Final Report

Collection of Agricultural Equipment Activity Data

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Disclaimer

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Abstract

Off-road diesel engines are widely used in agricultural goods production and supply and can contribute to poor air quality in non-attainment areas for particulate matter (PM) and ozone. Agriculture tractors are one of the most prevalent pieces of equipment in the agriculture industry that utilize diesel engines. In order to understand the impact of California agriculture tractors on air quality, it is important to develop accurate emissions inventories based on their activity patterns and associated emissions. The objective of this research was to collect real-world activity data from agricultural tractors, which could be used to improve the emission inventory and to inform policies and incentive programs in California. The activity data included both engine parameters collected using data loggers and engine hour records. In total, 208 tractors were monitored through either engine hour records or data loggers, with 103 of these tractors monitored with data loggers. These tractors represented a range of crop types (row and tree crops), horsepower (hp, <50 to 650 hp), and farm sizes (<250 to 21,000 acres). The study results will help ensure that the future development of emission inventories, policies, and incentive programs can reflect more information collected from real-world farm activities.

The results showed that the average annual hours of usage for agriculture tractors located in the San Joaquin Valley, California declined as a function of engine age/older engine technology. The annual hours of usage were 739 hours, 741 hours, 143 hours, 130 hours, and 60 hours, respectively, for Tier 4, Tier 3, Tier 2, Tier 1, and Tier 0 tractors. The results show that there is a large drop-off in annual engine hours for the older Tier 0 and 1 equipment, with a much smaller drop-off for the Tier 2 tractors.

The results showed that the tractors on average were used for about 4 hours per day. During that time, the average engine load was typically between 22 and 33% for the different categories, with an overall average load percent of 28%, with an average idle percentage of around 27%. Average daily fuel use rates were 20 gallons per day, with a maximum of about 40 gallons per day for the 300-650 hp categories, while tractors in the less than 175 hp category had fuel use rates below 10 gallons per day. Average fuel use rates were 4.2 gallons per hour, with a maximum of about 8 gallons per hour for the 300-650 hp categories, while tractors in the below 175 hp category had fuel use rates of about 2 gallons per hour. Average diesel particle filter (DPF) outlet temperatures were at or above 250°C for both the tree and row crop categories and for all of the different hp categories. Temperature distributions showed that the DPF outlet temperature is above 200°C for 78.5% of the operational time, which in turn suggests that for 21.5% of the operating time, the DPF outlet temperature would not be sufficiently high to allow for the injection of urea into the selective catalytic reduction (SCR) to ensure it properly functions.

The in-use activity data covers a much broader range of operating conditions than are found in the certification cycles. In general, the distributions for the in-use data show that there is a more significant contribution at low load conditions than is captured in the certification cycles. Since low load operations could lead to low DPF outlet temperatures and thus lower SCR efficiencies, further investigation into the emissions contribution during low loads is needed. This report also identifies recommendations for further research on the topic of in-use activity of off-road equipment used in agricultural applications.

Acronyms and Abbreviations

CARB .... California Air Resources Board
CE-CERT .... College of Engineering-Center for Environmental Research and Technology (at the University of California, Riverside)
CRADA... Cooperative Research and Development Agreement
CSV .... comma-separated values
DPF .... diesel particulate filter
ECU.. engine control unit
EPA .... United States Environmental Protection Agency
EQUIP .... Natural Resources Conservation Services Environmental Quality Incentive Program
FARMER .... Funding Agriculture Replacement Measures for Emission Reductions
GPS .... Global Positioning System
hp.. horsepower
ISO .... International Organization of standards
kW.. kilowatt
NRTC .... nonroad transient cycle
NRSC .... nonroad steady state cycle or C1 cycle
NO_X .... oxides of nitrogen
PM.. particulate matter
PM2.5 .... fine particulate matter
QA/QC .... quality assurance and quality control
RPM .... revolutions per minute
SCR .... selective catalytic reduction
SJV .... San Joaquin Valley
UCR .... University of California at Riverside
U.S. EPA .... United States Environmental Protection Agency

Executive Summary

Agriculture is a key industrial sector and employer in California, producing over 400 different commodities that generate annual sales/added value that is estimated to be between $50 billion and $144.5 billion and over 400,000 to 1.57 million jobs statewide. [1,2,3] Off-road diesel engines are widely used in agricultural goods production and supply, and can contribute to poor air quality in non-attainment areas for particulate matter (PM) and ozone. In particular, the San Joaquin Valley (SJV) in California, which is classified as an extreme ozone nonattainment area and a serious nonattainment area for PM2.5, contains over 56% of the state's agricultural harvested acreage and equipment. In 2020, approximately 22% of nitrogen oxide (NOx) emissions from mobile sources in the SJV originated from farm equipment. A number of incentive programs have been developed to help promote the purchase of newer and lower-emitting agriculture equipment. This has included CARB's Carl Moyer Program, the San Joaquin Valley Air Pollution Control District's Tractor Replacement Program, the Natural Resources Conservation Services Environmental Quality Incentive Program (EQUIP), and the Funding Agriculture Replacement Measures for Emission Reductions (FARMER) incentive program. CARB's FARMER incentive program was developed to provide funds for the conversion of tractors and harvesters to cleaner equipment, and had distributed $461 million in funds as of September 2023 and resulted in reductions of 26,600 tons of NOx, 1,580 tons of fine particulate matter (PM 2.5), and 368,000 metric tons of carbon dioxide equivalents.[4]

In order to understand the impact of these agriculture tractors on air quality in California, it is important to develop accurate inventories of their activity patterns and associated emissions. The objective of this research was to collect real-world activity data from agricultural equipment, which will be used to improve the emission inventory and to inform policies and incentive programs in California. For this research, Engine Control Unit (ECU) data were collected under actual working conditions related to engine and aftertreatment performance, such as engine load, engine speed, engine torque, fuel economy, and aftertreatment temperatures. Additional data were collected from monitoring the engine hours of tractors to determine their level of use over an annual cycle of agriculture operations. The study results will help ensure that the future development of emission inventories, policies, and incentive programs can reflect more information collected from real-world farm activities.

In total, 208 tractors were monitored through either engine hour records or data loggers, with 103 of these tractors monitored with data loggers. This included 168 Tier 3 and 4 tractors, with 99 monitored with data loggers and 69 monitored from engine hour records. A total of 40 Tier 0 to 2 tractors were monitored, with 36 of these monitored from engine hour records and 4 monitored with data loggers over a year period ending in 2024. More detailed information on the text matrix for the activity monitoring is provided in Table ES-1. The tractors monitored for this program came from a total of 22 individual farms.

[1] CARB, 2021 Emissions Inventory for Agricultural Diesel Vehicles
[2] https://data.bls.gov/cew/apps/data_views/data_views.htm#tab=Tables
[3] Houk, E., 2022, The Contribution of Agriculture to Northeastern California's Economy in 2020, Report by the Agribusiness Institute College of agriculture California state University at Chico.
[4] FARMER Program Infographic, https://ww2.arb.ca.gov/sites/default/files/classic/ag/agincentives/outreach/farmerinfographic.pdf

Table ES-1: Test Matrix of agricultural tractors monitored based on engine tier, hp and commodity served

	Group 1: Tree /Orchard /Nut				Group 2: Field and Row Crops			
	Tier 0,1,2		Tier 3 & 4		Tier 0,1,2		Tier 3 & 4	
Engine HP Rating	**Total**	**HEM Logged**	**Total**	**HEM Logged**	**Total**	**HEM Logged**	**Total**	**HEM Logged**
hp < 50	3	0	7	0	1	0	1	1
50 ≤ hp < 175	25	1	69	18	8	2	32	22
175 ≤ hp < 300	1	0	7	7	2	1	19	19
300 ≤ hp < 600	0	0	8	8	0	0	25	24
Total	29	1	91	33	11	3	77	66

The results of the data analysis for the agriculture tractors are summarized below:

Figure ES-1 shows the average daily use for the tractors by category, with the error bars representing one standard deviation on the average. The overall average use for all tractors was about 4 hours per day. The data show a few trends of note. The results show that for the newer Tier 3-4 tractors, row crops show higher hours of use per day averaging about 5 hours per day for the 175-299 hp and 300-650 hp categories, and about 4 hours for the 75-174 hp category. For the tree crops for the Tier 3-4 tractors, the average hours of use per day was about 4 hours for the 175-299 hp and 300-600 hp categories, and 3 hours for the 75-174 hp category. The Tier 1-2 tractors generally showed lower operating hours per day, with averages of around 2.5 hours per day for the Tier 1-2 75-174 hp and 175-299 hp categories for row crops, but did have higher average hours, at nearly 4 hours per day for the 75-174 hp tree crop tractors.

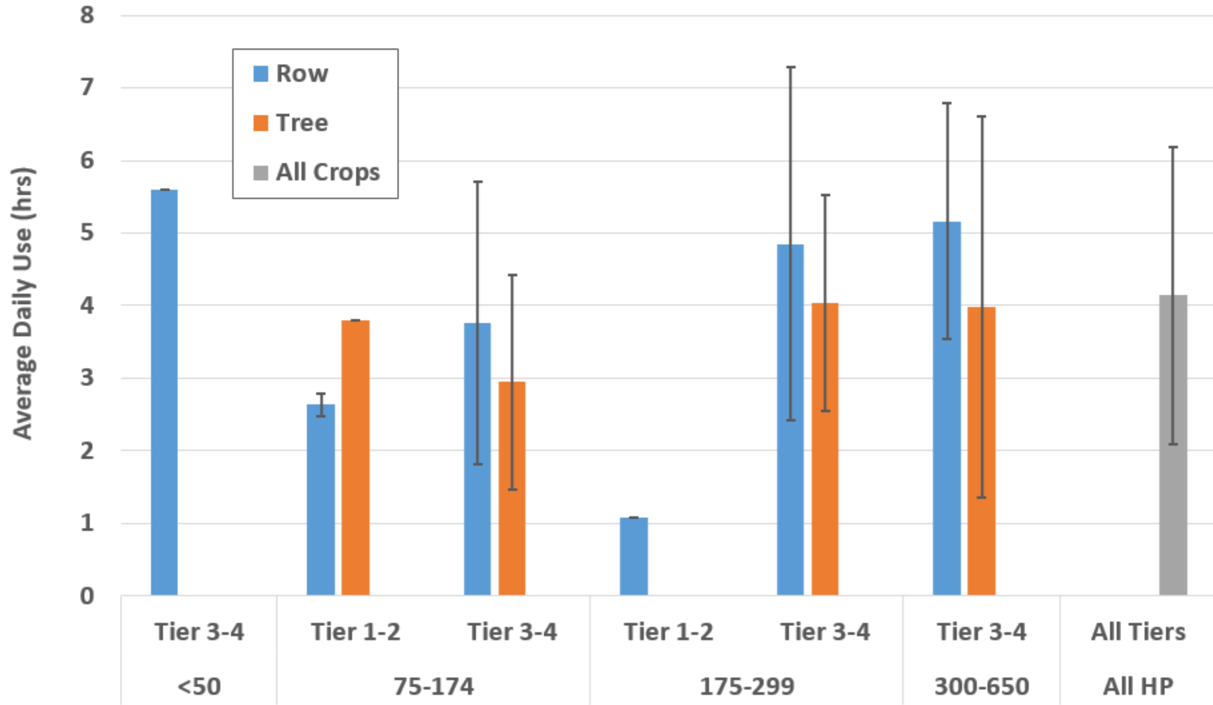

Figure ES-1. Average Hours of Use per Day by Crop Type, Engine Power Rating, and Engine Technology

Figure ES-2 and ES-3 show the annual engine hours for the individual tractors monitored in this study, and the averages by engine Tier, respectively. Figure ES-3 is shown as a box whisker plot, which shows the range of the data from the 25^{th} to the 75^{th} quartile within the upper and lower limits of the box, the median, which is the line in the box, and average, which is the “x” in the box, and outlier points, which are shown outside of the box. The average annual hours of usage were 60 hours, 130 hours, 143 hours, 741 hours, and 739 hours, respectively, for Tier 0, Tier 1, Tier 2, Tier 3, and Tier 4 tractors. The Tier 3 and Tier 4 tractors showed similar patterns of annual use. The results show that there is a large drop-off in annual engine hours for the older Tier 0 and 1 equipment, with a much smaller drop-off for the Tier 2 tractors.

