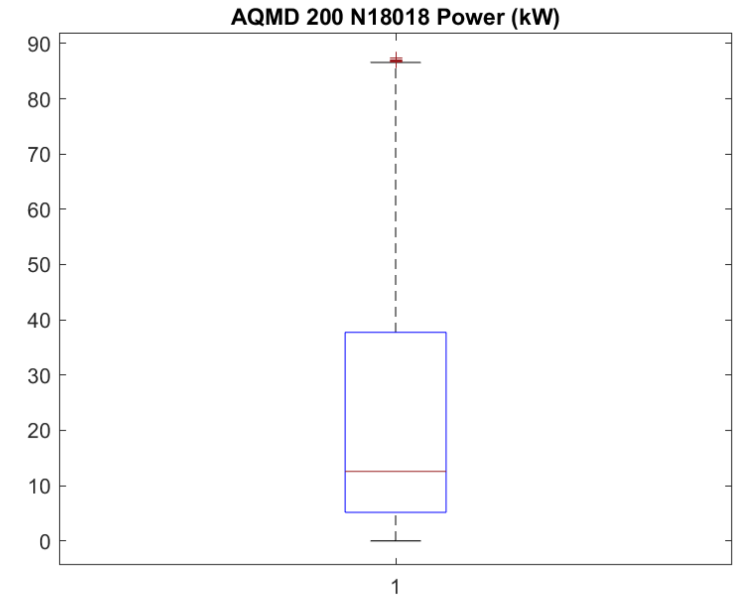

AQMD 200 N18023 Power (kW)
120
100
80
60
40
20
0
1

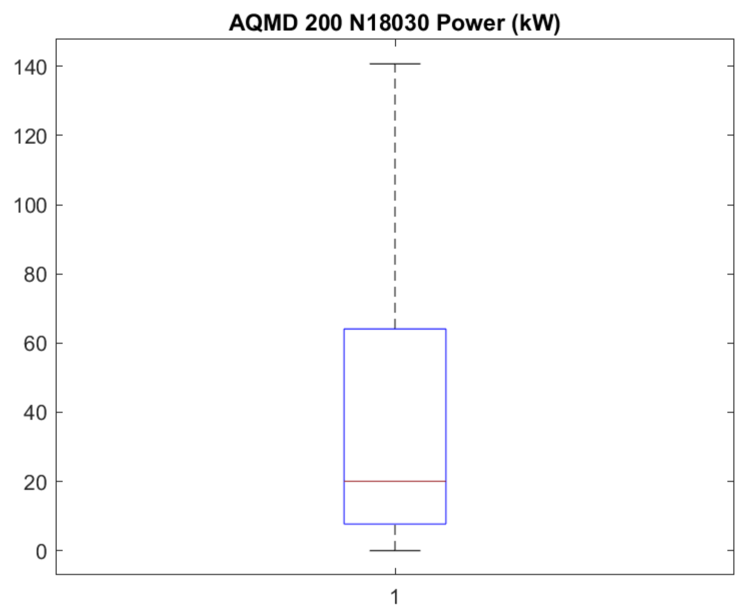
Off-Highway Tractors



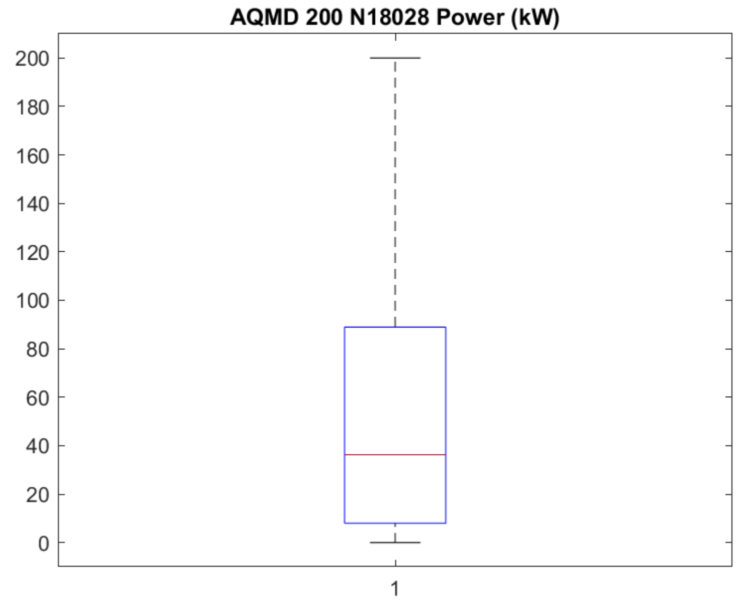


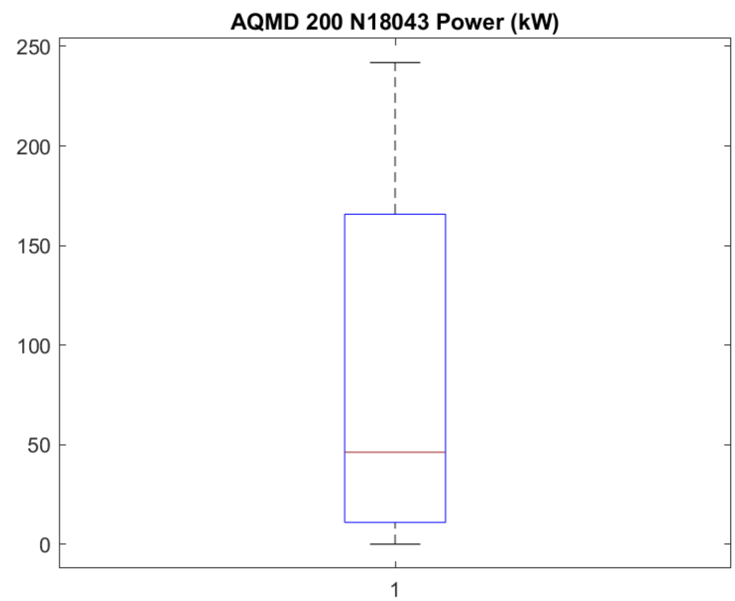
Rubber Tired Loaders



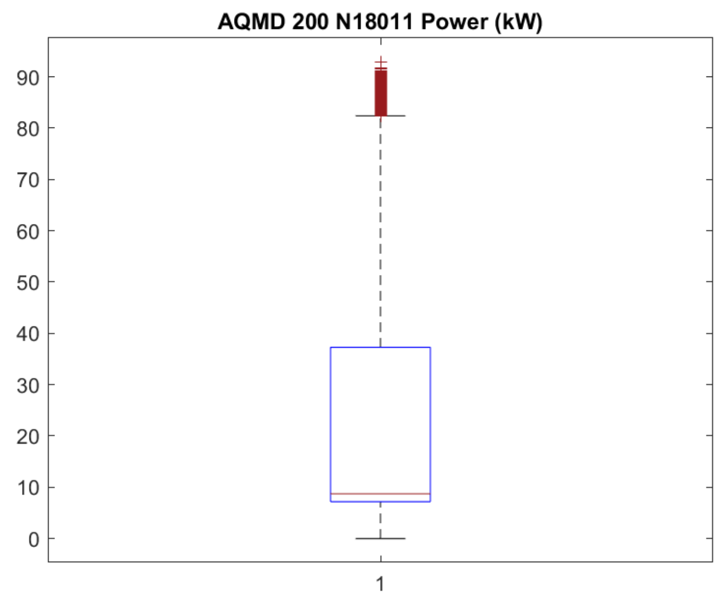


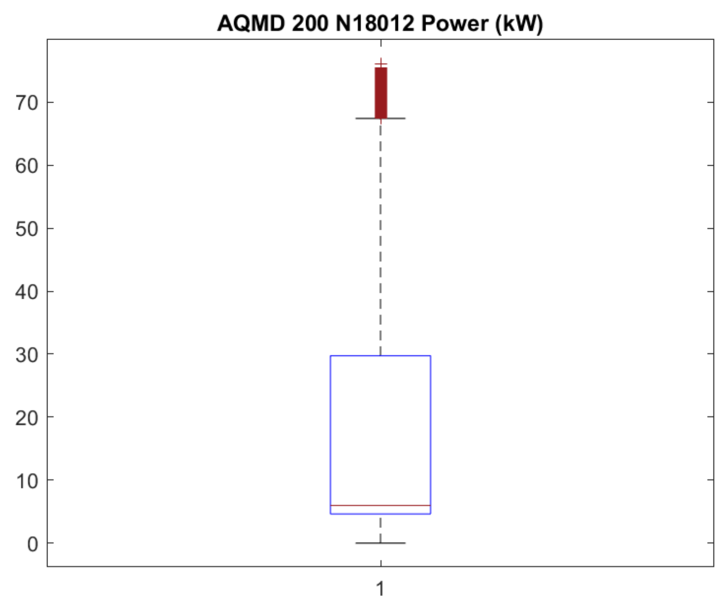
Scraper

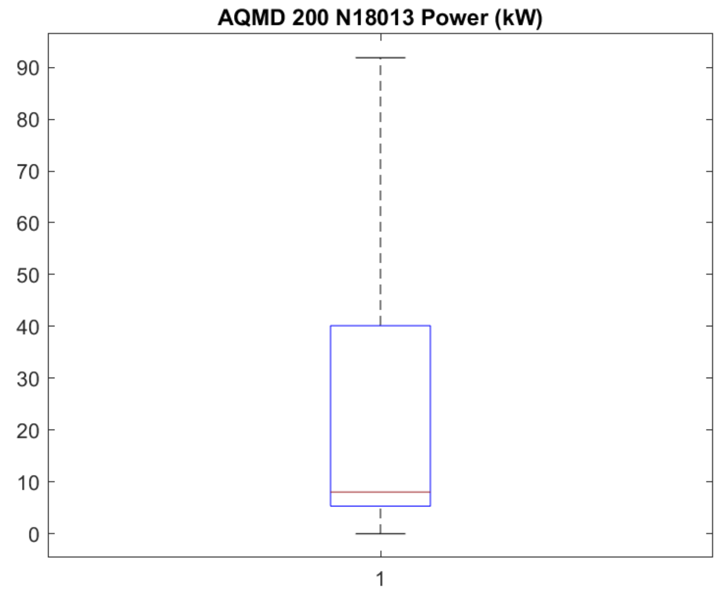

AQMD 200 N18028 Power (kW)
200
180
160
140
120
100
80
60
40
20
0
1


AQMD 200 N18043 Power (kW)
250
200
150
100
50
0
1

Tractor/Loaders/Backhoes





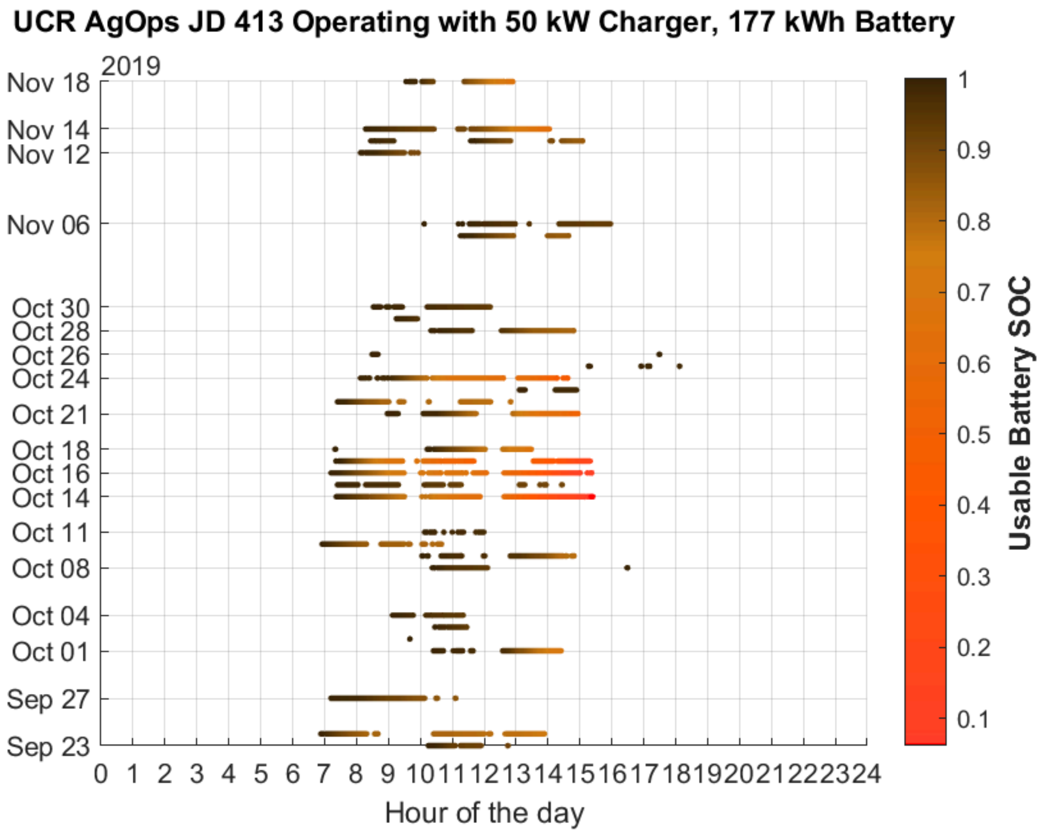

AQMD 200 N18013 Power (kW)
90
80
70
60
50
40
30
20
10
0
1

Appendix G: Diary Plots of Equipment Activity