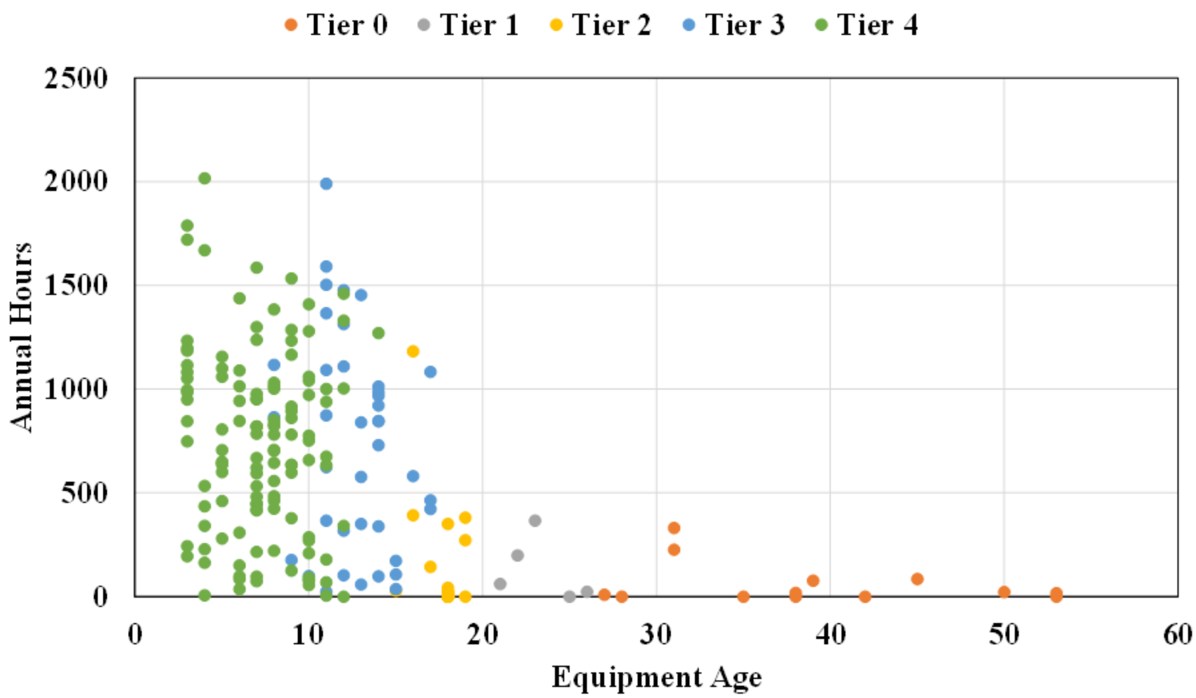

Figure ES-2. Annual Hours by Engine Tier Technology

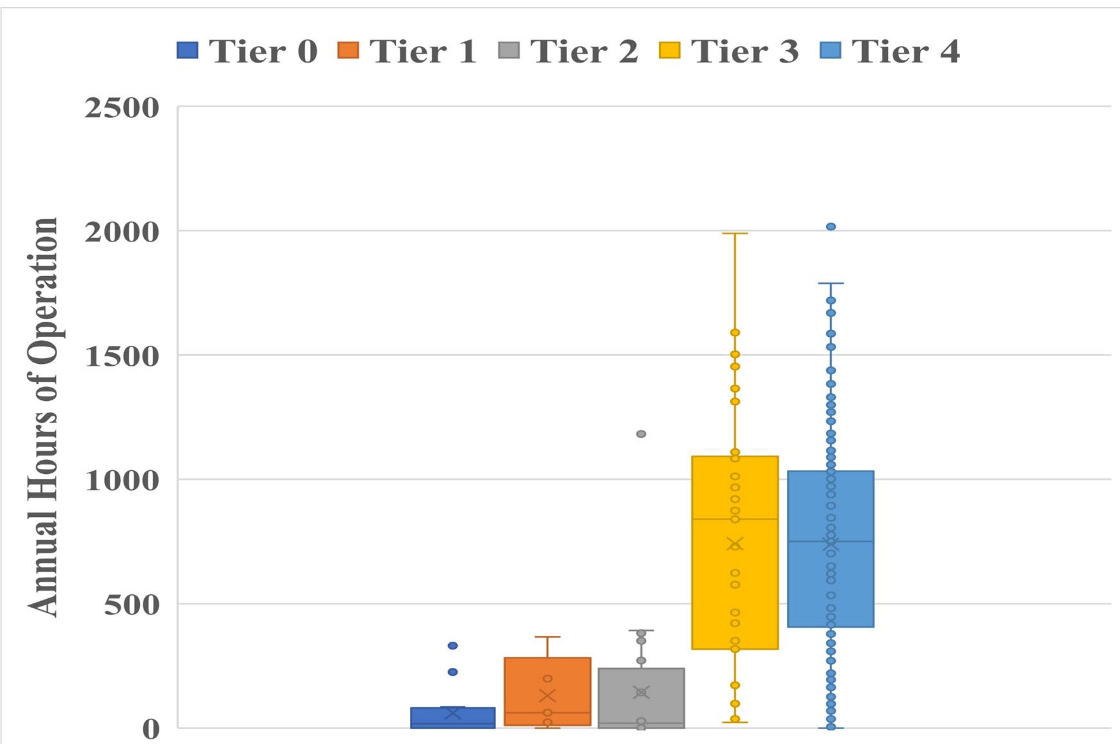

Figure ES-3. Average Annual Hours by Engine Tier Technology

Figure ES-4 shows the average engine load percent relative to the maximum power for the tractors by category. Typical average loads for the tractors are similar, as a function of the engine's hp level. The data show relatively consistent load levels with the loads between 22 and 35% for the different tractor categories, with an overall average load percent of 28%. The data did not show significant differences between tractors for tree or row crops, or for different engine hp categories. It should be noted that the average load factors include idle time, so it does not necessarily represent the typical load for tractor during the working portion of their operation.

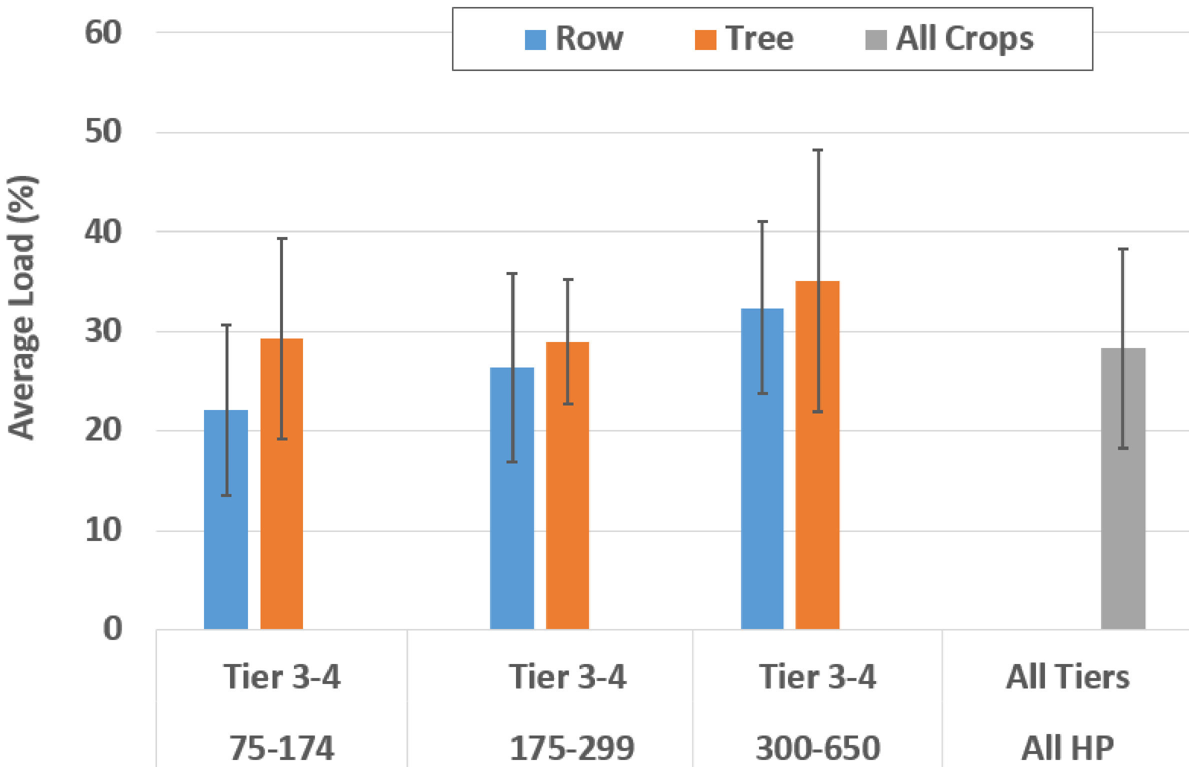

Figure ES-4. Average Load Factor by Crop Type, Engine Power Rating, and Engine Technology

Figure ES-5 and Figure ES-6 show the average fuel use per hour for the individual tractors and the tractors by category. Overall, the data show a positive upward trend in fuel use in gals/hour as a function of increasing hp, as expected. The trend lines between the Tier 3 and 4 tractors and the Tier 2 tractors were comparable, but the data available for the older tractors was limited and only for lower-hp tractors. Average fuel use rates were 4.2 gallons per hour, with a maximum of about 8 gallons per hour for the 300-650 hp category, while the below 175 hp categories had fuel use rates of about 2 gallons or less per hour. Additional measurements for fuel consumption for four Tier 0 to Tier 2 tractors were also conducted by manually measuring fuel consumption over the period of a day. These tractors ranged in size from 76 to 105 hp, and showed fuel consumption ranging from 1.5 to 1.9 gals/hr, consistent with the results seen over longer periods of time for data collected by the data loggers.

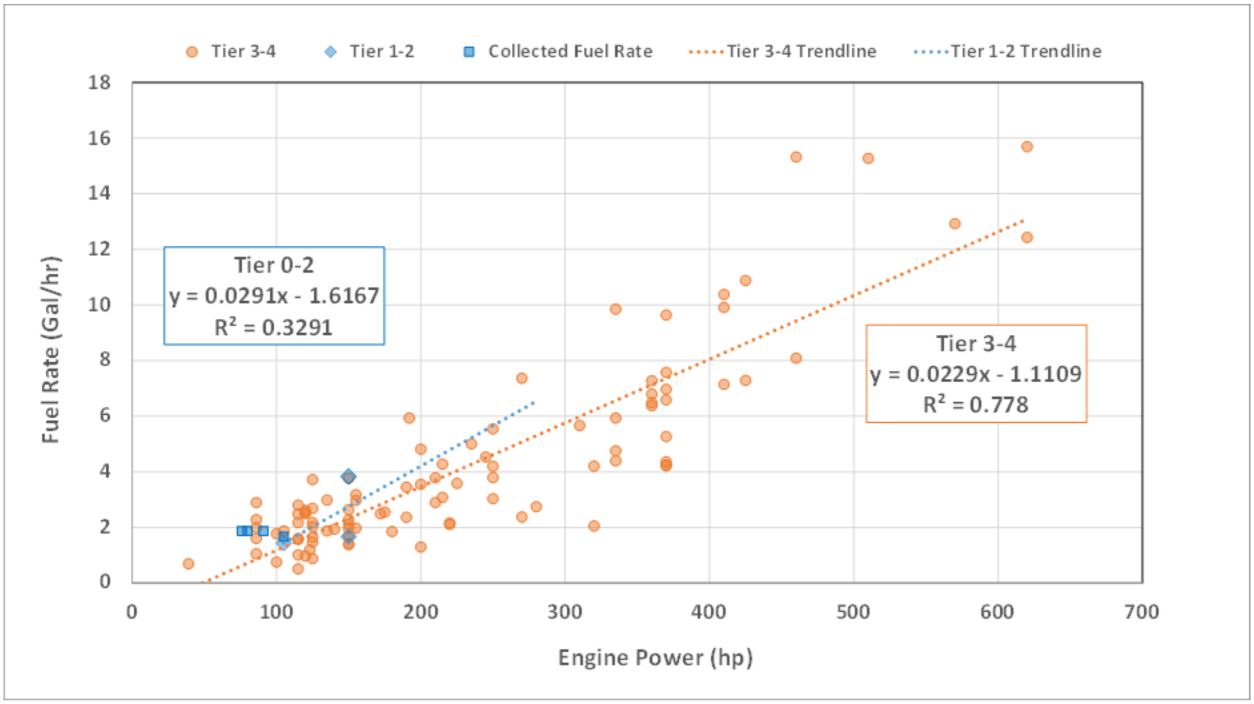

Figure ES-5. Average Fuel Use per Hour by Engine Power Rating

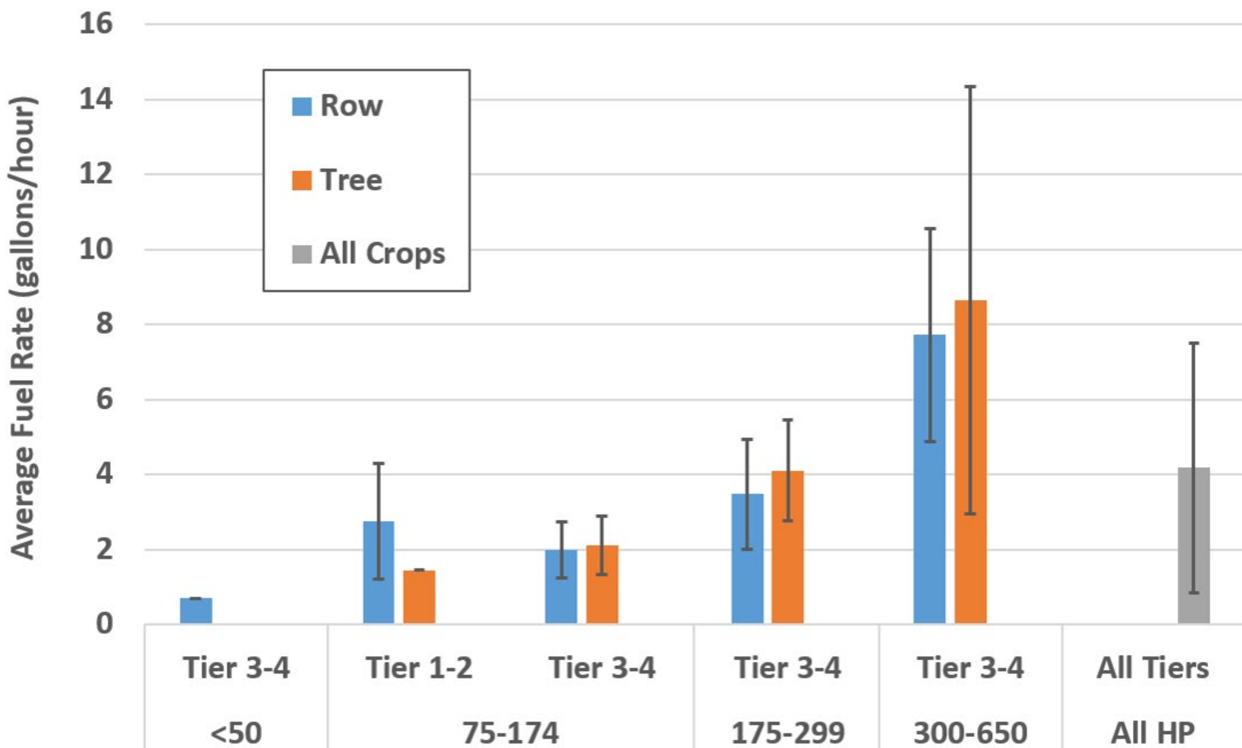

Figure ES-6. Average Fuel Use per Hour by Crop Type, Engine Power Rating, and Engine Technology

Figure ES-7 and Figure ES-8 show the average DPF outlet temperature for the tractors by category and a distribution of the DPF outlet temperature, respectively. Note that the DPF outlet temperature is the best approximation of the inlet temperature for the SCR that was available in the ECU data, as the DPF is positioned just before the SCR in a typical DPF/SCR setup. Average DPF outlet temperatures for the tree and row crops and the different hp categories were similar. The average DPF temperatures were at or above 250°C category for both the tree and row crops and for all of the different hp categories. Frequency distributions of DPF outlet temperatures show that the DPF outlet temperature is above 200°C for 78.5% of the operational time, which in turn suggests that for 21.5% of the operating time, the DPF outlet temperature would not be sufficiently high to allow for the injection of urea into the SCR.