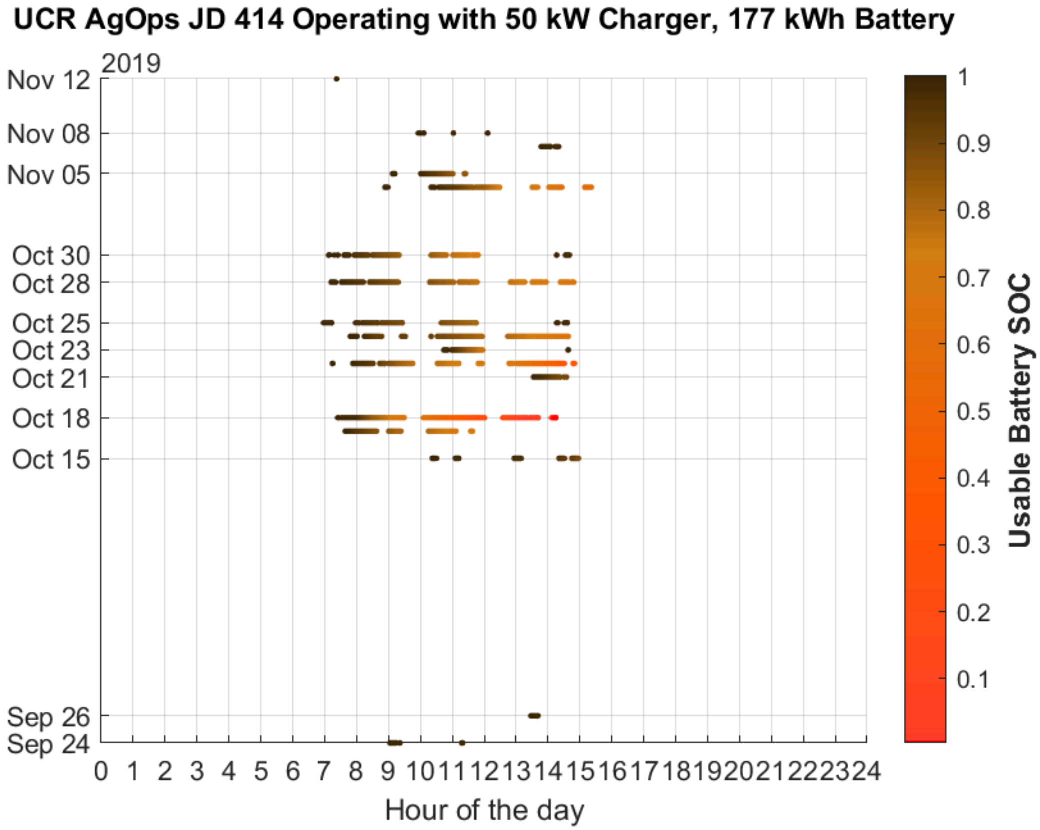
This appendix presents diary plots of activity for each piece of equipment, as described in Section 4.1.3. The colormap indicates usable battery SOC at each active event. Red dots indicate activities that cannot be served due to insufficient remaining battery.

Ag Tractor

JD 413

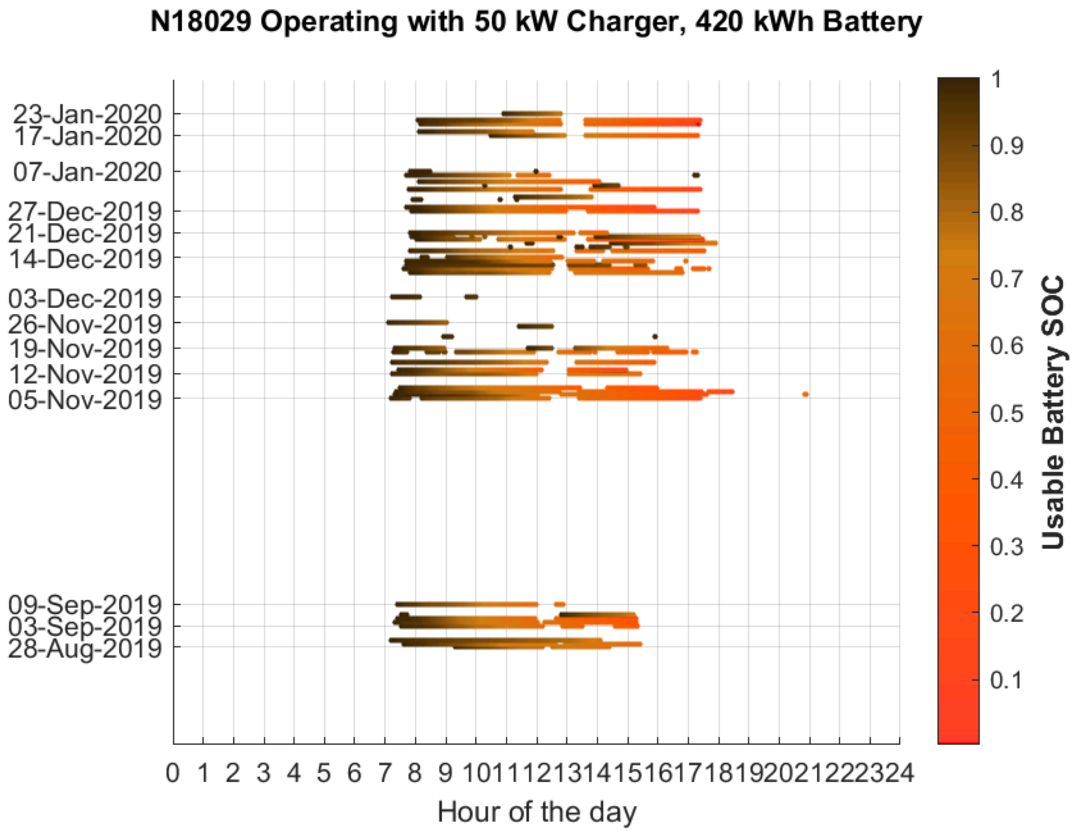


JD 414


UCR AgOps JD 414 Operating with 50 kW Charger, 177 kWh Battery
2019
Nov 12
Nov 08
Nov 05
Oct 30
Oct 28
Oct 25
Oct 23
Oct 21
Oct 18
Oct 15
Sep 26
Sep 24
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Hour of the day
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
Usable Battery SOC