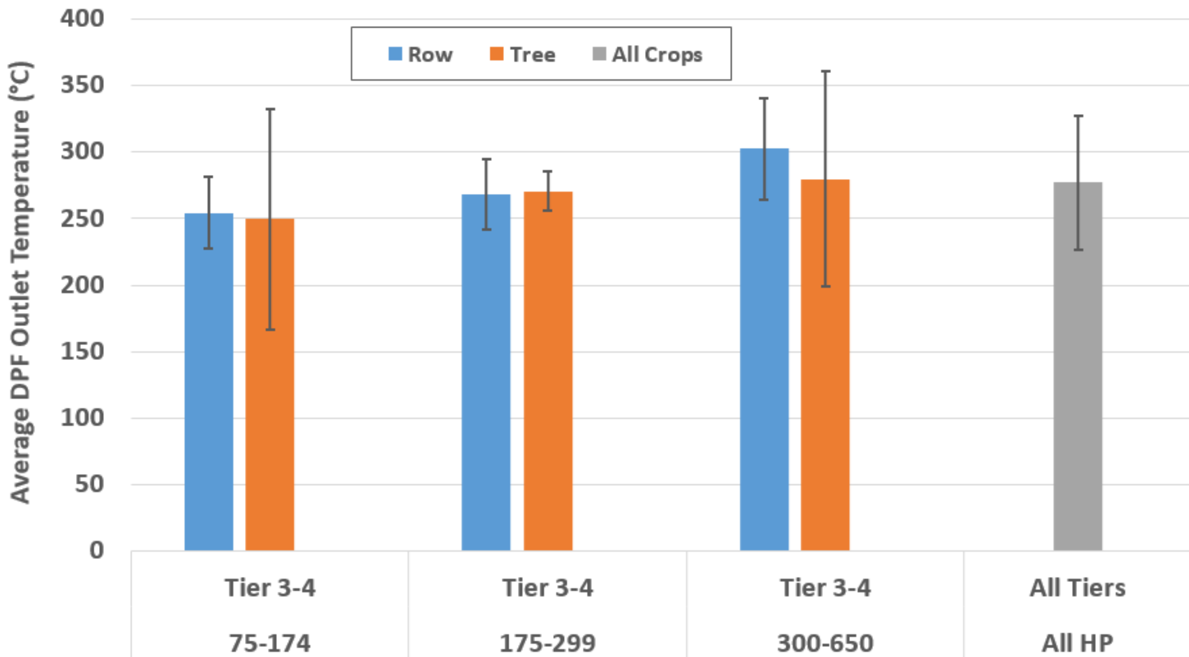

Figure ES-7. Average Exhaust/DPF Outlet Temperature by Crop Type, Engine Power Rating, and Engine Technology

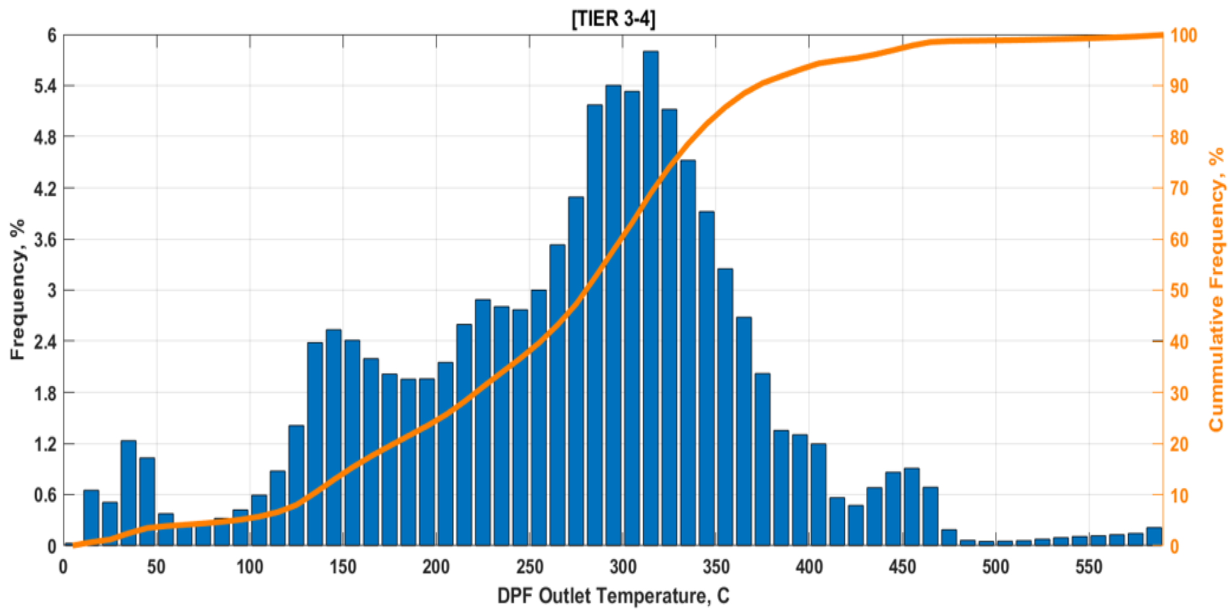

Figure ES-8. DPF Outlet Temperature Distributions for the Tractors.

Figure ES-9 shows the average idle percentage for the tractors by category. For this analysis, an idle event was defined as when the engine rpm falls within an engines idle speed range for a period of at least 10 seconds. Average idle times are relatively consistent for different crops (tree and row) and the engine power ratings. Across the engine power ratings, idle emissions showed a range from 23% to 28% for most power ratings, with some higher and lower exceptions. The overall average idle percentage was 26%.

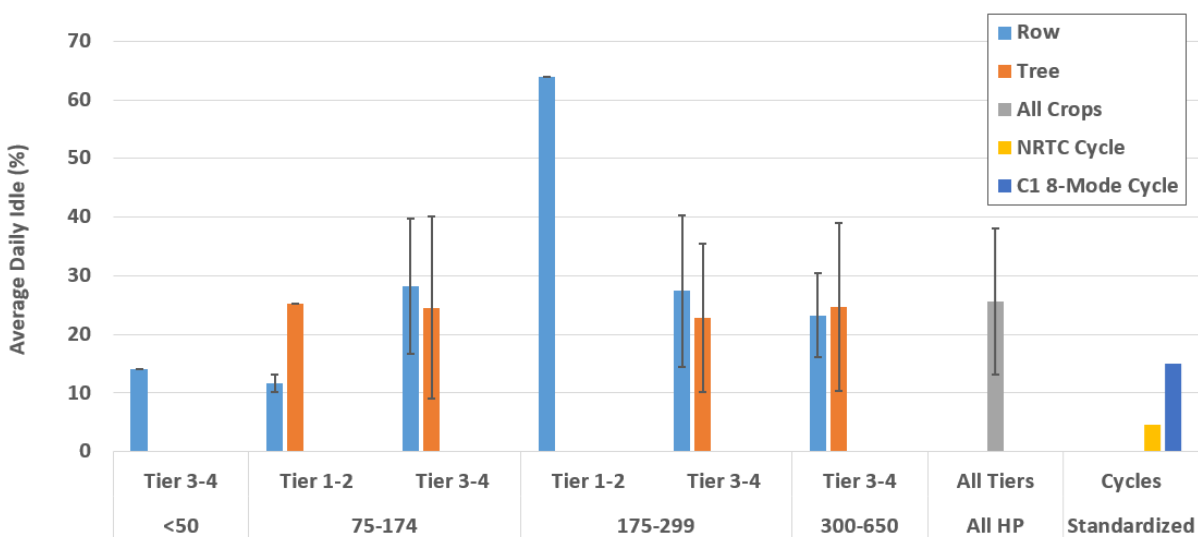

Figure ES-9. Average Idle Percentage by Crop Type, Engine Power Rating, and Engine Technology

The average number of starts per day is presented in Figure ES-10. Here, a start was defined as a period after an engine off event, where the engine rpm was below 300 rpm for a period of greater than 30 seconds. The average number of starts per day was approximately 3.4 starts, with a range from slightly less than 2 to 5 starts per day. Hot starts (with soak durations ≥ 30 seconds and ≤ 60 minutes) represented the highest fraction of starts per day, with an average of approximately 2.2 hot starts per day, with a range from < 1 to slightly greater than 3 hot starts between the different categories. The number of intermediate starts (with soak durations ≥ 60 minutes and ≤ 720 minutes) was on average about 0.4 per day, with the number of intermediate starts averaging 0.5 per day or less for all categories. The average hot start soak duration was approximately 15 minutes, with a range from approximately 10 to 20 minutes between different categories. The average intermediate start soak duration was approximately 200 minutes, with a range from approximately 150 to 250 minutes between different categories.

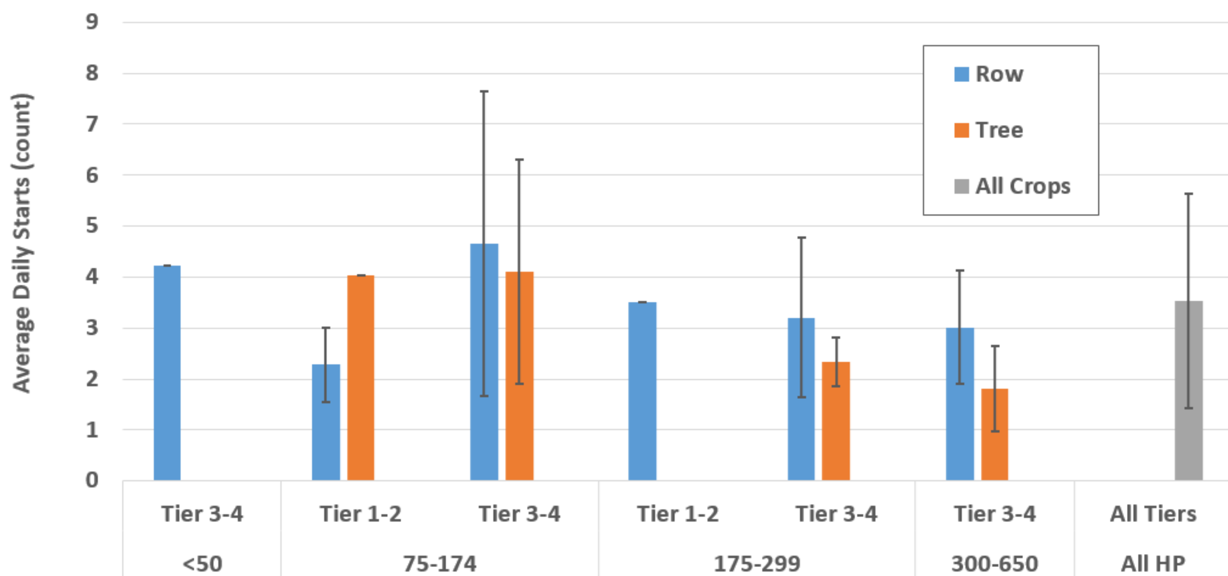

Figure ES-10. Average Number of Engine Starts by Crop Type, Engine Power Rating, and Engine Technology

Figure ES-11 shows a frequency distribution of the normalized continuous torque and engine speed data for the overall average of the Tier 3 and 4 agriculture tractor activity data. The normalized continuous torque and engine speed data for the NRTC and C1 cycles are shown in Figure ES-12 and ES-13, respectively. The in-use activity data covers a much broader range of operating conditions than are found in the certification cycles. In general, the distributions for the in-use data show that there is a more significant contribution at low load conditions than is captured in the certification cycles.

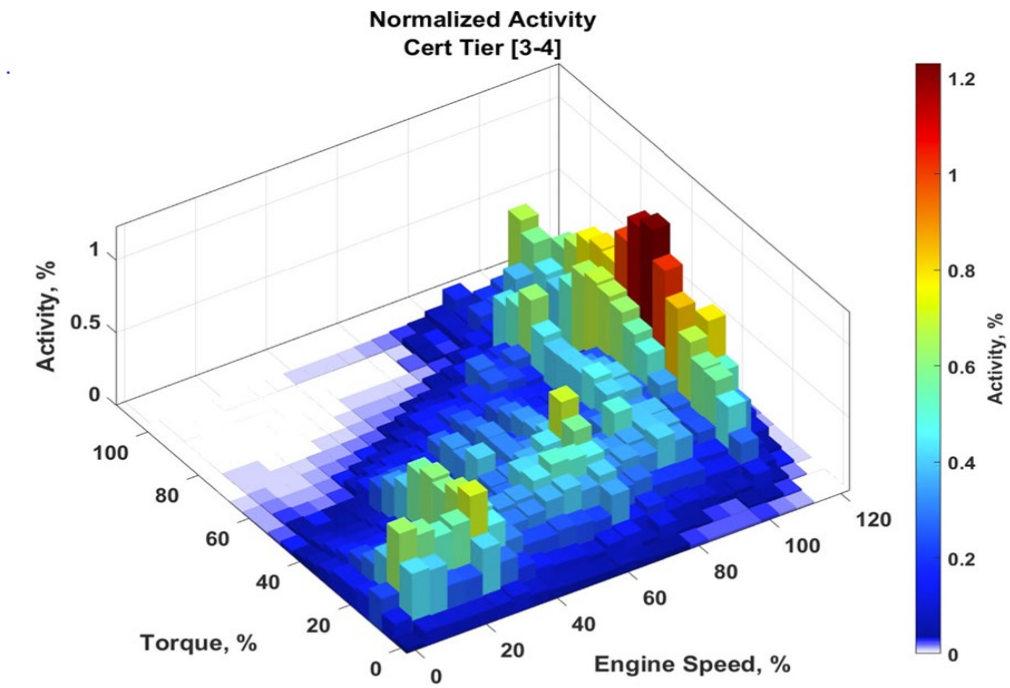

Figure ES-11. Frequency distribution of torque and engine speed for the overall average of the in-use agriculture tractor data.

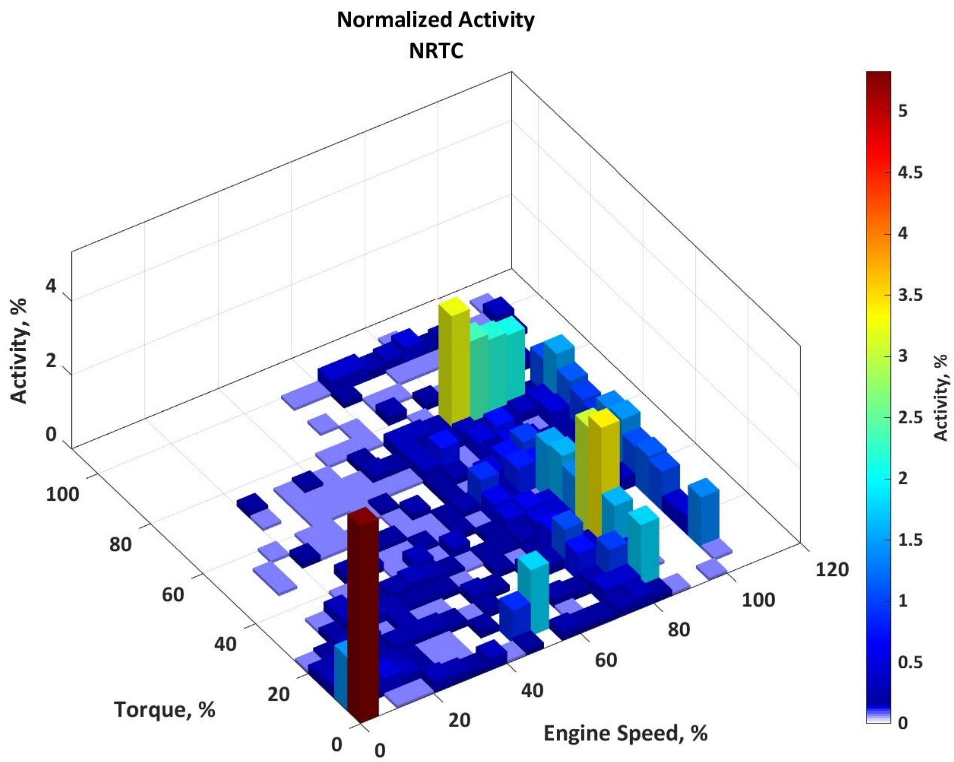

Figure ES-12. Frequency distribution comparisons of torque and engine speed for the normalized NRTC cycle.

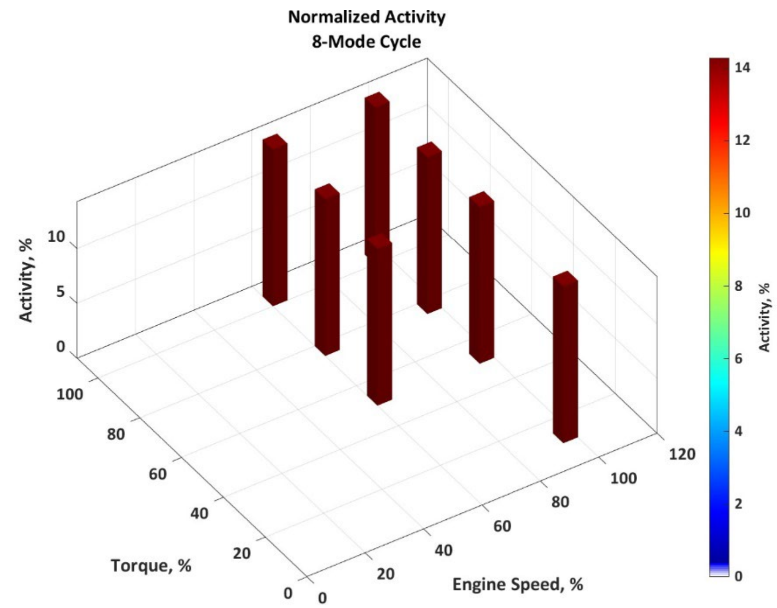

Figure ES-13. Frequency distribution comparisons of torque and engine speed for the normalized C1 cycle.