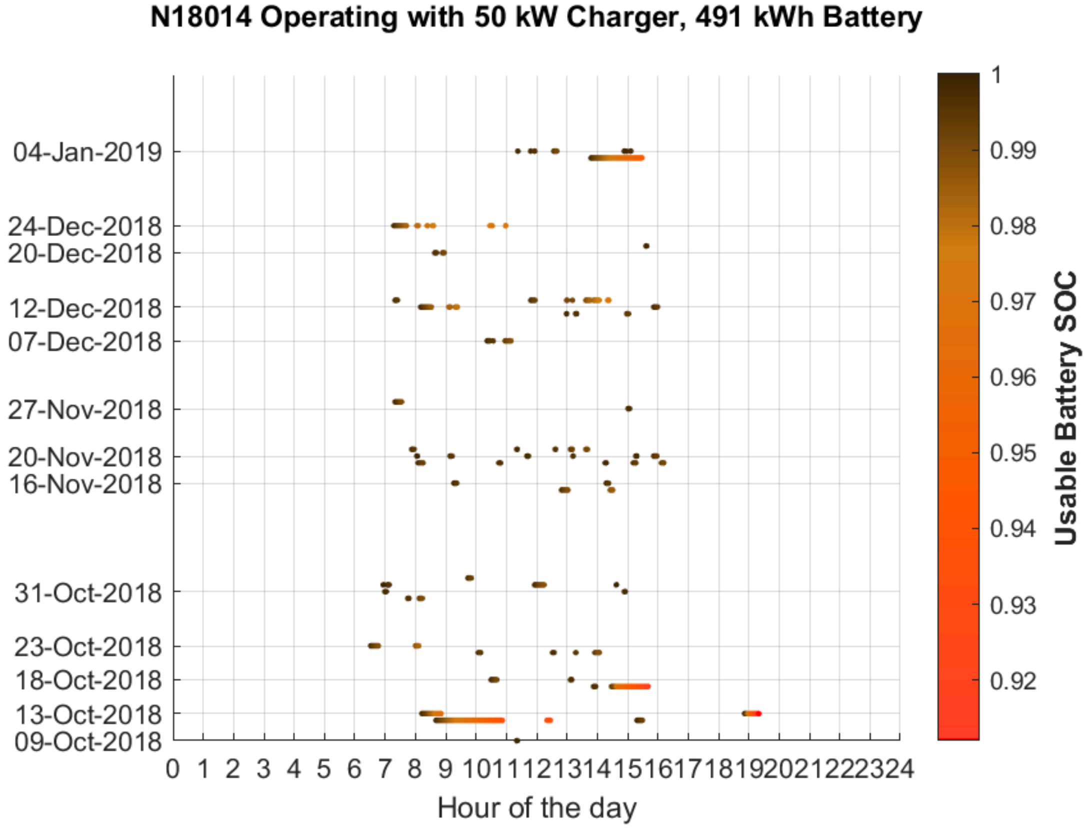
Excavator

N18029

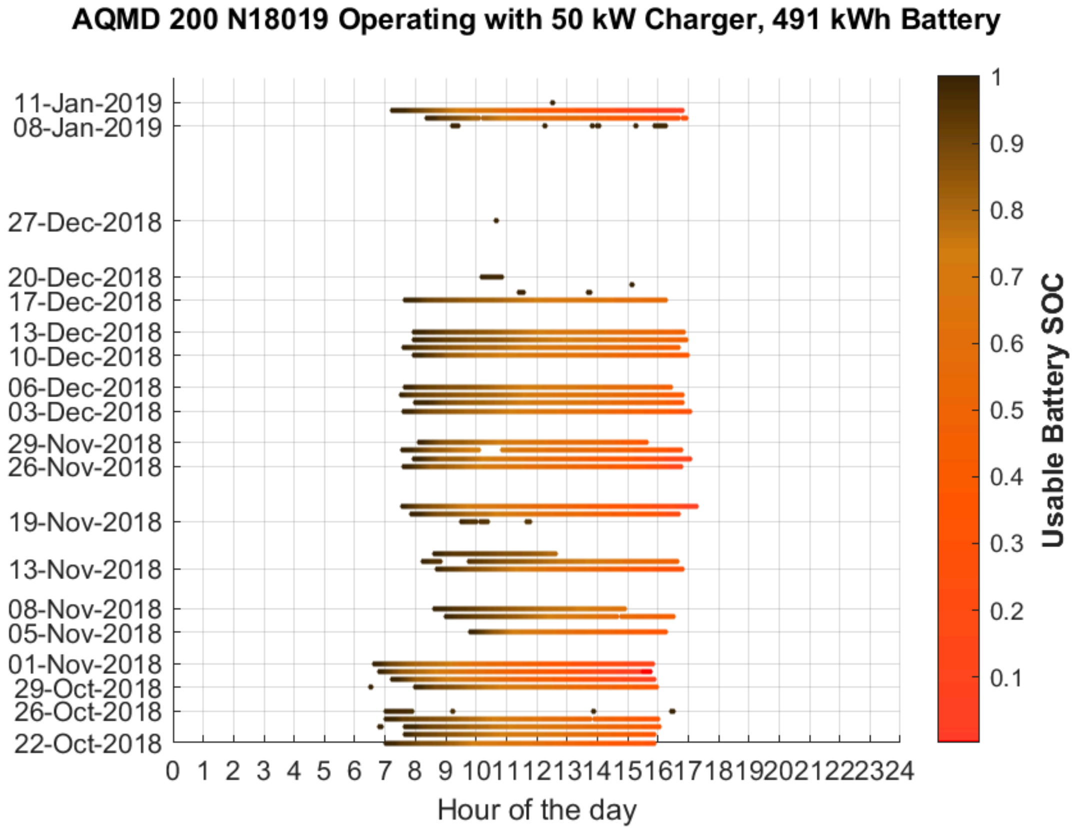


Grader

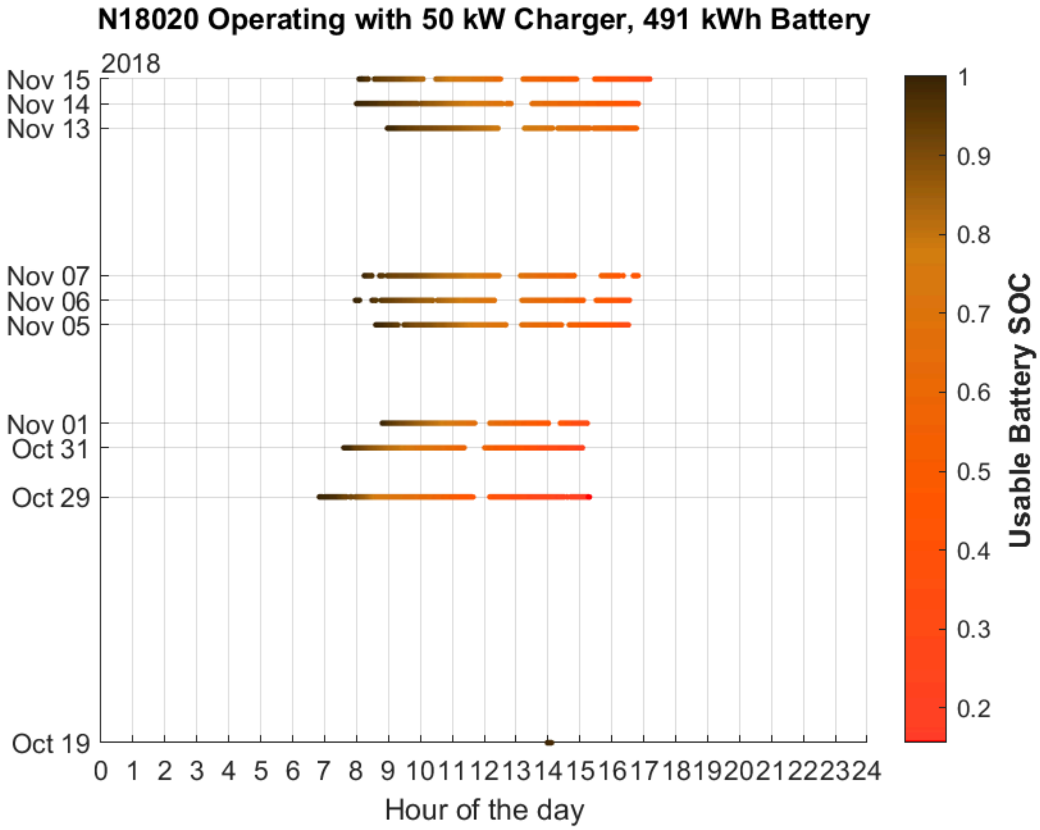
N18014



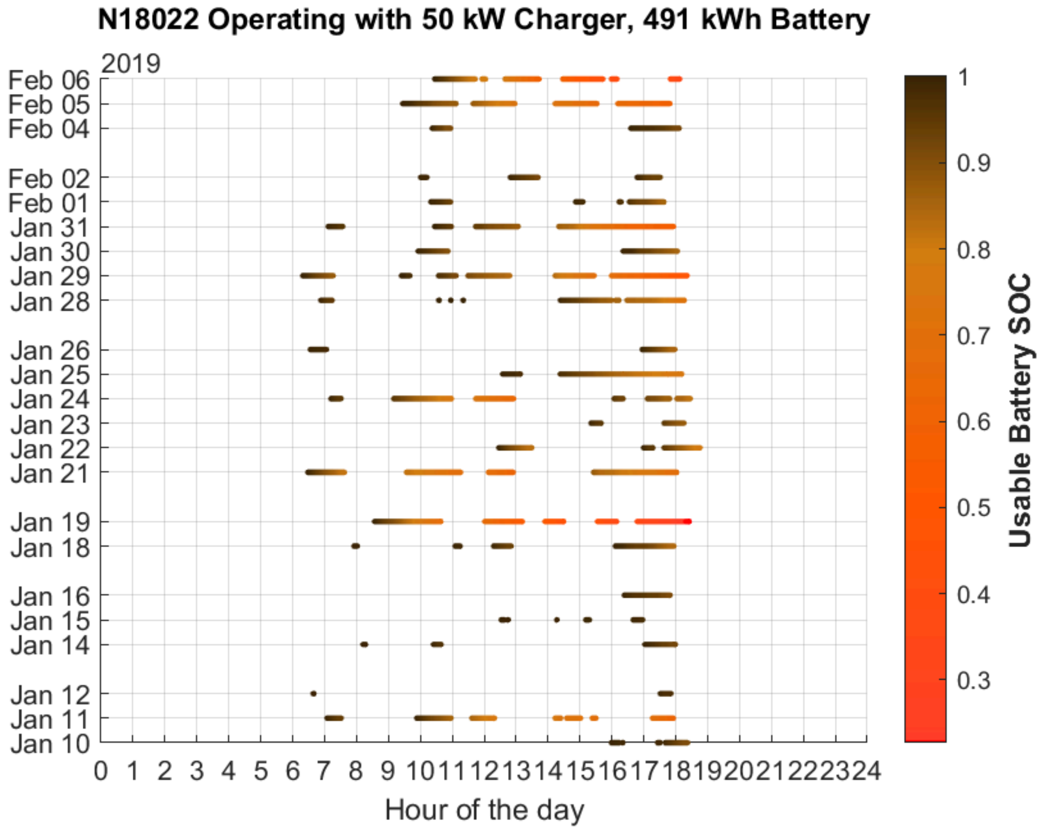
N18019


AQMD 200 N18019 Operating with 50 kW Charger, 491 kWh Battery
11-Jan-2019
08-Jan-2019
27-Dec-2018
20-Dec-2018
17-Dec-2018
13-Dec-2018
10-Dec-2018
06-Dec-2018
03-Dec-2018
29-Nov-2018
26-Nov-2018
19-Nov-2018
13-Nov-2018
08-Nov-2018
05-Nov-2018
01-Nov-2018
29-Oct-2018
26-Oct-2018
22-Oct-2018
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Hour of the day
Usable Battery SOC
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1

N18020

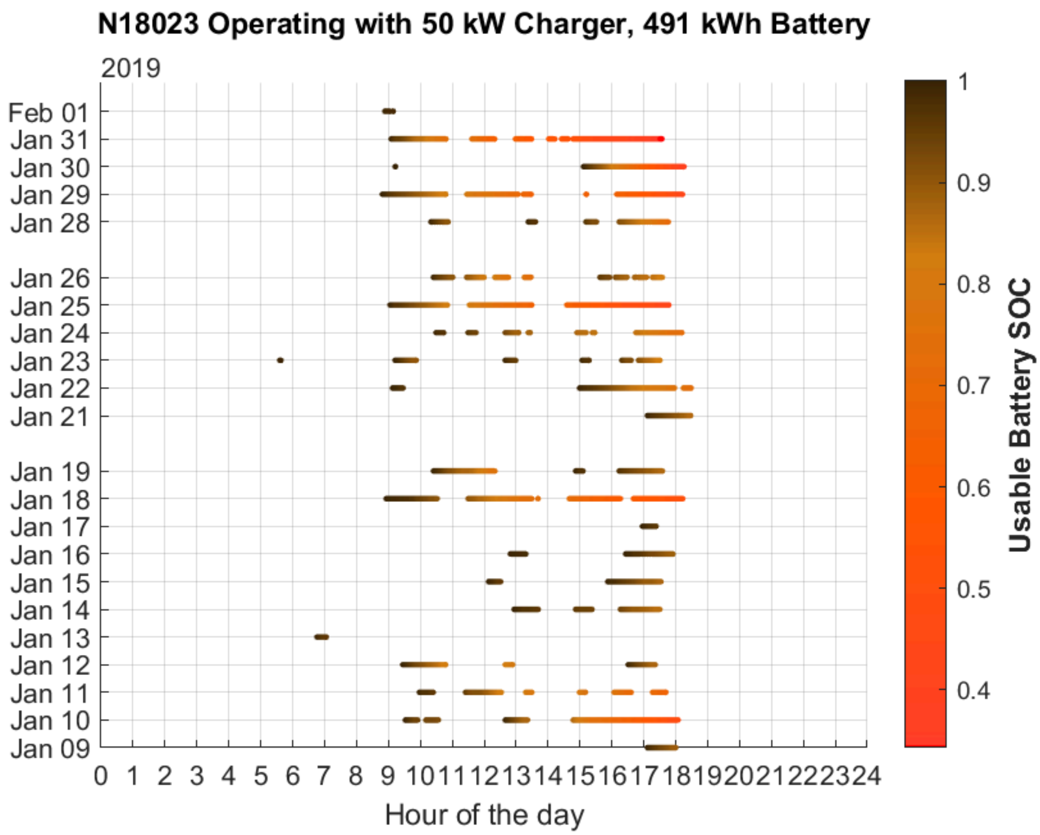

N18020 Operating with 50 kW Charger, 491 kWh Battery
2018
Nov 15
Nov 14
Nov 13
Nov 07
Nov 06
Nov 05
Nov 01
Oct 31
Oct 29
Oct 19
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Hour of the day
Usable Battery SOC
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2

N18022



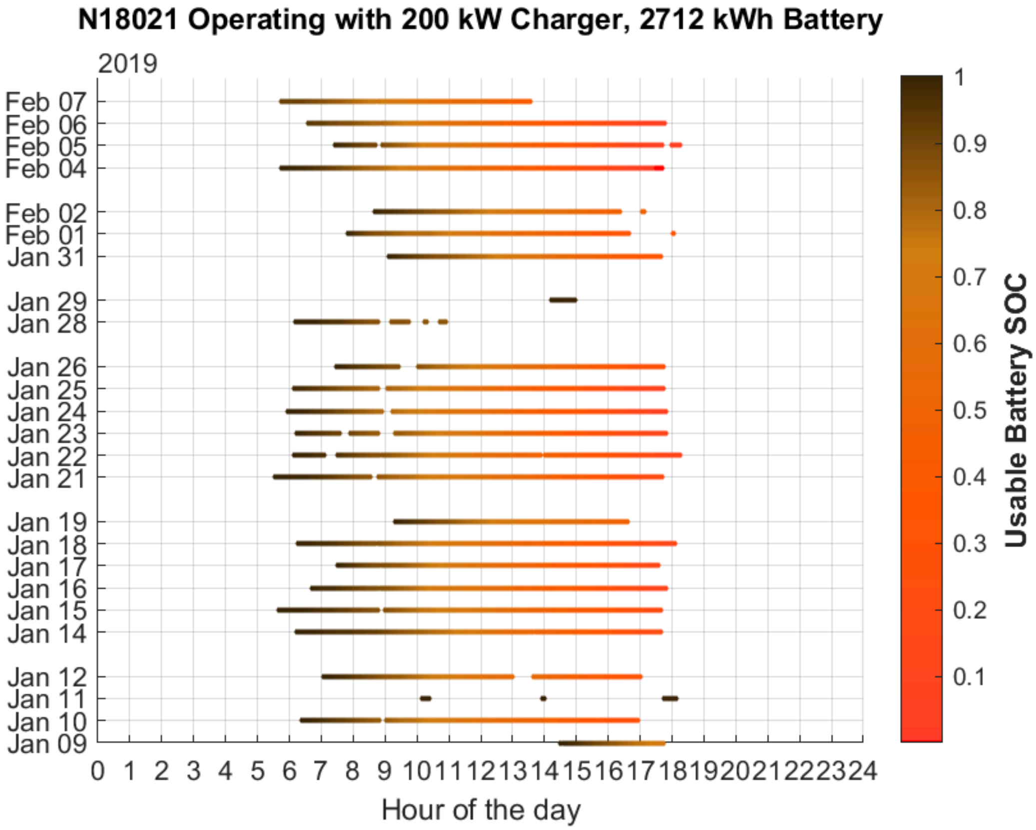
N18022 Operating with 50 kW Charger, 491 kWh Battery
2019
Feb 06
Feb 05
Feb 04
Feb 02
Feb 01
Jan 31
Jan 30
Jan 29
Jan 28
Jan 26
Jan 25
Jan 24
Jan 23
Jan 22
Jan 21
Jan 19
Jan 18
Jan 16
Jan 15
Jan 14
Jan 12
Jan 11
Jan 10
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Hour of the day
Usable Battery SOC
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3