This study provides an initial robust dataset for the distribution of engine loads and other activity updates for off-road equipment used in agricultural applications. For next steps, we recommend that CARB and local air districts analyze these data alongside additional data that are available to update emissions inventories. These updated inventories will inform air quality programs, such as the FARMER incentive program. In performing emissions inventory updates to inform programs, we specifically recommend that air quality agencies should consider the following:

- How other studies providing total annual activity (engine operating hours per year) compare with those reported from the 208 pieces of equipment included in this study. For example, in the near-term, consider conducting a randomized survey of growers and/or farms, stratified by crop type, geographic location, and any other variables, to include a larger number of pieces of equipment to further refine the total annual activity of off-road agricultural equipment.
- Using surveys, or other data sources mentioned above, to evaluate how the distribution of engine activity compares with equipment age, or other surrogates such as engine age or tier level. Improving the relationship between operating hours and equipment age will help refine the emissions impacts of older equipment (such as Tier 2 and older) that is operating in the agricultural fields of California.
- Using a survey or other data source, update the distribution of equipment tier to reflect the impacts of incentives, natural turnover, and any other factors that affect the emissions levels of the in-use fleet of agricultural equipment.
- Consider longitudinal assessments of both total annual activity and engine load distribution (including the fraction of idling time) to assess whether trends in operating behaviors of equipment are changing. Such assessments will be valuable especially for decadal assessment of trends of the agricultural sector and would be less valuable for near-term updates to emissions inventories.

1. Background

Agriculture is a key industrial sector and employer in California, producing over 400 different commodities that generate annual sales/added value that is estimated to be between $50 billion and $144.5 billion and over 400,000 to 1.57 million jobs statewide (Bureau of Labor Statistics; CARB, 2021; Houk, 2022). Off-road diesel engines are widely used in agricultural goods production and supply. They are also important contributors to poor air quality in non-attainment areas for particulate matter (PM) and ozone. In particular, the San Joaquin Valley (SJV), which is classified as an extreme ozone nonattainment area, contains over 56% of the state's agricultural harvested acreage and its associated equipment (CARB, 2021). In 2012, approximately 14% of nitrogen oxide (NOx) emissions from mobile sources in the SJV originated from farm equipment. This relative fraction increased to 22% in 2020, however, mostly due to the decline of emissions from on- and other off-road vehicles. A number of incentive programs have put in place to help promote the purchase of newer and lower-emitting agriculture equipment., This has included CARB's Carl Moyer Program, the San Joaquin Valley Air Pollution Control District's Tractor Replacement Program, the Natural Resources Conservation Services Environmental Quality Incentive Program (EQUIP), and the Funding Agriculture Replacement Measures for Emission Reductions (FARMER) incentive program. As of September 2023, for example, $461 million in FARMER incentive funds have been used to for the purchase of cleaner equipment, which has resulted in reductions of 26,600 tons of NOx, 1,580 tons of fine particulate matter (PM 2.5), and 368,000 metric tons of carbon dioxide equivalents (Farmer, 2023). To improve air quality and develop effective incentive strategies for the SJV, constructing an accurate agricultural emissions inventory with the latest data is critical.

The California Air Resources Board (CARB) has updated the 2011 agricultural emissions inventory based on a 2008 survey of diesel agricultural equipment in 2021 using 2018 survey data (CARB, 2018a, 2018b, 2021). This inventory has significantly improved the understanding of California's agricultural equipment population, usage, emissions, and the importance of incentives. The new 2018 survey was completed with the help of agricultural stakeholders. New findings in this survey, such as consolidation of smaller farms and a greater deployment of Tier 4f equipment than expected, have impacted the results of the 2021 emissions inventory. However, the recent agricultural inventory could benefit from understanding real-world activity patterns and fuel consumption for agricultural engines, and there is a lack of data on how agricultural engine operation differs from that for other off-road equipment.

The objective of this research was to collect real-world activity data from agricultural equipment that will be considered when next updating the emission inventory and to inform air quality programs, policies and incentive programs in California. For this research, engine hour and Engine Control Unit (ECU) data were collected under actual working conditions to determine the use patterns for over 200 agriculture tractors from participating farms. The ECU data were also used to evaluate engine and aftertreatment performance, such as engine load, engine speed, engine torque, fuel economy, and aftertreatment temperatures. Additional engine hour data was also obtained from dealer agriculture tractor rentals. The study data will help ensure that the future development of off-road emission inventories and regulatory standards can reflect more information collected from real-world farm activities.

2. Experimental Methods

2.1 Test Matrix

The test matrix for this program was based on the distribution of tractors obtained during the recruitment process, in conjunction with feedback from CARB and the agriculture stakeholders. Feedback that was considered in the development of the test matrix included tractor population estimates, as well as stakeholder insight into farming activities and needs for emissions inventory modeling. The test matrix for the main data collection from the participating farms is provided in Table 2-1 for the crop categories outlined in Table 2-2. The test matrix includes a breakdown of tractors based on Tree/Orchard/Nut and Field and Row Crop farms, engine horsepower ratings, and emissions standard level, i.e., Tier 0 to 4. The test matrix includes the total number of tractors monitored overall, and the number of tractors that were monitored with HEM data loggers, as discussed below. One practical consideration in recruiting tractors was that the availability of older tractors was more limited than originally anticipated, as many older tractors have been replaced by newer tractors due to natural turnover and also through incentive fund programs.

Table 2-1: Test Matrix of agricultural tractors monitored based on engine tier, hp and commodity served

	Group 1: Tree /Orchard /Nut				Group 2: Field and Row Crops			
	Tier 0,1,2		Tier 3 & 4		Tier 0,1,2		Tier 3 & 4	
Engine HP Rating	Total	HEM Logged	Total	HEM Logged	Total	HEM Logged	Total	HEM Logged
hp < 50	3	0	7	0	1	0	1	1
50 ≤ hp < 175	25	1	69	18	8	2	32	22
175 ≤ hp < 300	1	0	7	7	2	1	19	19
300 ≤ hp < 600	0	0	8	8	0	0	25	24
Total	29	1	91	33	11	3	77	66

Table 2-2: Commodity groups served by participating tractors

Group 1 Tree/Orchard/Nut	*Examples*	Group 2 Field and Row Crops	*Examples*
Citrus	*Orange, Lemon, etc.*	**Row Crops**	*Corn, Cotton*
Nut Crops	*Pistachio, Almond, Pecan*	**Vegetables**	*Carrot, Potato*
Tree Fruit	*Apple, Pear, Stone Fruit, Cherry*	**Grains (rice, oats)**	*Rice, Oat, Wheat*
Grapes	*Table, Raisin*	**Hay, Forage, Pasture**	*Grass, Hay*

In total, 208 tractors were monitored through either engine hour records or data loggers, with 103 of these tractors monitored with data loggers. This included 168 Tier 3 and 4 tractors, with 99 monitored with HEM data loggers and 69 monitored from engine hour records. A total of 40 Tier 0 to 2 tractors were monitored, with 36 of these monitored from engine hour records and 4 monitored with HEM data loggers. Of the 103 tractors with HEM data logger information, two tractors had less than 5 minutes of data records, so they were not included in the associated data analysis.

The tractors monitored for this program came from a total of 22 individual farms. These farms were recruited from contacts provided from the agriculture industry stakeholders, which facilitated in getting farmers to agree to participate in the program. The size of the farms ranged from <250 acres to over 2,000 acres, and included a custom farm where the tractors are essentially utilized on a contract basis on multiple farms. A breakdown of the sample matrix by farm size is provided in Table 2-3. This shows that the highest fraction of farms represented in the test matrix were for medium-sized (250-999 acres) and larger (2,000-9,999 acre) farms. Note that the classification of farms based on tree vs. row crops was based on the predominant number of tractors doing that farming operation at a particular farm, as some farms included both operations.

Table 2-3: A Breakdown of the Sample Matrix by Farm Size

			Group 1: Tree/Orchard/Nut				Group 2: Field and Row Crops			
			Tier 0,1,2				Tier 3 and 4			
Farm Size	**# Farms**	**# Tractors**	**hp < 50**	**50 ≤ hp < 175**	**175 ≤ hp < 300**	**300 ≤ hp < 600**	**hp < 50**	**50 ≤ hp < 175**	**175 ≤ hp < 300**	**300 ≤ hp < 600**
<250	3	6	0	1	0	0	1	4	0	0
250-999	6	48	3	20	1	0	6	16	1	1
1000-1999	2	13	0	6	1	0	0	2	2	2
2000-9,999	7	92	1	3	1	0	0	50	18	19
10,000-21,000	3	40	0	3	0	0	1	20	5	11
Custom farm	1	9	0	0	0	0	0	9	0	0
Total	22	208	4	33	3	0	8	101	26	33

Understanding the activity/use levels as a function of tractor age was an important element of the study, as such information is important in the development of emissions inventory models. A distribution of the age of the tractors monitored in this study is provided in Figure 2-1. This figure shows that the majority of the tractors were 18 years or newer, although a total of 23 tractors older than 18 years were also sampled.

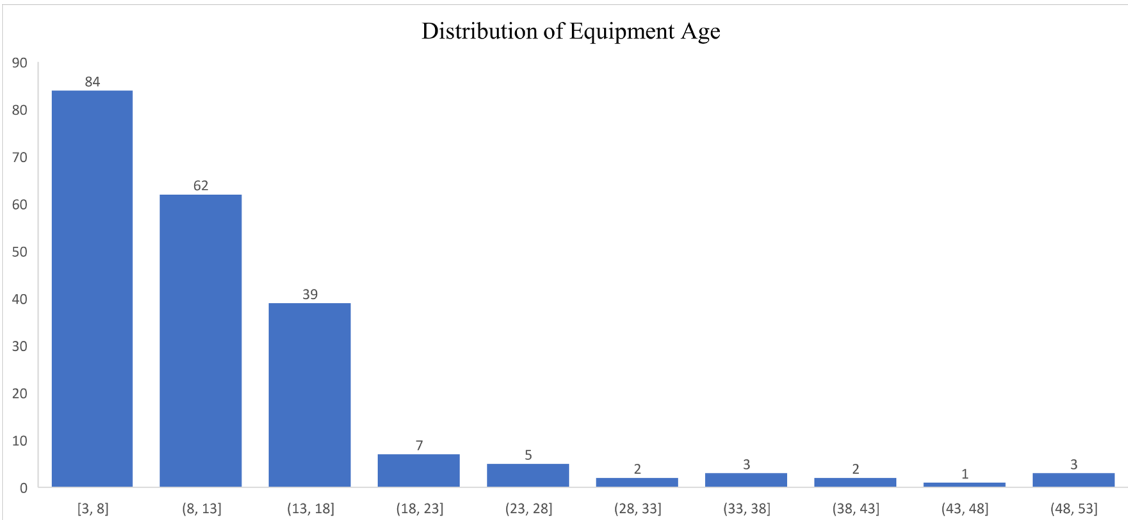

Figure 2-1. Distribution of the Age of the Tractors Monitored

The type of soil where the tractor is working is another potential factor that might affect the work being done by the tractor. The soil type for each farm was obtained by surveying the farmers directly. For most of the farms, the soil composition included multiple types of soil. The data obtained from a subset of farmers was cross-compared with soil maps from different sources, and in general the data showed good comparability. Soil type was collected on the equipment data collection sheet approximately every 3 months, as part of the typical data collection efforts in conjunction with the field data collection.

The distribution of soil types for the data collection effort are shown in Figure 2-2. This distribution is based on the number of tractors for each farm distributed proportionately based on the number of soil types represented on that farm. The distribution of soil types including nearly all of the commonly classified soils, which are illustrated in Figure 2-3. The main types of soil included Sandy Loam, Clay Loam, Loam, and Clay. It should be noted that this information is somewhat qualitative in nature, as the soil type can differ even between different areas in a particular farm, and a tractor may have operations in areas with different soil types over the course of the monitoring period in between visits. Nevertheless, the primary consideration for this study is that the tractors sampled operated in a diverse range of soils such that it is representative of a wide range of operations, which the data in show is the case.

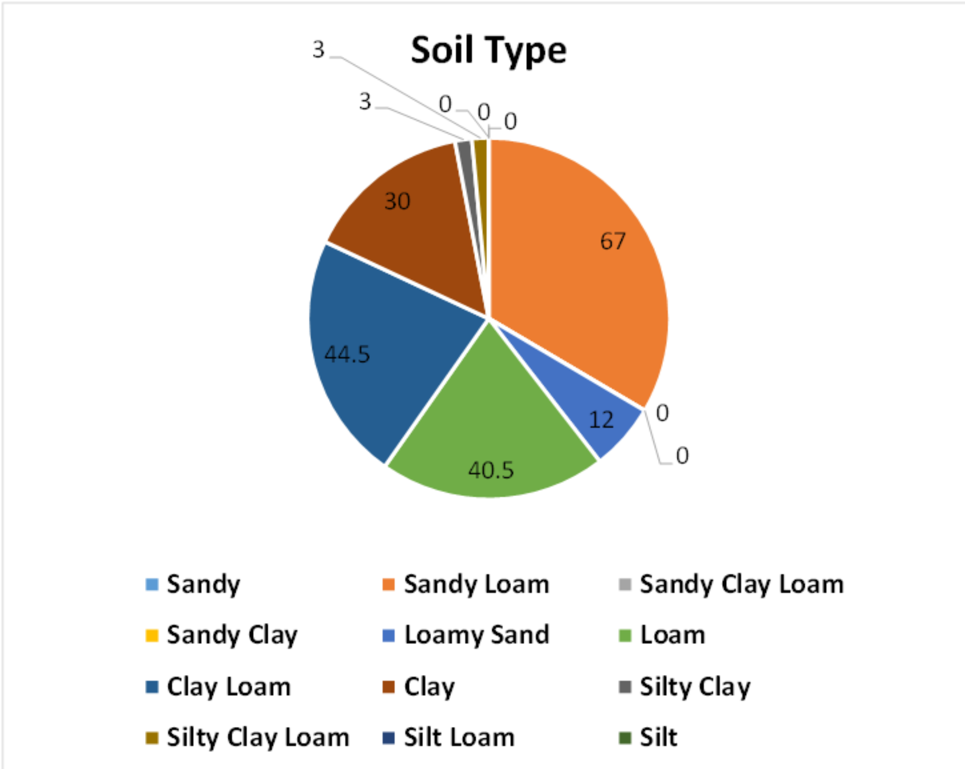

Figure 2-2. Distribution of the Soil Types of the Operation for the Tractors Monitored

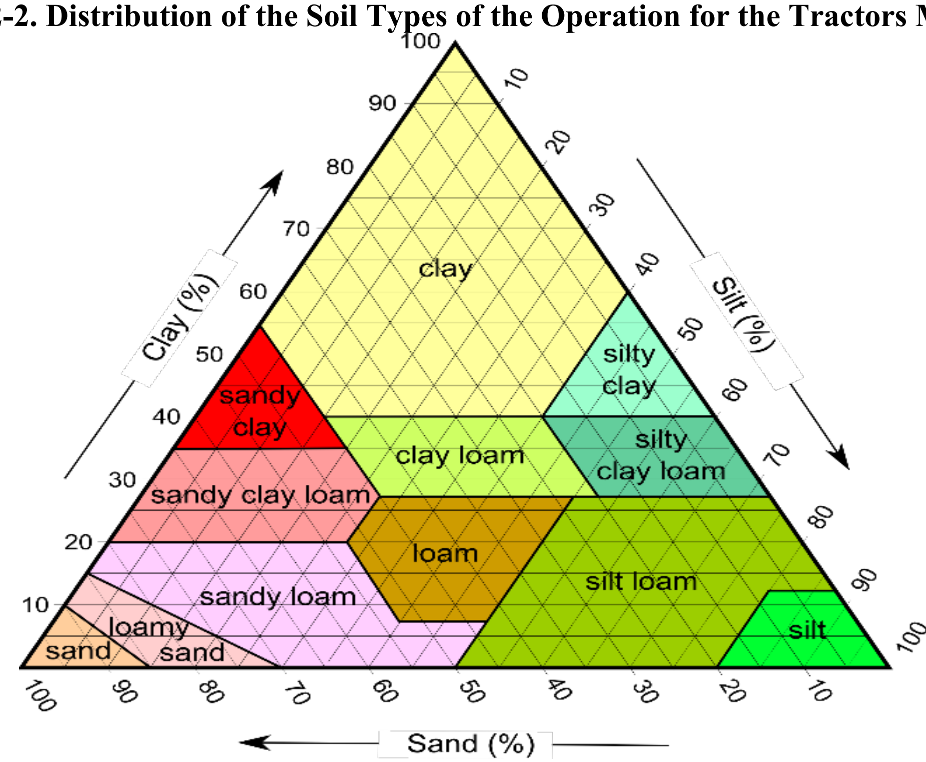

Figure 2-3. Illustration of Primary Soil Types (USDA, 2024)

2.2 Data Collection Methods

Data for this study was collected through a combination of data loggers and engine hour monitoring. The procedures utilized during the data collection are discussed in greater detail in this section.