N18023

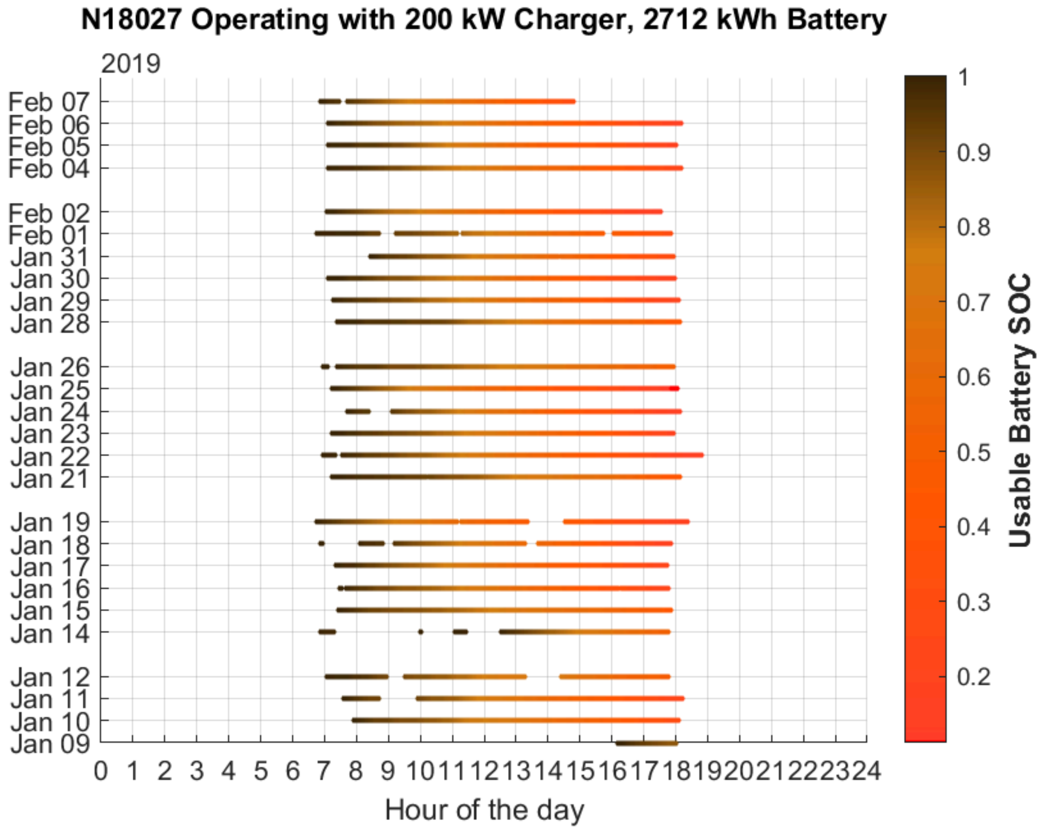

N18023 Operating with 50 kW Charger, 491 kWh Battery
2019
Feb 01
Jan 31
Jan 30
Jan 29
Jan 28
Jan 26
Jan 25
Jan 24
Jan 23
Jan 22
Jan 21
Jan 19
Jan 18
Jan 17
Jan 16
Jan 15
Jan 14
Jan 13
Jan 12
Jan 11
Jan 10
Jan 09
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Hour of the day
Usable Battery SOC
1
0.9
0.8
0.7
0.6
0.5
0.4

Off-Highway Tractors

N18021

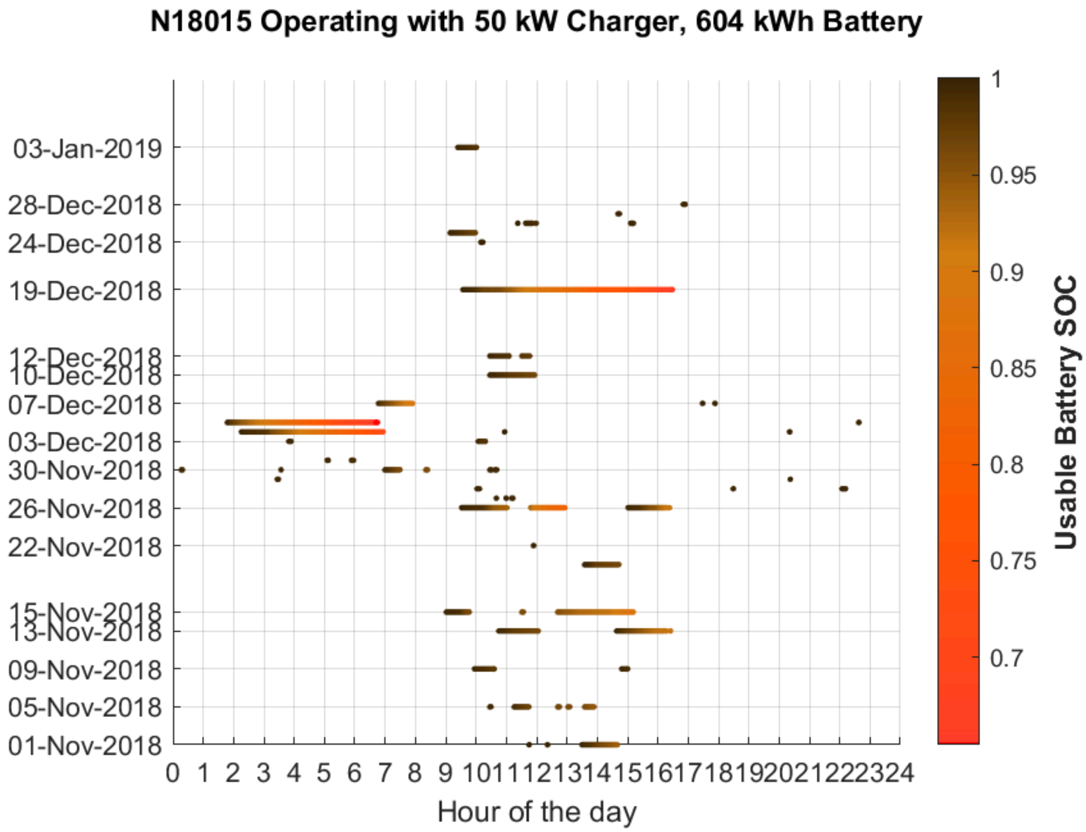


N18027

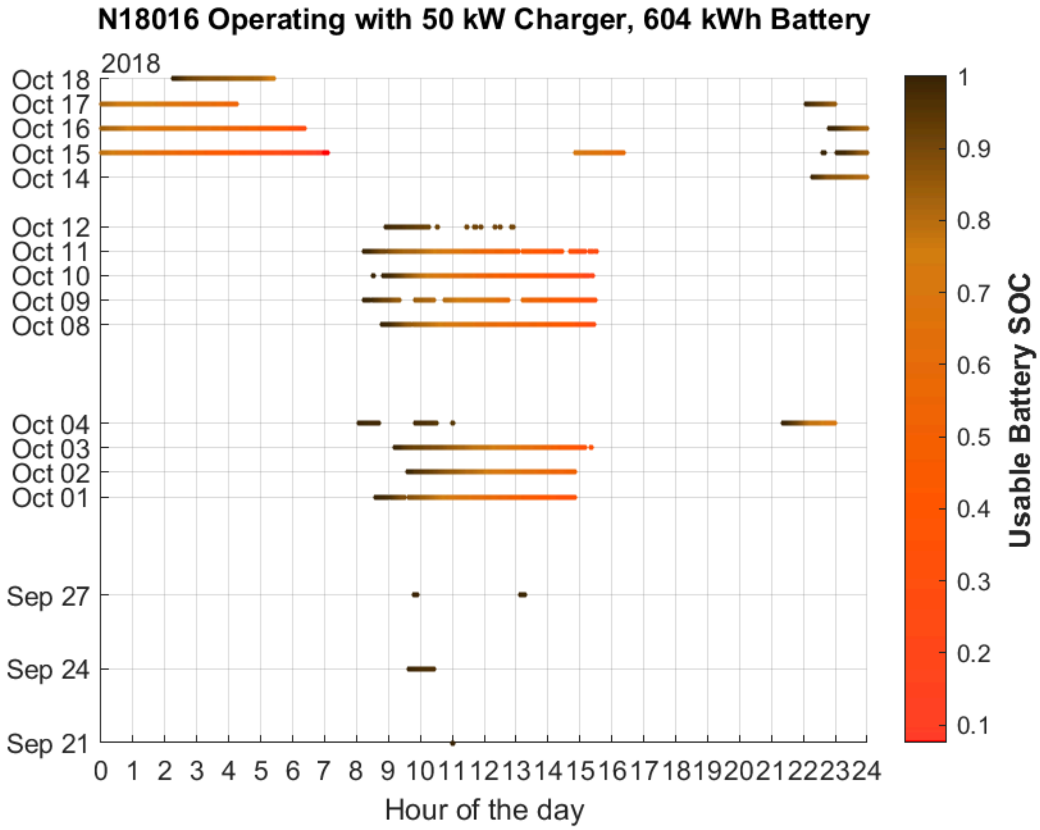

N18027 Operating with 200 kW Charger, 2712 kWh Battery
2019
Feb 07
Feb 06
Feb 05
Feb 04
Feb 02
Feb 01
Jan 31
Jan 30
Jan 29
Jan 28
Jan 26
Jan 25
Jan 24
Jan 23
Jan 22
Jan 21
Jan 19
Jan 18
Jan 17
Jan 16
Jan 15
Jan 14
Jan 12
Jan 11
Jan 10
Jan 09
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Hour of the day
Usable Battery SOC
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2

Rubber Tired Loaders

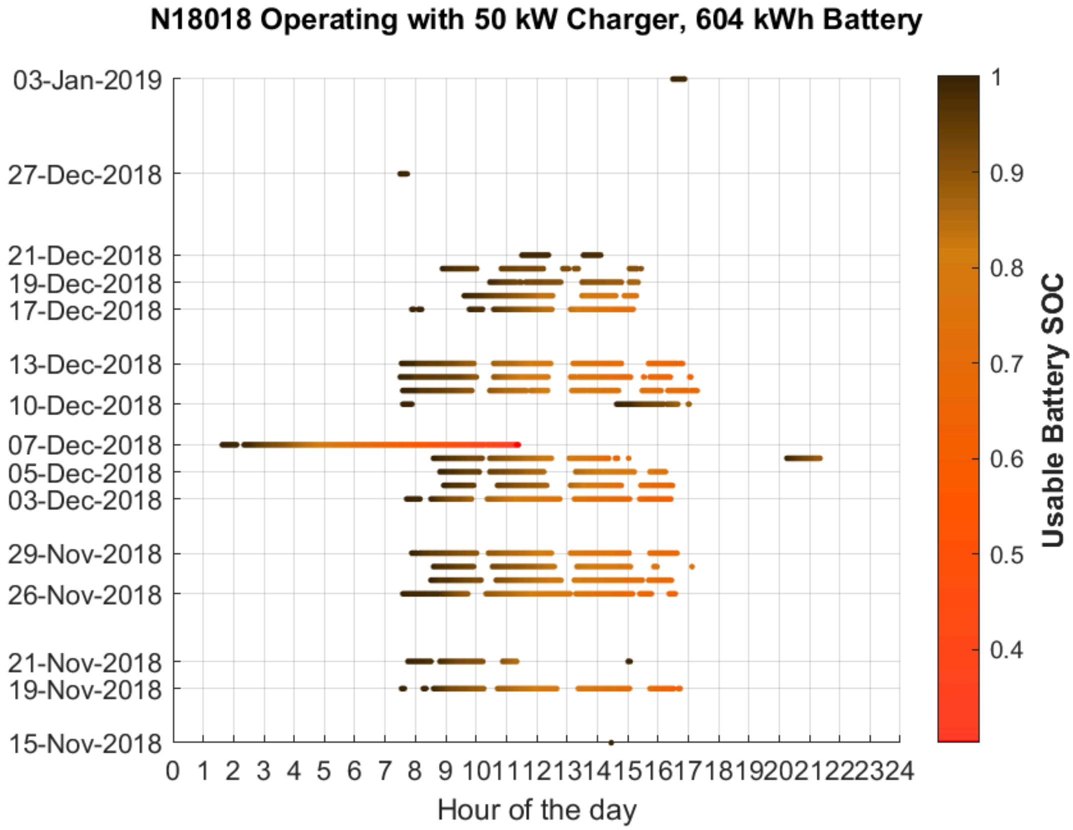
N18015



N18016

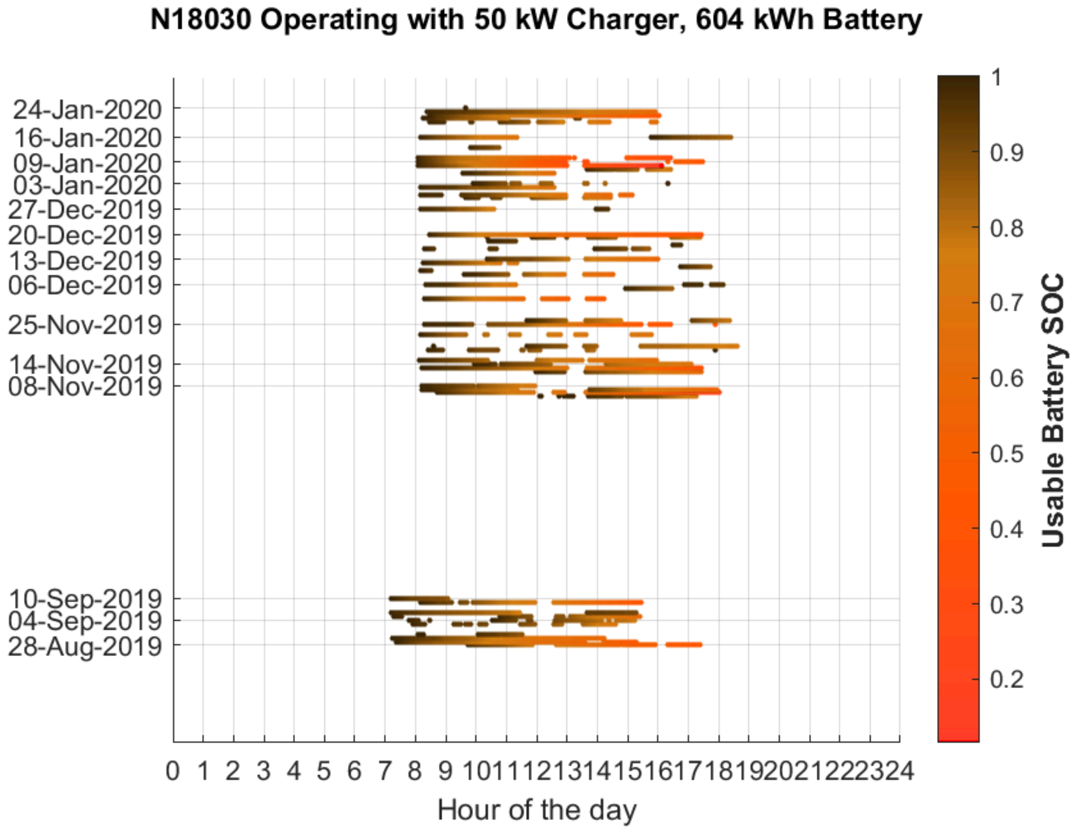

N18016 Operating with 50 kW Charger, 604 kWh Battery
2018
Oct 18
Oct 17
Oct 16
Oct 15
Oct 14
Oct 12
Oct 11
Oct 10
Oct 09
Oct 08
Oct 04
Oct 03
Oct 02
Oct 01
Sep 27
Sep 24
Sep 21
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Hour of the day
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
Usable Battery SOC

N18018



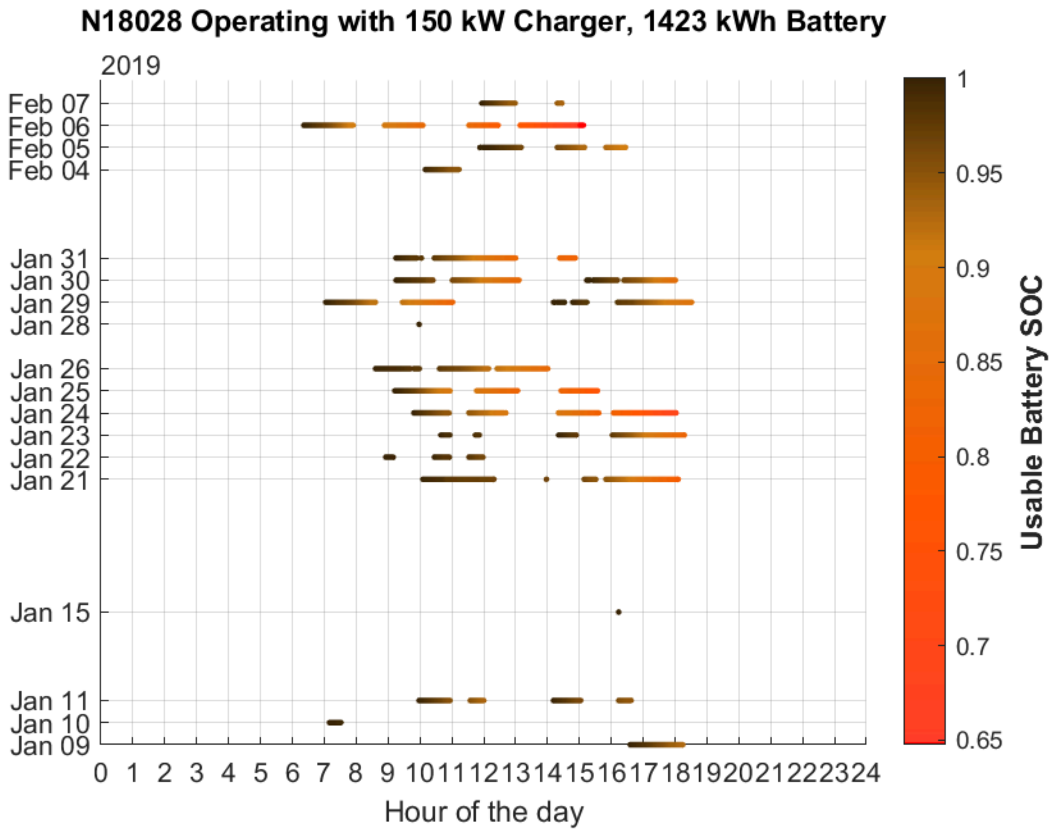
N18018 Operating with 50 kW Charger, 604 kWh Battery
03-Jan-2019
27-Dec-2018
21-Dec-2018
19-Dec-2018
17-Dec-2018
13-Dec-2018
10-Dec-2018
07-Dec-2018
05-Dec-2018
03-Dec-2018
29-Nov-2018
26-Nov-2018
21-Nov-2018
19-Nov-2018
15-Nov-2018
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Hour of the day
1
0.9
0.8
0.7
0.6
0.5
0.4
Usable Battery SOC