2.2.1. Data Collection Sheet

A data collection sheet was used to record information specific to each tractor being monitored (such as engine and equipment make, model, hp rating, certification standard, hours of use, and after-treatment configuration), and the details of the activity that tractor was doing over the data collection period between visits in terms of what crop it was used for, the type of soil it was working in (although it should be noted that soil type can vary significantly even within the same field), and whatever attachments or implements may have been using. The equipment data collected is provided in Appendix A. The data collection sheet was the main method used for recording the data for the tractors that were monitored based on their engine hour meters, and in particular, the Tier 0 to 2 tractors. The base information for each tractor was collected via photographs during the initial visit. During subsequent visits, the engine hour reading would be photographed for each tractor, and the information on the tractor activity for the data collection period would be obtained from the farmer, to the extent possible. Note that the information collection sheet was anonymous in terms of identifying any information related to the tractor owner, outside of their numerical identifier. It should be noted that a tractor might also have been used for a number of operations during the season. As such, the team inquired as to any changes in the operations during each of the visits to the farm.

2.2.3. Data Logging Procedures and Methods

The vehicle activity measurements were made with data loggers obtained from the United States Environmental Protection Agency (U.S. EPA) via our Cooperative Research and Development Agreement (CRADA), as well as through CARB. These data loggers were maintained and utilized in accordance with standard EPA protocols, and as such met the highest standards for data measurement quality. The data loggers used for this study were HEM data loggers capable of collecting a full range of information from the engine control unit (ECU), including exhaust temperatures for aftertreatment systems, fuel consumption, engine load, and engine speed in revolutions per minute (rpm). A summary of some of the primary parameters targeted for this project is included in Table 2-4. It should be noted that level of available data for the Tier 3 and Tier 4 tractors was fairly complete for most of the parameters, while pre-Tier 3 tractors typically did not provide full information to determine the absolute engine load, or in many cases fuel consumption.

Table 2-4. Key Targeted ECU Parameters

Engine and Equipment Information	ECU Data
	Engine Hours
Engine Make	Engine Load Percentage
Engine Model	Engine Actual Torque Percentage

Engine Size	Engine Frictional Torque Percentage
Engine Model Year	Engine Reference Torque
Engine Peak Horsepower	Engine RPM
Engine Peak Torque	Fuel Rate
Equipment Model Year	DPF Aftertreatment Temperature
Equipment Type	Equipment Speed
Equipment Weight	
VIN	
Vocational Use	

The data loggers communicate with the engine's ECU/OBD. The HEM data loggers are a small unit that can be attached quickly to the engine ECU connector. This is shown in the example in Figure 2-4, where for an actual installation a tie wrap would be used to concisely package the data logger and associated cables. The HEM data loggers are self-triggering to start automatically when a test vehicle is started and stop automatically when the test vehicle is stopped. The data loggers are designed to store up to 6 months of data. After installation, the data loggers were downloaded periodically (approximately every 3 months) by swapping out the data loggers. The data could then be downloaded in a laboratory/office area, since the download process is too time-consuming to be conducted in the field.

Given the potential diversity of ECU parameters that can be available for different engines and different engine model years or technology categories, and potentially large files that might be generated from collecting data over multiple months, it was decided the data loggers would be set up with a configuration file consisting of a subset of ECU parameters that would be the focus of the data collection. A more complete list of the ECU parameters and values calculated from the parameters characterized in this study is provided in Appendix B. The configuration file was set up to include a limitation that the ECU parameters were also collected at a frequency of 1 Hz, to prevent the collection of overlarge files that could hinder the data analysis or data collection. It should be noted that the data loggers were also equipped with a Global Positioning System (GPS) that can measure the tractor's location (latitude and longitude) and altitude. For this project, the GPS feature was disabled such that GPS data was not collected, to ensure that the identity of the tractor and farm remained anonymous.

Figure 2-4. Installation of HEM Data Logger on a Typical Farm Tractor

2.2.3. Data Collection for Tier 0 – 2 Tractors

Data collection for the older equipment in the Tier 0 to Tier 2 categories was primarily done through monitoring of the engine hour meter. This is because the CAN data outputs were typically not available from the ECU. The potential for data logging such equipment using a combination of optical sensors for engine rpm, manifold pressure sensors, and exhaust temperature sensors was also investigated. These preliminary investigations suggested that the feasibility of doing such installations is beyond the scope of this study, due to the complexity and amount of time needed to install such equipment, and the unlikelihood of such equipment reliably operating over the course of a full year. It should be noted that ECU data was available for a small subset of their 0 – 2 tractors, which was included in the data analysis.

Another strategy that was utilized to supplement the engine hour monitoring for the older tractor was the collection of additional fuel use records. This was done through working with a subset of farm stakeholders to obtain fuel use as a function of hours of use for different tractors. This was done with short campaigns in which tractors' fuel use was recorded for short periods of time. Once data on fuel use per hour is obtained, the data can be extrapolated to obtain the fuel use over longer periods of time based on the engine hours monitored over the one-year data collection period by multiplying the engine hours by the fuel use per hour to get the fuel use over the full monitoring period.

2.2.4. Data Collection for Rental Equipment

Efforts were also made to obtain activity data information from businesses that rent tractors. Rental records were obtained from two rental agencies/dealers that were provided by the agricultural stakeholders. One of these rental agencies provided records for 3 years while the other provided data for a single year. The records included the make and model of the tractor rented, the period of the rental, the number of hours accumulated for that period, and for one of the rental agencies the crop type where the rental tractor was used. It should be noted that the records provided were for shorter periods of time relative to the in-field data logging, ranging from less than 1 month to 5 months. It should also be noted that over the course of the main project, from early 2021 to spring of 2023, there was very limited availability for rental tractors, as most tractors that were in stock were needed to satisfy needs for tractor sales, due to the impacts of the COVID pandemic and supply chain issues.

2.3 Data Analysis

2.3.1. Data Compilation and QA/QC Procedures

After being downloaded from the data loggers, the data was uploaded to a server maintained by UCR. The J1939 Mini Logger^{TM} files from the data logger download are binary files for each key on/key off trip in an .IOS file format. The data was then converted using the DawnEdit software from HEM into a comma-separated values (CSV) file before the following processing and analysis steps.

The data files were read into Matlab where it was reviewed, QA/QC'd, and corrected as needed. To make the HEM data files readable into Matlab, the data are preformatted into a consistent structure. This includes excluding extraneous dates and some equipment specific information that are included in the file header, and adding commas to make the number of commas the same in each line. After reading the data into Matlab, the entire dataset (all parameters) for each piece of equipment was concatenated into a single file. The data files were developed to be as consistent as possible with our on-going data collection efforts with CARB and the U.S. EPA. 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 ECU data. Each row in the data table represents one second of data, with every second of data uniquely identified by timestamp.

Once concatenated, the files are then processed for QA/QC criteria. The procedures for the data QA/QC for activity data for agriculture tractors have been developed as part of a series of data collection programs with CARB and the U.S. EPA CRADA to ensure that the final data sets are at the level of quality expected for application in emissions models and other uses for these agencies. In order to streamline the QA/QC of large amounts of ECU data, computer programs have been developed to identify suspect values for different parameters on a second-by-second basis based on several criteria. These criteria include SAE J1939 operational ranges, acquisition stability issues, data identified as suspect using SAE J1939 fault mode indicators, parameter behavior such as dynamic variables that fall static (either within or outside of SAE J1939 ranges), or variables that could be suspect due to certain operational conditions (such as data collected during engine start-up or key-on/engine-off episodes). Criteria for ECU data filtering depend on the individual ECU data parameter (e.g., engine speed, exhaust temperature) per their specifications as defined in the J1939 standard. Data for specific variables are evaluated to ensure that it meets SAE J1939 specifications in terms of values, field ranges, character types, variable lengths, and other metrics. This includes limits on the maximum values of parameters, such as engine speed and engine torque. For some parameters, additional operating range limits may also be applied to identify invalid data. Parameters for which operating range limits are commonly applied include percent load, torque percent load (in the case of negative numbers), reference torque (with a maximum value of 8,000 Newton-Meters [Nm]), and exhaust temperature (with a maximum value of 910°C). Data that are outside of the J1939 specifications or operating ranges are replaced with "NaN", or not a number. It should be noted that to the extent that a data point is deemed to be invalid, other values within that second of data are still retained, so long as they are valid, to ensure the data will be as continuous as possible. Calculations of the power are also made as part of this processing. The power is calculated based on the reference torque (when available), the actual torque percentage, the friction torque percentage, and the engine speed.

Another element of the QA/QC processing is the generation of plots to allow the data to be visually evaluated for outliers, missing data, unusual trends, or other data issues. This stage of the QA/QC is typically done on smaller data sets with subsets of the more critical parameters. Based on this evaluation, additional data may be classified as invalid, and denoted at "NaN".

Following processing, the full set of 1 Hertz data files for each piece of equipment was provided to CARB. The data for individual farms included generic IDs that did not identify any personal protected data related to either the farm or its owner. These data were provided in both CSV and Matlab file formats at various stages of the project. The data was shared with CARB through a secured FTP site that allows potentially large datasets to be downloaded.

2.3.2 Data Analysis for Activity Characterization

After the data compilation and QA/QC processing, data analyses were conducted to obtain summary statistics for different activity parameters. Computer scripts were also utilized for these analyses. The activity characteristics include average operational hours per day, average engine load percent (relative to the maximum load), fuel use per day and per hour, idle percentage, and average DPF outlet temperatures. These statistics were generated for different groups of data based on the test matrix, as well as overall averages. The groupings of data were separated by technology (Tier 0-2 or Tier 3-4), horsepower rating (<50, ≤75 to <175 hp, ≤175 to <300, ≤300 to <650), and between tree and row crops. Note that there were no 50 to 75 tractors available for the data logging, so this horsepower range is not included in the category groupings for the data logger analysis. The average values overall and for each of the groupings were based on averages of the average values for each tractor, such that tractors with more or less data were equally weighted in the averages. A number of the tractor activity statistics were expressed on a per day basis, including the number of hours of operation per day and fuel use per day or hour. Other analyses included frequency distributions and hourly and other distributions. Other statistics are based on specific metrics that are defined particularly for this program. Additional information on some of the unique tractor activity metrics and concepts is provided below.

The daily average statistics for most variables, including hours of use, load factor, fuel use, idle percent, and number of starts (cold-start, intermediate, and hot-start), were calculated individually for each individual tractor within a given category. For each tractor, the parameter of interest, for example hours of use, were calculated by calculating the hours of use for each day in the data set date range, and then averaging daily hours of use for each day in the date range with non-zero activity. So, the daily averages for a given activity were averages of the individual daily values that had activity. For the daily average exhaust temperature, on the other hand, the average was just calculated based on the average over all of the values in the dataset.

The engine load percent was determined from the engine rpm and the torque values. The maximum horsepower and torque values were determined from the reference torque or, to the extent possible, from the engine plate information. To the extent that the engine plate information is given on the engine nameplate, this information can be used directly. Otherwise, the engine information can be cross-checked against the CARB executive order for that particular engine family, model, and year. When the monitored equipment engine information is insufficient to cross-check with a CARB executive order, lug curves are searched for on manufacturer's websites or other sources identified on the internet. The maximum torque value from the lug curve was then multiplied by the actual torque percentage ECU CAN output channel to provide a value for torque.

torque_nm = Ref_Torque_nm x (Actual_Engine_Percent_Torque_per - Nominal_Friction_Percent_Torque_per)/100;
power_kw = torque_nm x Engine_Speed_rpm /9549;

where, Actual_Engine_Percent_Torque _per = SPN 513
Nominal_Friction_Percent_Torque_per = SPN 514
Ref_Torque_nm = SPN 544
Engine_Speed_rpm = SPN 190

Engine idle events were 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 ten seconds.

The determination of the engine idle speed for each piece of equipment was done via a numerical evaluation of the data. Engine idle speed typically fluctuates within a range of values, as depicted in the histogram of example data in Figure 2-5. The idle range for a particular engine was determined by first finding the mode of engine speeds in the general range between 500 and 1200 rpm. So, the idle analysis focused on low idle and did not include high idle events. The primary idle speed is determined as the speed in this range that has the most frequent observations. Once this speed was determined, the idle range was determined by utilizing a range (depicted in green in Figure 2-5) of ± 6 rpm around the primary idle speed.

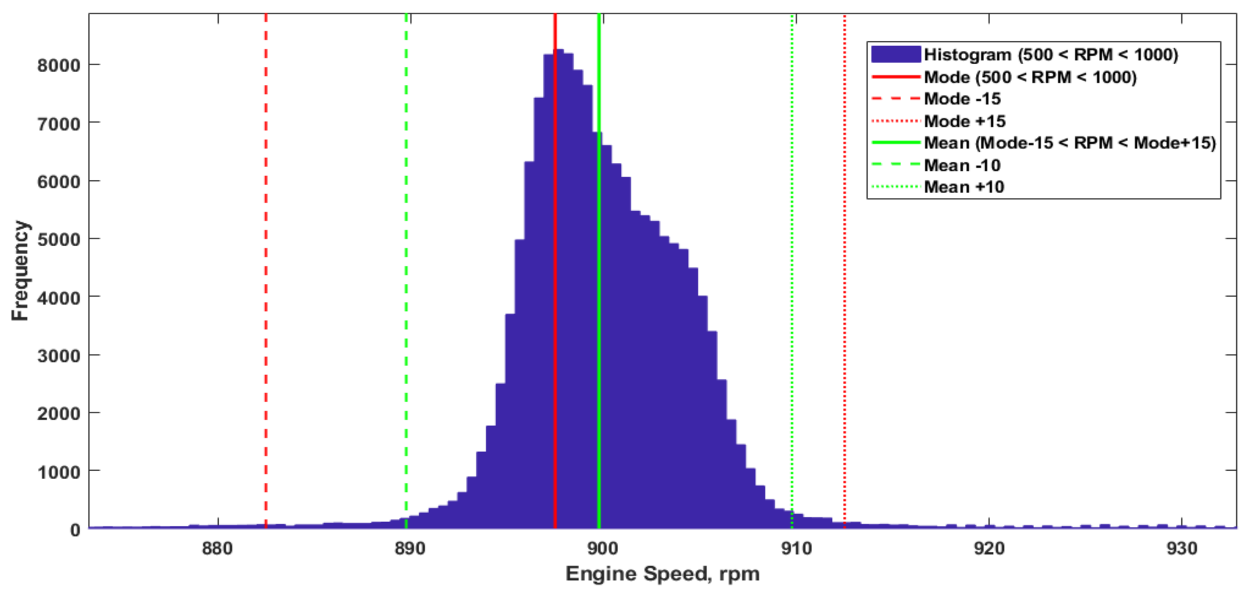

Figure 2-5. Histogram and descriptive statistics of example engine speed data within the range of 500 to 1000 rpm

Calculations were also performed to determine the average number of daily starts and the average hot soaks durations. The calculations were done based on the engine speed. The engine was considered to be off for engine speeds below 300 rpm. Engine-off events were defined as periods of time where the engine speed was less than 300 rpm for a period of greater than 30 seconds. Daily starts were quantified as the number of times per day when there was a transition between an engine-off condition and a start, where the engine rpm rises and stays above 300 rpm. For the purpose of this study, starts were further categorized based on their soak duration into cold starts (≥ 720 minute soaks), hot starts (≥ 30 seconds and ≤ 60 minutes), and intermediate starts (≥ 60 minutes and ≤ 720 minutes) (CARB, 2020). Soak duration is defined as the amount of time between a previous engine-off event and a subsequent engine on event, again where the engine rpm rises and says above 300 rpm. It should be noted that the start algorithm just looks at data gaps and does not try to interpret whether data gaps are valid, which could include more complicated criteria such as some measure of engine or fluid temperatures. As such, activity after a missing chunk of engine speed data (> 30 seconds) would look like a start. Daily starts and average hot soak durations were only quantified for days for which there is noticeable activity for the tractor. No minimum activity was set for daily activity to be classified as an "operational day". As such, shorter days of operation that generate activity, such as if the tractor was just started, re-parked, etc., would be counted as operational days.

Frequency Distributions

Frequency distributions were developed for several different parameters. This includes distributions of DPF outlet temperatures, hourly distributions on a per day basis, hourly load distributions, and temperature distributions as a function of load. These analyses are described in greater detail in this subsection, with additional information provided in the results section. These analyses were also performed using computer scripts developed as part of a series of activity data studies.

One element of this study was to better understand how agriculture tractor activity patterns might impact the effectiveness of selective catalytic reduction (SCR) systems. This analysis focused on the DPF outlet temperature data obtained from the ECU of the vehicles. While direct SCR temperature is often available for on-highway vehicles, this parameter is not typically broadcast on off-road equipment. Additionally, many off-road equipment types are not equipped with SCR systems yet. Since the DPF exhaust outlet temperature is essentially the temperature immediately before the exhaust enters the SCR or the temperature of the exhaust that would enter the SCR in the case of equipment that is not SCR-equipped, DPF exhaust outlet temperature provides a suitable metric for evaluating the effective SCR operating temperature.

The analysis of the DPF outlet temperature was done by plotting the frequency distribution as well as the cumulative frequency distribution of the DPF outlet temperature. The frequency distribution allows for the identification of a range of temperatures that the equipment typically operates in. The cumulative frequency distribution makes it convenient to determine how often the SCR temperature is below a certain threshold. For SCRs, for example, the urea injection is typically not utilized at temperatures slightly below 200°C in order to prevent deposit formation. SCRs also tend to reach more optimal effectiveness at temperatures above 250°C. So, the percentage of operating time above or below these temperature thresholds is an important metric of how effective SCRs are or would be in a particular application.

Hourly load percentage distributions were also determined for the overall data set. The load percentage was determined by dividing the actual hp for each moment of operation and dividing the equipment's maximum hp for each individual piece of equipment. To obtain the hourly load percent, the average hp during any given hour was divided by the maximum hp for that given unit. The distributions of load percent for the individual agriculture tractor were then averaged to obtain the overall load distribution as a function of a hour of day, the data from all of the individual tractors were averaged for each load/hour bin in the matrix. The hourly data was binned for each hour of the 24-hour day and the load bins were defined in 5% intervals from 0% to 100%.

A distribution of DPF outlet temperatures as a function of engine load was also developed. For this distribution, the load bins were defined in 5% intervals from 0% to 100% and the temperature bins were defined in 25°C intervals between 0°C and 600°C.

2.3.3 Duty Cycle Evaluations and Comparisons Engine Dynamometer Test Cycles

The summary statistics for the engine torque and speed for the different data collection bins for the equipment will also be compared with the engine torque and speed patterns for the transient and steady-state off-road test cycles typically used for engine dynamometers certification of off-road engines. For this study, the non-road transient (NRTC) was the transient cycle that was used for comparison, and the International Organization of Standards (ISO) C1 cycles was the steady-state cycle that was used for comparison (Dieselnet, 2024a, 2024b). These engine cycles are discussed in greater detail in Appendix C.

Frequency distributions for engine speed and torque on a percent basis were developed for the full matrix of tractors for 6 main categories. These frequency distributions were compared against the frequency distributions of the normalized engine speed and torque for the NRTC and C1 cycles to better understand how representative their certifications are of real-world activity patterns. The six main categories included tree and row crop tractors for three different hp categories where there was enough data for a robust analysis (75 to 174 hp, 175 to 299 hp, and 300 to 650 hp). The data set used for each category was based on all the Tier 3 and 4 tractor available for that category. The Tier 0-2 tractor data within a given category was not utilized to develop these frequency distributions, as the Tier 0-2 tractor data was limited, and as Tier 0-2 agriculture tractor engines are not currently being certified. The development of these graphs was a several step process, as the activity data is obtained in absolute engine rpm units and percent of the maximum torque, whereas the cycles are represented as percent of engine speed and percent of torque at a given engine speed, as opposed to percent of maximum torque. In order to develop the distributions as normalized engine speed and torque for a given equipment category. The normalized engine speed and torque values first needed to be developed for each individual piece of equipment. This was done by plotting the actual values for engine speed and torque on an x-y plot. The resulting plots essentially provided the "lug curve" from which percent engine speed and percent torque at a given engine speed could be derived. Based on this information, the second-by-second engine speed and torque actual values were translated into second-by-second percent engine speed and percent of torque maximum at a given speed using the equations below. The files representing activity for each piece of equipment were then normalized based on the number of data points for that piece of equipment. This data was then used to develop an engine speed vs. torque scatter plot for each piece of equipment. These files for each individual tractor were then averaged for an overall distribution and used to develop x-y plots of percent engine speed and percent torque for the overall data set and for each category, as presented in section 3.2.1 below.

For normalizing engine speed:

Nnorm = 100 (Nsk-Nidle) / (Nref-Nidle)

where,

Nnorm = the normalized engine speed,
Nsk = actual engine speed,
Nidle = engine idle,
Nref = is the reference engine speed in rpm
Nref = Nn + 0.95(Nv-Nn)

where,

Nn = low engine speed (the lowest engine speed where 50% of rated power is delivered)
Nv = high engine speed (the highest engine speed where 70% of rated power is delivered)
Nn and Nv are determined from the lug curve.

For normalizing engine torque: Mnorm = 100 x Msk / Mmax

where,

Mnorm = normalized engine torque
Msk = actual engine torque
Mmax = maximal engine torque at a given engine speed

Engine Dynamometer Test Cycles Based on the Agriculture Tractor Activity Data

Engine dynamometer cycles were developed based on the percent engine speed and percent engine torque files for each tractor. These files were separated into individual files based on key-on to key-off events. Evaluation of these files indicated that a majority of the files (~90%) were greater than 10,000 seconds, with 95-98% of the files greater than 1,800 seconds in length.

Based on this, the files were segmented in 1,800 second intervals, to make the cycles representative of a typical test cycle. A series of 1,800 second snippets were then developed with each succeeding cycle starting 10 seconds after the proceeding snippet started. For example, a file with a length of 2000 seconds would be segmented into twenty-one snippets of 1800, follows: 0-1800, 10-1810, 20-1820, ..., 180-1980, 190-1990, 200-2000. This process is illustrated in Figure 2-6.

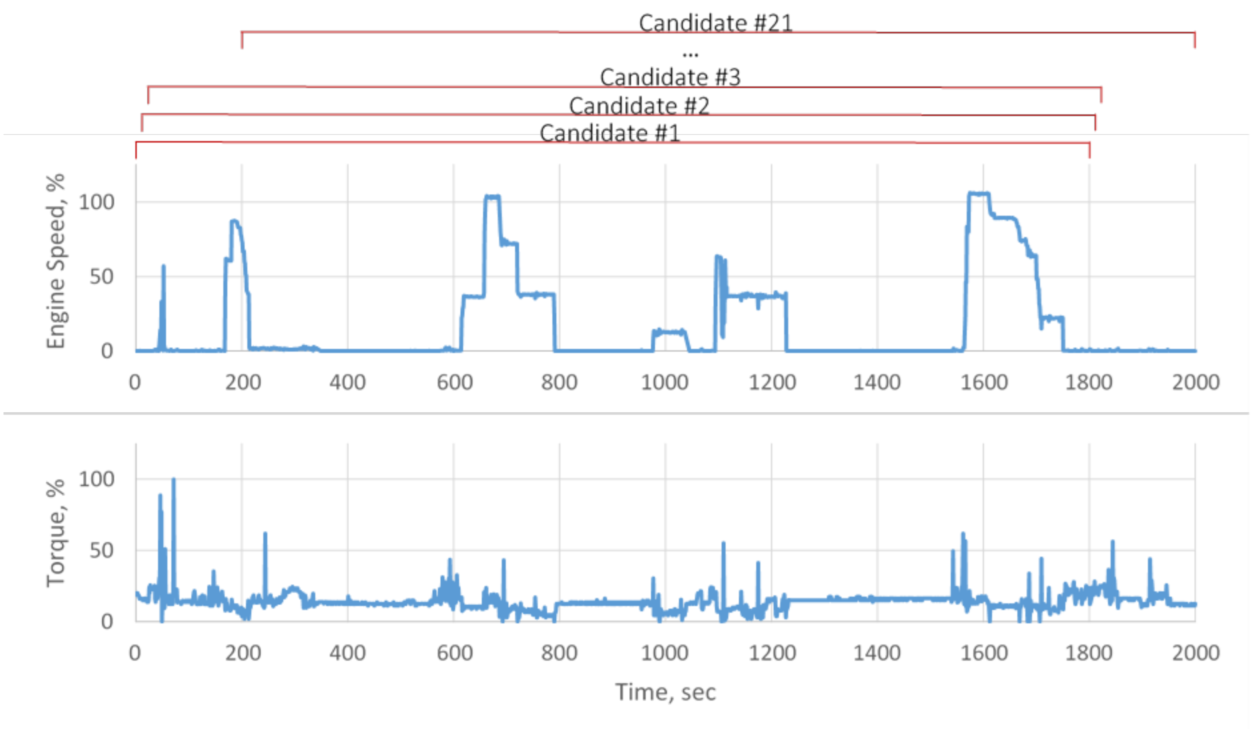

Figure 2-6: Illustration of Cycle Snippet Development Process

The data were then separated in engine speed vs. torque bins, as shown in Table 2-5, with a total of 110 bins. The torque percentage bins were based on 10 categories representing each 10% in torque percent going from 0 to 100%. The engine rpm percentage bins were based on 11 categories representing 10% increments from 0 to >100. These calculations were done for the full data set, and six separate categories based on crop types (tree vs. row crop) and engine hp ratings (25<x<75, 75<x<300, >300). Note that since Tier 0 to 2 tractors did not broadcast load data, this analysis was restricted to only the Tier 3 and 4 tractors.

Table 2-5: Engine RPM and Torque Bins for the Engine Dynamometer Test Cycle Determination

	Torque,%									
Engine Speed,%	**0 - 10**	**10 - 20**	**20 - 30**	**30 - 40**	**40 - 50**	**50 - 60**	**60 - 70**	**70 - 80**	**80 - 90**	**90+**
0 - 10	1	2	3	4	5	6	7	8	9	10
10 - 20	11	12	13	14	15	16	17	18	19	20
20 - 30	21	22	23	24	25	26	27	28	29	30
30 - 40	31	32	33	34	35	36	37	38	39	40
40 - 50	41	42	43	44	45	46	47	48	49	50
50 - 60	51	52	53	54	55	56	57	58	59	60
60 - 70	61	62	63	64	65	66	67	68	69	70
70 - 80	71	72	73	74	75	76	77	78	79	80
80 - 90	81	82	83	84	85	86	87	88	89	90
90 - 100	91	92	93	94	95	96	97	98	99	100
100+	101	102	103	104	105	106	107	108	109	110

The most representative engine speed and torque profile for the engine dynamometer test cycle was then determined by whichever snippet showed the most similar breakdown in terms of percentages in each bin compared to the whole population file, based a mean square error. The mean squared error (MSE) calculation is provided below. This methodology evaluates how close a series of operating bin of a candidate cycle is to that of the data population. The comparison process is illustrated in Figure 2-7, which shows a representation of the bin breakdown for the population for the entire data set, for a target cycle, and then for a final cycle that represents the snippet that most closely matched the snippet.

$$\text{MSE of the bin distribution} = \frac{1}{N}\sum_{i=1}^{N}\left[\left(OM_i^c - OM_i^p\right)^2\right]$$

where: OM_i^c is frequency of operating mode i in driving cycle
OM_i^p is frequency of operating mode i in data population
w_i is contribution of mode i to total emission in data population
N is number of operating modes (23)