N18030

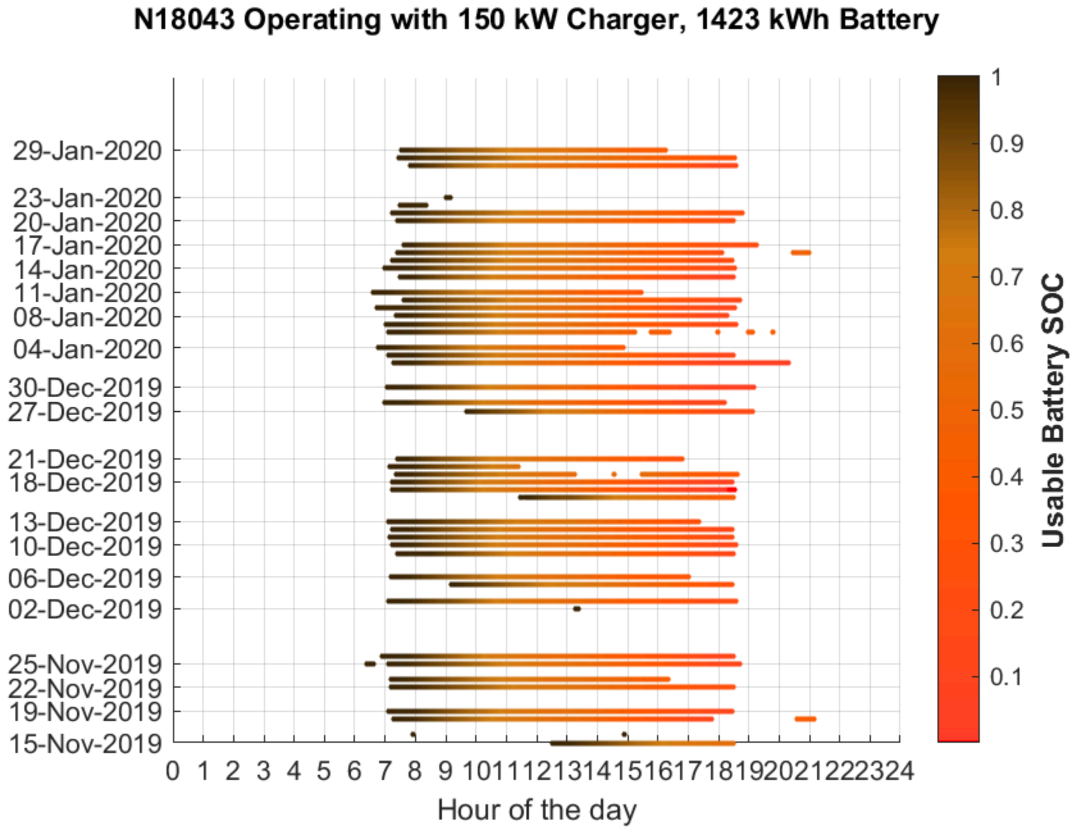

N18030 Operating with 50 kW Charger, 604 kWh Battery
24-Jan-2020
16-Jan-2020
09-Jan-2020
03-Jan-2020
27-Dec-2019
20-Dec-2019
13-Dec-2019
06-Dec-2019
25-Nov-2019
14-Nov-2019
08-Nov-2019
10-Sep-2019
04-Sep-2019
28-Aug-2019
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Hour of the day
Usable Battery SOC
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2

Scraper

N18028

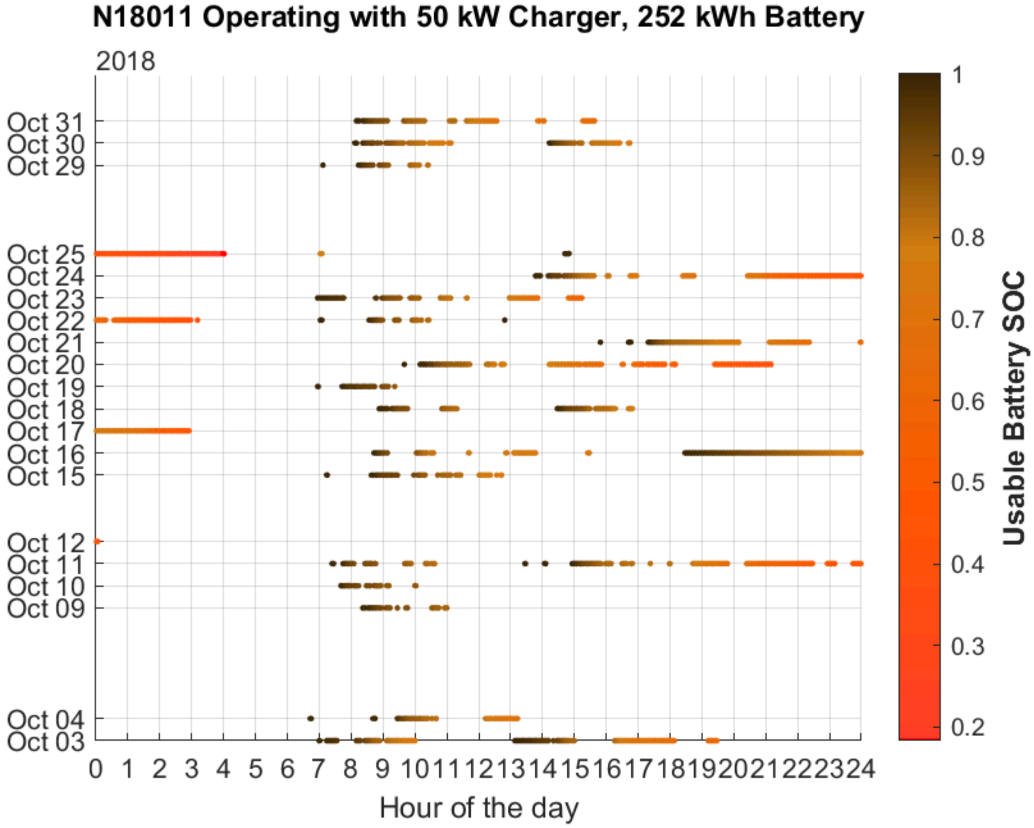


N18043

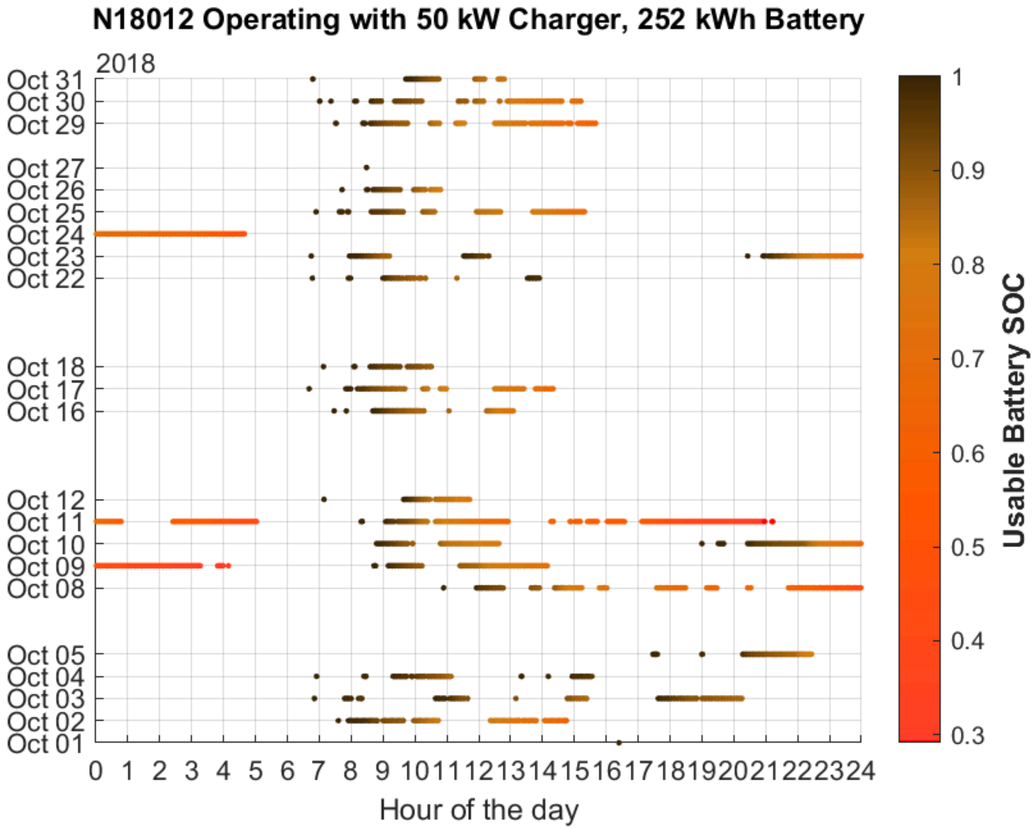

N18043 Operating with 150 kW Charger, 1423 kWh Battery
29-Jan-2020
23-Jan-2020
20-Jan-2020
17-Jan-2020
14-Jan-2020
11-Jan-2020
08-Jan-2020
04-Jan-2020
30-Dec-2019
27-Dec-2019
21-Dec-2019
18-Dec-2019
13-Dec-2019
10-Dec-2019
06-Dec-2019
02-Dec-2019
25-Nov-2019
22-Nov-2019
19-Nov-2019
15-Nov-2019
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Hour of the day
Usable Battery SOC
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1