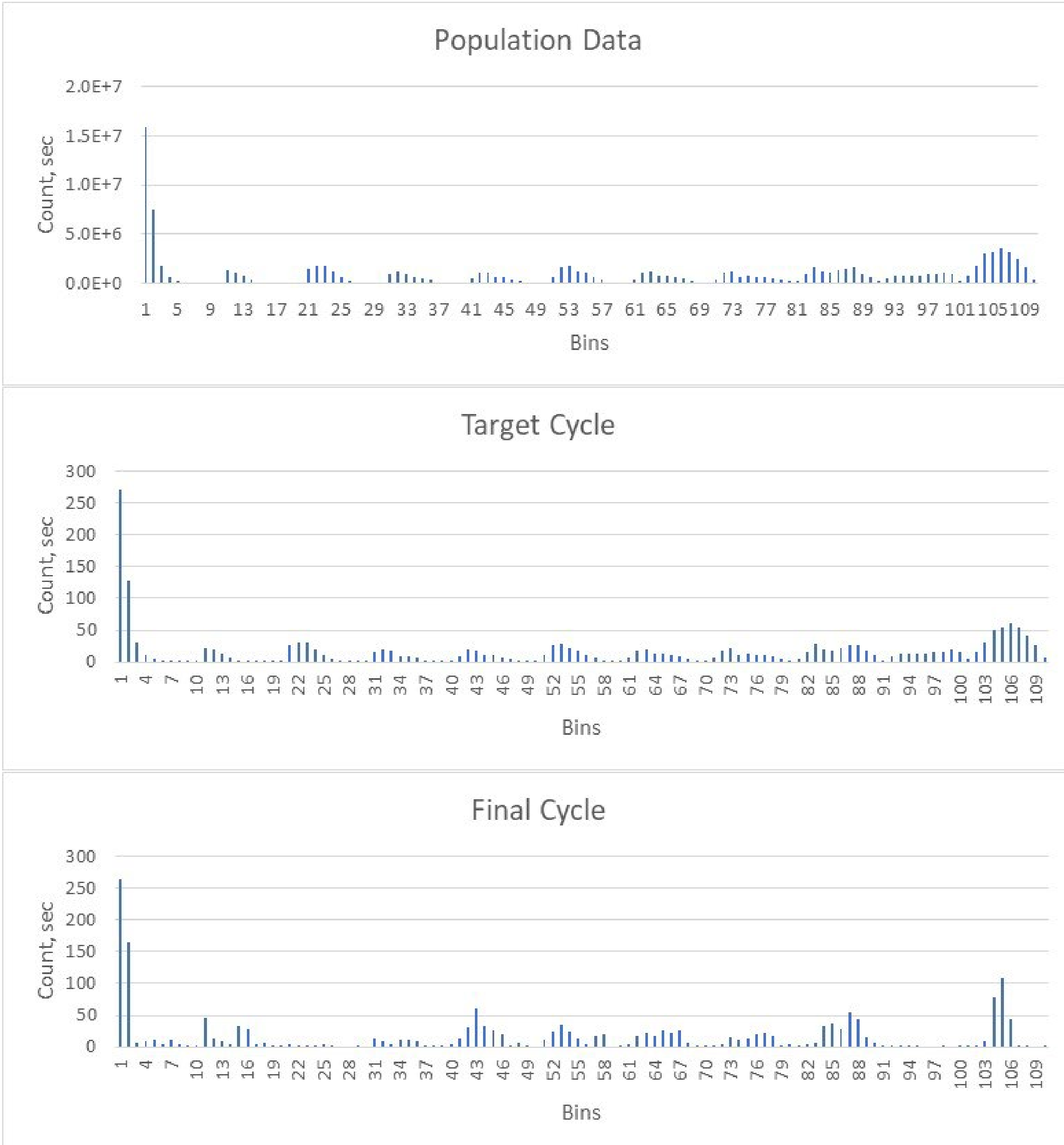

Figure 2-7: Illustration of Bin Breakdowns for a Population, a Target Cycle, and a Final Cycle

3 Results

This section describes the results obtained from analyzing the engine hour and ECU data from agriculture tractors that were monitored. The overall results for the activity statistics are provided in the first subsection. In the second subsection, the activity data statistics were compared against the characteristics for the relevant certification test cycles to evaluate how representative these cycles are for typical agriculture tractor activity. Duty cycles based on the agriculture tractor data are also provided in the second subsection.

3.1 Activity statistics

The following subsection presents the average summary activity statistics for the monitored tractors for the different crop types (tree vs. row crop), engine hp ratings ($x<50$, $50 \leq x < 175$, $175 \leq x < 300$, $300 \leq x < 650$), and certification Tier (0-2, 3 and 4). Note that there were no 50 to 75 tractors available for the data logging, so this horsepower range is not included in the category groupings for the data logger analysis. Summary statistics are presented for average hours of use per day, average load factor, average gallons of fuel used per day and per hour, average exhaust/DPF outlet temperature, and idle percentage. More detailed analysis results, including the average values, the median values, the standard deviation values, and the 1-sigma upper and lower bounds are provided in Appendix D. Note that the sample size for Tier 0 – 2 tractors for a number of these statistics (with the exception of annual hours of use) was relatively small because most of these statistics were obtained from the data logger information, as the monitoring of the engine hour meter data did not provide any information on daily activity use or engine operation statistics.

3.1.1. Average Hours of Use per Day and per Year

The average hours of use per operating day by crop type, engine power rating, and engine technology are presented in Figure 3-1. The overall average use for all tractors was about 4 hours per day. The data show a few trends of note. The results show that for the newer Tier 3-4 tractors, row crops show higher hours of use per day with the tractors for the row crops averaging about 5 hours per day for the 175-299 hp and 300-650 hp categories, and about 4 hours for the 75-174 hp category. For the tree crops for the Tier 3-4 tractors, the average hours of use per day was about 4 hours for the 175-299 hp and 300-600 hp categories, and 3 hours for the 75-174 hp category. The Tier 1-2 tractors generally showed lower operating hours per day, with averages of around 2.5 hours per day for the 75-174 hp and 1 hour per day for the 175-299 hp categories row crops, but did have higher average hours, at nearly 4 hours per day for the 75-174 hp tree crop tractors. The small number of Tier 0-2 tractors makes it difficult to definitively quantify the differences between the daily hour of use statistics for the older (Tier 0 to 2) and newer (Tier 3-4) tractors. Some additional analyses were also done on daily operating hours as a function of farm size, as shown in Appendix D. Average daily operating hours for different farm size categories varied from 3.4 to 4.5 hours, with no clear trends between farms size outside of the variability in the data.

The distribution of the number of tractors based on the daily operating time is shown in Figure 3-2. This shows that most Tier 3-4 tractors operated between 2 to 7 hours per day. The Tier 1-2 tractors on average showed less use per day than the newer tractors, ranging from 1 to 4 hours per day.

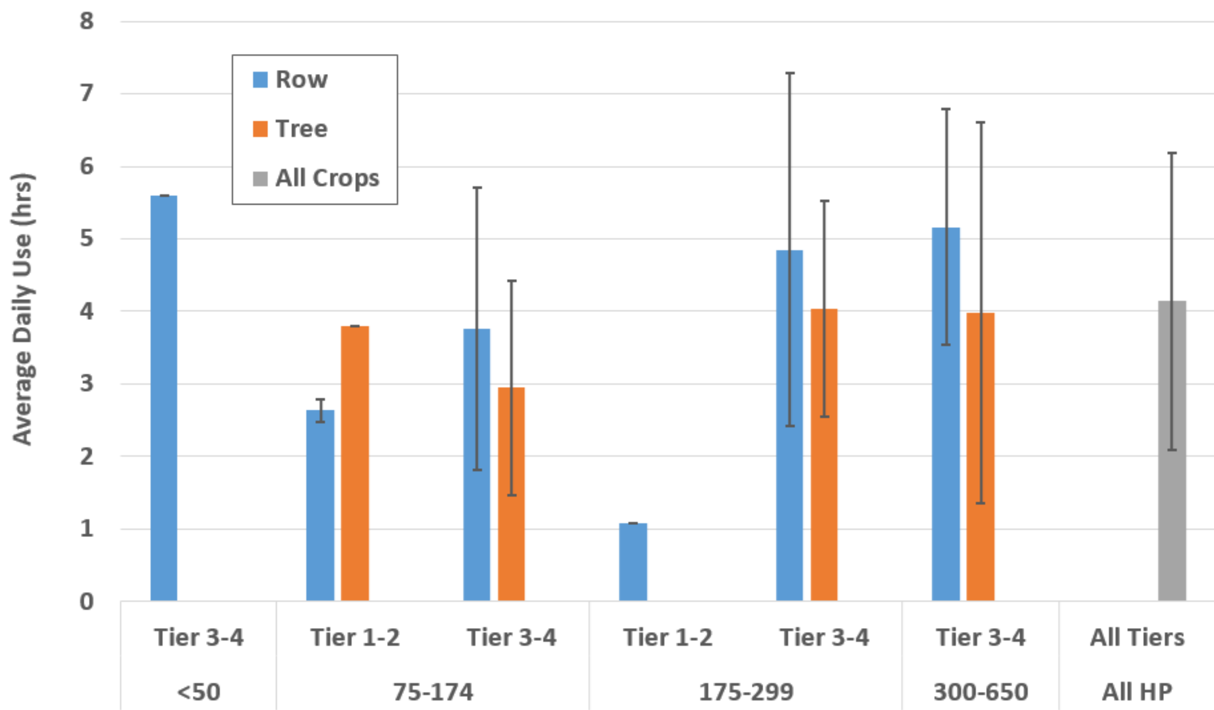

Figure 3-1. Average Hours of Use per Day by Crop Type, Engine Power Rating, and Engine Technology

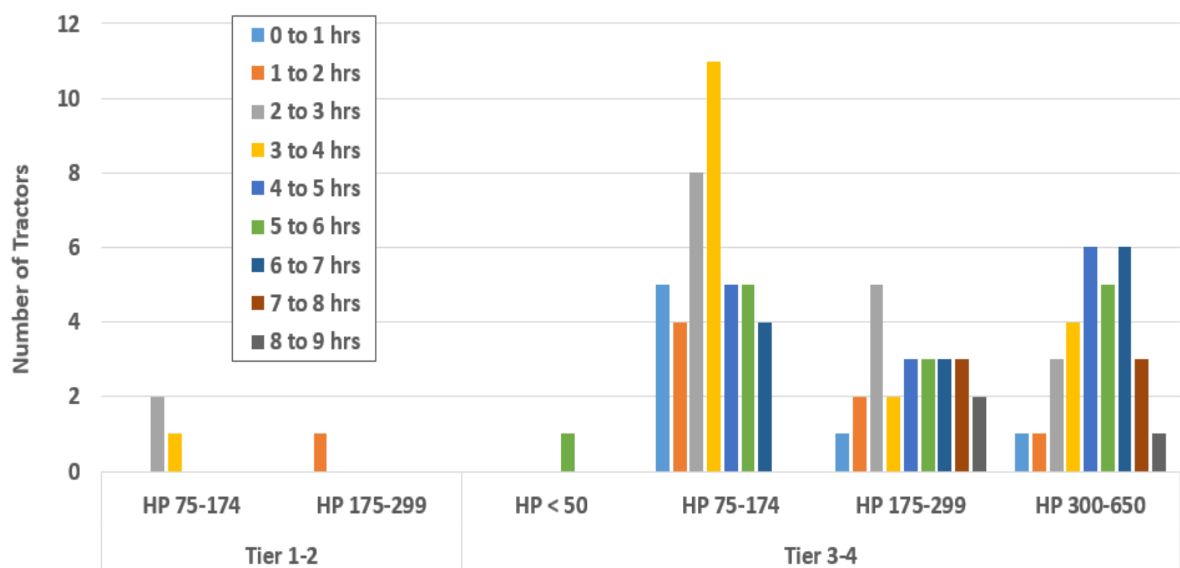

Figure 3-2. Distribution of the Number of Tractors by average Hours of Use per Day

Another important statistic is the number of operating hours per year, as this is a statistic that is important for emissions inventory modeling. The annual engine hours for the individual tractors monitored in this study are shown in Figure 3-3 in a scatter plot. The averages by engine Tier in shown in Figure 3-4 in a box whisker plot. The box whisker plots show the range of the data from the 25th to the 75th quartile within the upper and lower limits of the box, the median, which is the line in the box, and average, which is the "x" in the box, and outlier points, which are shown outside of the box. These data were based primarily on the engine hour readings over the monitoring period for each of the tractors that were monitored and had two engine hour readings over a period of over 10 months. This time period was deemed to be sufficient to capture the seasonality of the tractor operation, as most of the tractors that were monitored for over 10 months, were monitored for around 10.85 month (or nearly 11 months). The data were prorated to a one-year time period for tractors where the amount of data collected was either over or under a year of monitoring time. Note that this methodology accounts for days where the tractors were not used for any activity. The results show that there is a large drop-off in annual engine hours of usage for the Tier 0 and 1 equipment, with a much smaller drop-off for the Tier 2 tractors. The Tier 3 and Tier 4 tractors showed similar patterns of annual use. The average annual hours of usage were 60 hours, 130 hours, 143 hours, 741 hours, and 739 hours, respectively, for Tier 0, Tier 1, Tier 2, Tier 3, and Tier 4 tractors.

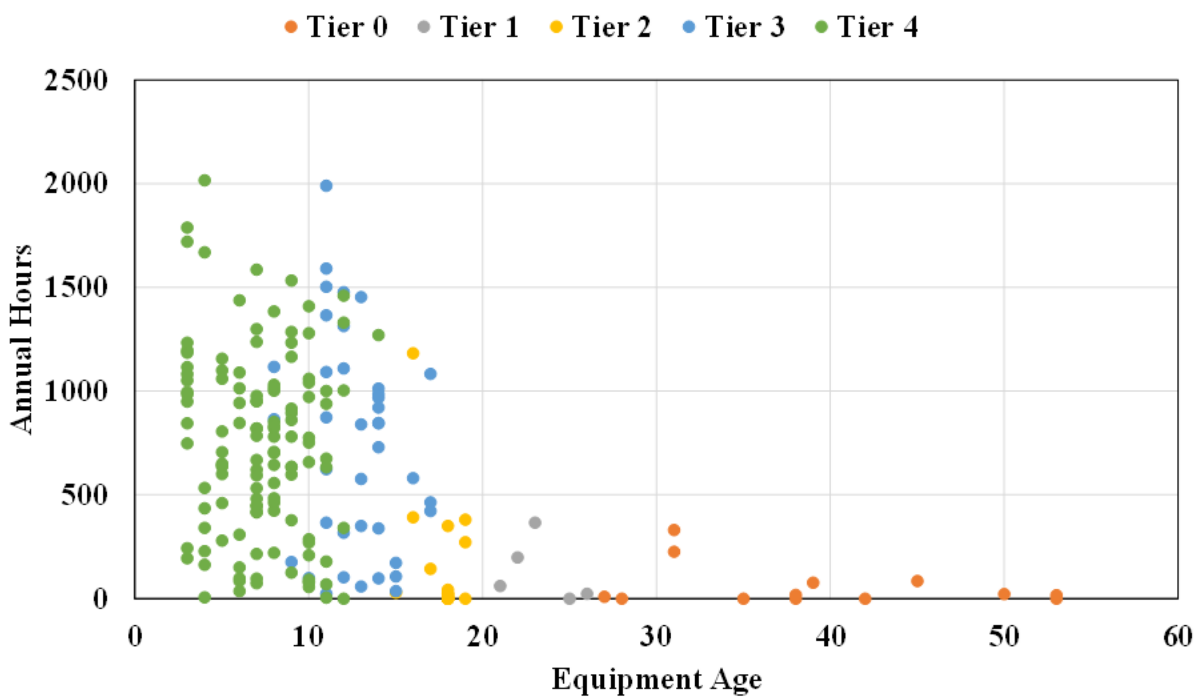

Figure 3-3. Annual Hours by Engine Tier Technology

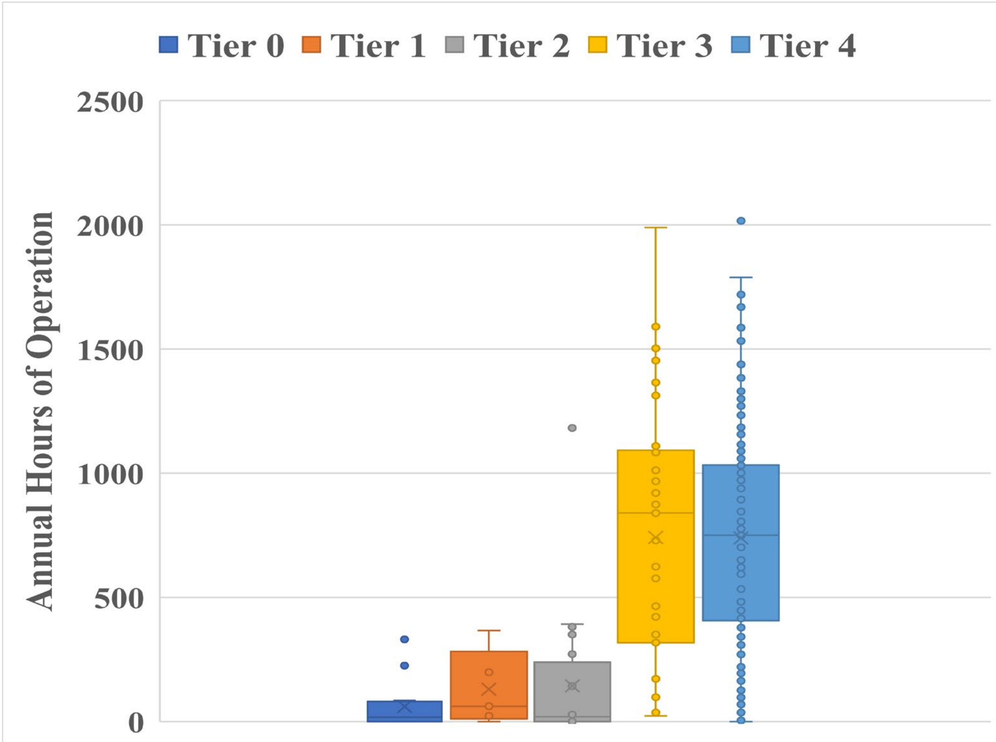

Figure 3-4. Average Annual Hours by Engine Tier Technology

The seasonality of the agriculture tractor use is another important statistic in understanding the activity of tractors over the course of a full year, particularly as tractors get more extensively used during the planting and harvesting periods of the year. The average hours of use per month is shown in Figure 3-5 for the tree and row crops, and for all crops combined. These data show some indication of higher activity in the spring time (March to April) when the crops are planted, and in the fall (September to October) when the crops would be harvested, although there is still a reasonable amount of activity during other parts of the year as well.