Tractor/Loaders/Backhoes

N18011

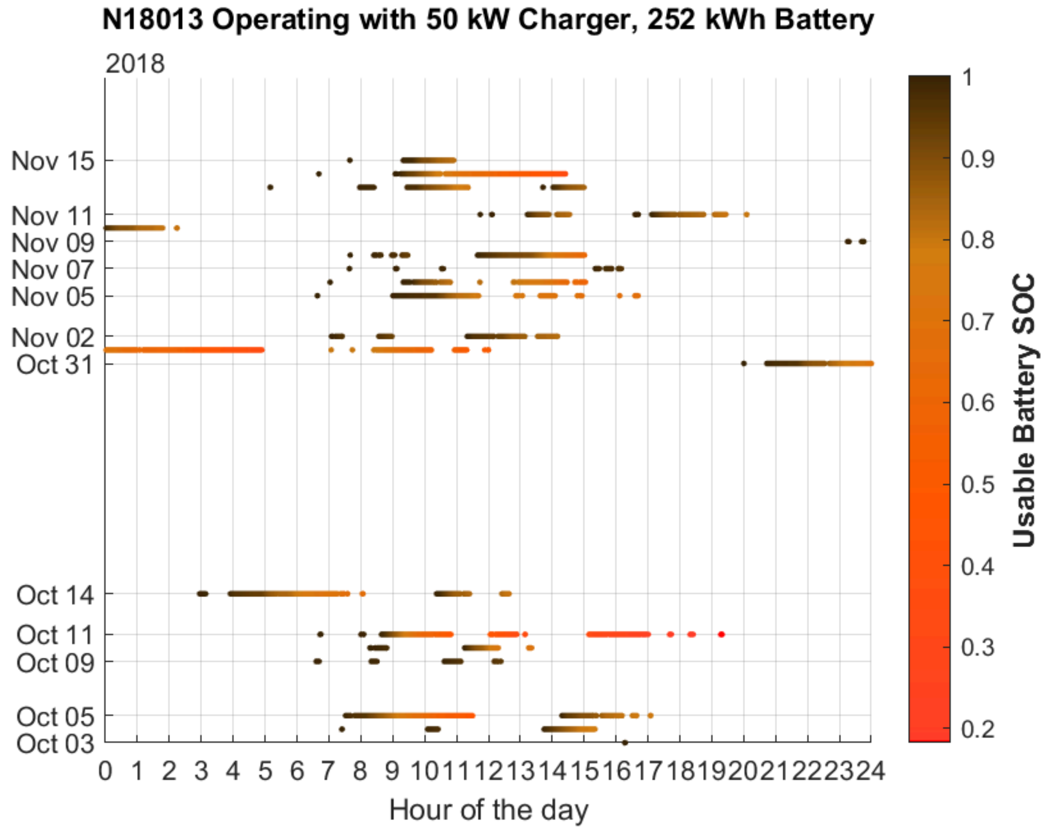


N18012



N18012 Operating with 50 kW Charger, 252 kWh Battery
2018
Oct 31
Oct 30
Oct 29
Oct 27
Oct 26
Oct 25
Oct 24
Oct 23
Oct 22
Oct 18
Oct 17
Oct 16
Oct 12
Oct 11
Oct 10
Oct 09
Oct 08
Oct 05
Oct 04
Oct 03
Oct 02
Oct 01
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Hour of the day
Usable Battery SOC
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3

N18013


N18013 Operating with 50 kW Charger, 252 kWh Battery
2018
Nov 15
Nov 11
Nov 09
Nov 07
Nov 05
Nov 02
Oct 31
Oct 14
Oct 11
Oct 09
Oct 05
Oct 03
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Hour of the day
Usable Battery SOC
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2

Appendix H: Equipment Activity Statistics

Data Source	Equipment	Data Collection Duration (Days)	No. of Days Operating	% Operating Days	Rolling % of Operating Days
UCR	N18011	28	20	71%	71.43%
UCR	N18012	29	22	76%	73.68%
UCR	N18013	42	20	48%	62.63%
UCR	N18031	97	72	74%	68.37%
UCR	N18033	26	19	73%	68.92%
UCR	N18034	83	47	57%	65.57%
UCR	N18021	28	25	89%	67.57%
UCR	N18027	28	26	93%	69.53%
UCR	N18054	33	18	55%	68.27%
UCR	N18024	28	28	100%	70.38%
UCR	N18025	18	17	94%	71.36%
UCR	N18044	134	52	39%	63.76%
UCR	N18029	148	46	31%	57.06%
UCR	N18014	87	27	31%	54.26%
UCR	N18019	81	39	48%	53.71%
UCR	N18020	27	10	37%	53.22%
UCR	N18022	27	23	85%	54.13%
UCR	N18023	22	22	100%	55.18%
UCR	N18045	140	38	27%	51.63%
UCR	N18046	106	39	37%	50.33%
UCR	N18047	108	62	57%	50.91%
UCR	N18048	64	17	27%	49.78%
UCR	N18049	28	19	68%	50.14%
UCR	N18050	30	19	63%	50.42%
UCR	N18015	62	26	42%	50.07%
UCR	N18016	26	17	65%	50.33%
UCR	N18018	49	23	47%	50.22%
UCR	N18026	34	27	79%	50.84%
UCR	N18030	148	53	36%	49.57%
UCR	N18028	28	18	64%	49.80%
UCR	N18043	75	47	63%	50.32%
UCR	N18068	55	32	58%	50.55%
UCR	N18069	55	27	49%	50.51%
UCR	N18070	10	6	60%	50.55%
UCR	JD_413	56	31	55%	50.69%
UCR	JD_414	48	17	35%	50.34%

Data Source	Equipment	Data Collection Duration (Days)	No. of Days Operating	% Operating Days	Rolling % of Operating Days
UCR	N18071	55	28	51%	50.35%
[149]	20070401-1	7	2	29%	50.28%
[149]	20070503-1	7	4	57%	50.30%
[149]	20070508-1	7	4	57%	50.32%
[149]	20070515-1	7	4	57%	50.35%
[149]	20070515-2	7	5	71%	50.41%
[149]	20070515-3	7	3	43%	50.39%
[149]	20070516-1	7	3	43%	50.36%
[149]	20070517-1	7	3	43%	50.34%
[149]	20070521-1	7	3	43%	50.32%
[149]	20070522-1	7	5	71%	50.38%
[149]	20070522-2	7	4	57%	50.41%
[149]	20070523-1	7	1	14%	50.29%
[149]	20070524-1	7	3	43%	50.27%
[149]	20070526-1	7	2	29%	50.20%
[149]	20070529-1	7	5	71%	50.27%
[149]	20070529-2	7	5	71%	50.33%
[149]	20070530-1	7	7	100%	50.49%
[149]	20070530-2	7	6	86%	50.59%
[149]	20070531-1	7	4	57%	50.62%
[149]	20070601-1	7	1	14%	50.50%
[149]	20070602-1	7	3	43%	50.48%
[149]	20070602-2	7	6	86%	50.59%
[149]	20070604-1	7	5	71%	50.65%
[149]	20070605-1	7	2	29%	50.58%
[149]	20070605-2	7	6	86%	50.69%
[149]	20070605-3	7	4	57%	50.71%
[149]	20070606-1	9	4	44%	50.69%
[149]	20070606-2	8	5	63%	50.73%
[149]	20070607-1	7	1	14%	50.62%
[149]	20070609-1	7	7	100%	50.76%
[149]	20070612-1	7	1	14%	50.66%
[149]	20070614-1	7	7	100%	50.80%
[149]	20070615-1	7	4	57%	50.82%
[149]	20070616-1	7	5	71%	50.88%
[149]	20070622-1	7	5	71%	50.94%
[149]	20070624-1	8	2	25%	50.85%
[149]	20070628-1	7	4	57%	50.87%
[149]	20070705-1	8	7	88%	50.99%

Data Source	Equipment	Data Collection Duration (Days)	No. of Days Operating	% Operating Days	Rolling % of Operating Days
[149]	20070709-1	7	3	43%	50.97%
[149]	20070716-1	7	3	43%	50.95%
[149]	20070718-1	7	7	100%	51.09%
[149]	20070729-1	7	5	71%	51.15%
[149]	20070803-1	7	5	71%	51.20%
[149]	20070823-1	7	4	57%	51.22%
[149]	20070824-1	7	3	43%	51.20%
[149]	20070824-2	7	6	86%	51.30%
[149]	20070824-3	7	4	57%	51.31%
[149]	20070826-1	7	2	29%	51.25%
[149]	20070830-1	7	3	43%	51.22%
[149]	20070831-1	8	5	63%	51.26%
[149]	20070831-2	7	2	29%	51.20%
[149]	20070831-3	8	5	63%	51.23%
[149]	20070831-4	8	4	50%	51.23%
[149]	20070906-1	9	7	78%	51.32%
[149]	20070907-1	8	5	63%	51.36%
[149]	20070913-1	7	3	43%	51.34%
[149]	20070917-1	9	4	44%	51.31%
[149]	20070919-1	8	4	50%	51.31%
[149]	20070923-1	7	2	29%	51.25%
[149]	20070926-1	7	3	43%	51.22%
[149]	20070930-1	7	3	43%	51.20%
[149]	20071004-1	8	5	63%	51.23%
[149]	20071010-1	8	3	38%	51.19%
[149]	20071018-1	7	6	86%	51.29%
[149]	20071025-1	7	2	29%	51.22%
[149]	20071101-1	7	3	43%	51.20%
[149]	20071108-1	7	3	43%	51.18%
[149]	20071112-1	7	4	57%	51.20%
[149]	20071115-1	7	5	71%	51.25%
[149]	20071124-1	7	2	29%	51.19%

Appendix I: Cost-Effectiveness Results

See *CARB_Off-road electrification_cost effectiveness results.xlsx*