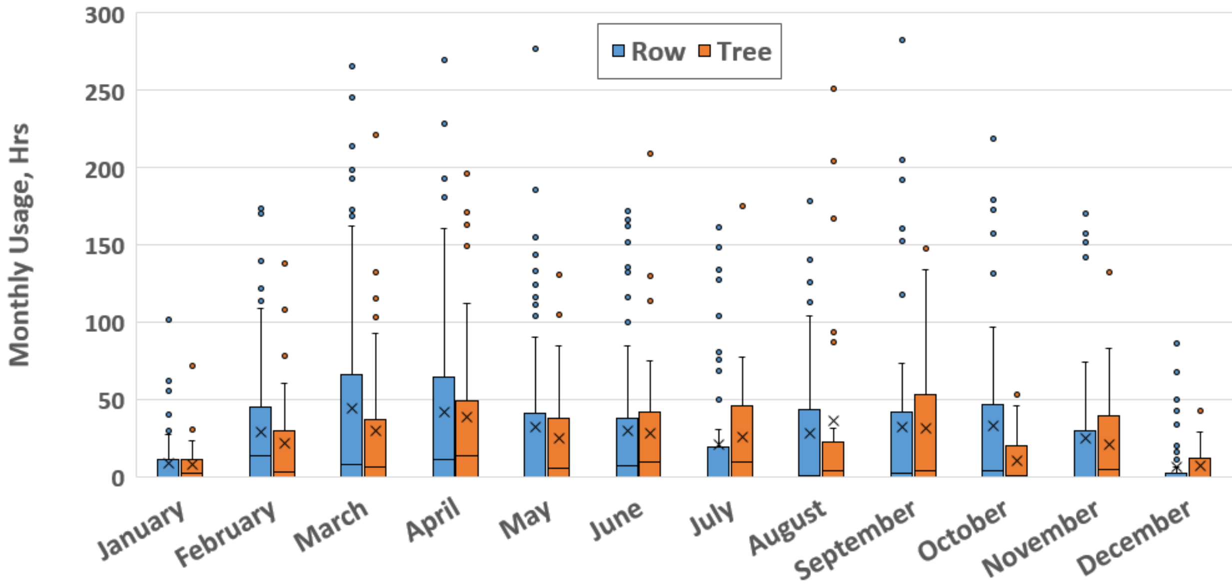

Figure 3-5. Average Hours of Use by Month

Some additional information on the hours of usage was also obtained from two separate tractor dealerships/rental agencies. The data that was provided from the two rental agencies are presented in Table 3-1 and Table 3-2. The data provided by rental agency #1 was provided for three different years. Although the data were only available for a limited period of time for rental agency #1, the overall daily averages for the different rental agency #1 tractor data sets ranged from 2.8 to 4.4 hours, which is consistent with the results obtained from the data logging. The tractors for rental agency #2 were primarily used for harvesting tree crops and grapes. The results from rental agency #2 showed greater hours of use, averaging 9.7 hours of use per day. These records cover only a single month period during harvest season, however, and may be less representative of average operation over the course of a full year.

Table 3-1: Activity Data for Rental Tractors from Rental Agency #1

Manufacturer	Model	Start Date	End Date	Rental Duration (Days)	Hours Logged	Hours/day	Hours/Month
John Deere	5085M	11/20/2019	2/26/2020	98	262	3.7	81.3
John Deere	6125M	2/21/2020	3/6/2020	14	31	3.1	67.3
John Deere	6115M	5/1/2020	5/5/2020	4	15	5.3	114.0
John Deere	5115ML	2/27/2020	5/26/2020	89	150	2.4	51.2
John Deere	5115ML	2/27/2020	6/8/2020	102	308	4.2	91.8
John Deere	5100ML	8/6/2020	10/1/2020	56	92	2.3	49.9
John Deere	5115ML	8/10/2020	10/1/2020	52	84	2.3	49.1
John Deere	4044M	9/23/2020	10/6/2020	13	19	2.0	44.4
John Deere	4044M	9/23/2020	10/6/2020	13	23	2.5	53.8
John Deere	5100ML	10/7/2020	10/22/2020	15	55	5.1	111.5
John Deere	5085M	8/3/2020	10/22/2020	80	115	2.0	43.7
John Deere	5115ML	8/3/2020	10/30/2020	88	261	4.2	90.2
John Deere	5100ML	8/3/2020	10/30/2020	88	380	6.0	131.3
John Deere	5075GL	8/20/2020	11/5/2020	77	203	3.7	80.1
John Deere	5115ML	11/3/2020	11/10/2020	7	33	6.6	143.3
John Deere	5115ML	8/3/2020	11/11/2020	100	411	5.8	124.9
John Deere	5115ML	8/3/2020	11/11/2020	100	397	5.6	120.7
John Deere	6125M	8/12/2020	11/13/2020	93	424	6.4	138.6
Kubota	M8560	8/12/2020	11/13/2020	93	317	4.8	103.6
John Deere	5100ML	11/10/2020	12/23/2020	43	107	3.5	75.6
			Average	61.3	184	4.1	88.3
Kubota	M9960	3/15/2021	4/29/2021	45	73	2.3	49.3
Kubota	M9960	3/15/2021	4/29/2021	45	55	1.7	37.2
John Deere	5075GL	3/24/2021	4/30/2021	37	88	3.3	72.3

John Deere	5100GN	8/12/2021	9/9/2021	28	246	12.3	267.1
John Deere	4044M	9/24/2021	10/6/2021	12	31	3.6	78.5
John Deere	4052M	9/24/2021	10/6/2021	12	42	4.9	106.4
John Deere	6125M	9/12/2021	12/9/2021	88	168	2.7	58.0
			Average	38.1	100	4.4	95.5
John Deere	5125ML	8/1/2022	9/26/2022	56	143	3.6	77.6
John Deere	3043D	9/16/2022	10/4/2022	18	27	2.1	45.6
John Deere	3043D	9/16/2022	10/4/2022	18	40	3.1	67.6
John Deere	5055E	8/10/2022	10/7/2022	58	108	2.6	56.6
John Deere	5115ML	8/10/2022	10/7/2022	58	64	1.5	33.5
John Deere	5115ML	6/12/2022	11/4/2022	145	34	0.3	7.1
John Deere	5115ML	8/1/2022	12/9/2022	130	492	5.3	115.1
John Deere	5125ML	8/24/2022	1/25/2023	154	463	4.2	91.4
			Average	79.6	171	2.8	61.8

Table 3-2: Activity Data for Rental Tractors from Rental Agency #2

Model Number	Manufacturer	Start Date	End Date	Rental Duration (Days)	Hours Logged	Hours/day	Hours/Month
5045E	John Deere/2021	09/01/2021	10/27/2021	56	184	4.6	99.9
5075E	John Deere/2021	09/01/2021	10/27/2021	56	342	8.6	185.7
5075E	John Deere/2021	09/01/2021	10/27/2021	56	278	7.0	150.9
5055E	John Deere/2021	09/01/2021	10/27/2021	56	165	4.1	89.6
5075E	John Deere/2022	09/01/2022	10/14/2022	43	317	10.3	224.1
5065E	John Deere/2022	09/01/2022	10/14/2022	43	246	8.0	173.9
5065E	John Deere/2022	09/01/2022	10/14/2022	43	471	15.3	333.0
5055E	John Deere/2022	09/01/2022	10/14/2022	43	275	9.0	194.4
5045E	John Deere/2022	09/01/2022	10/14/2022	43	430	14.0	304.0
5075E	John Deere/2022	09/01/2022	10/14/2022	43	458	14.9	323.8
5075E	John Deere/2022	09/01/2022	10/14/2022	43	348	11.3	246.0
5075E	John Deere/2022	09/01/2022	10/14/2022	43	279	9.1	197.2
			Average	47.3	316.1	9.7	210.2

3.1.2. Average Load Factor

The average load factor by crop type, engine power rating, and engine technology are presented in Figure 3-6. This load factor represents the load percent relative to the absolute maximum power of the engine. It should be noted that the Tier 1 and Tier 2 engines did not provide sufficient information to determine the work, so they are not included in the figure. The data suggests that the typical average loads for the tractors are similar, as a function of the engine's hp level. The data show relatively consistent load levels with the loads between 22 and 35% for the different categories, with an overall average load percent of 28%. The data did not show significant differences between tractors for tree and row crops, or for different engine hp categories. Additional data on load percent for different farm size categories is provided in Appendix D. It should be noted that the average load factors include idle time, so it does not necessarily represent the typical load for tractor during the working portion of their operation.

Figure 3-7 shows the load distribution in 5% load bins as a function of percentage of time of operation and time of day. This distribution represents an average of the distributions for individual tractors, with the distributions for the individual tractors weighted equally. The distribution shows that most of the tractor work is performed between 7 AM and 3 PM. The distributions show that the tractors spend the highest fraction of time (34%) at loads percentages below 10% with the highest fraction of time (21.5%) for loads below 5%. The fraction of time in load bins above 10% shows a steady decrease from 7.4% to 4.2% going from the 10-15% to the 45-50% load bins, with 45% of the total time spent in this load range. The tractors on average spent 21% of their operational time at loads greater that 50%, with 10.4% of their operational time at loads greater than 70%.

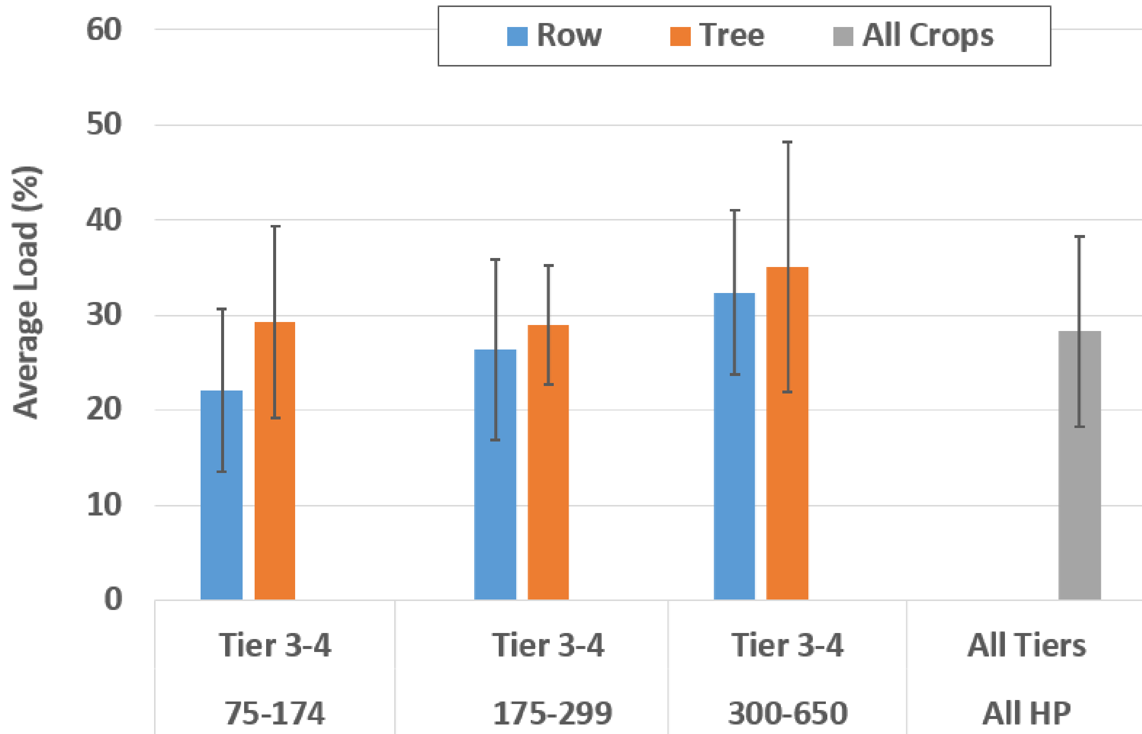

Figure 3-6. Average Load Factor by Crop Type, Engine Power Rating, and Engine Technology

Time Distribution in Load Range(%):

Hour	Total	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
Load Bins (%)		21.51	12.64	7.41	6.99	6.22	6.04	5.15	4.56	4.33	4.17	3.88	3.61	3.12	2.69	2.10	1.63	1.28	1.20	0.94	0.52
0	0.52	0.12	0.07	0.04	0.04	0.03	0.02	0.02	0.02	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01
1	0.38	0.10	0.04	0.04	0.03	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
2	0.34	0.06	0.05	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
3	0.33	0.06	0.04	0.01	0.02	0.05	0.02	0.04	0.02	0.01	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01
4	0.56	0.17	0.09	0.05	0.05	0.04	0.04	0.03	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.01	0.00
5	0.85	0.19	0.11	0.07	0.08	0.07	0.05	0.03	0.03	0.04	0.04	0.03	0.03	0.02	0.02	0.02	0.01	0.01	0.00	0.00	0.00
6	4.76	0.93	1.00	0.35	0.32	0.30	0.28	0.22	0.19	0.20	0.19	0.16	0.14	0.12	0.10	0.08	0.06	0.04	0.03	0.03	0.02
7	10.83	2.05	2.28	0.97	0.76	0.62	0.58	0.50	0.44	0.41	0.39	0.36	0.33	0.28	0.25	0.18	0.13	0.10	0.08	0.08	0.04
8	9.99	2.38	1.09	0.71	0.70	0.64	0.67	0.57	0.48	0.41	0.40	0.38	0.36	0.30	0.25	0.19	0.14	0.11	0.09	0.08	0.05
9	9.81	2.24	1.12	0.62	0.63	0.56	0.61	0.52	0.47	0.46	0.46	0.43	0.40	0.31	0.26	0.19	0.16	0.11	0.10	0.11	0.06
10	9.81	1.79	0.99	0.69	0.73	0.66	0.65	0.53	0.50	0.48	0.45	0.42	0.40	0.36	0.31	0.22	0.18	0.13	0.14	0.12	0.06
11	9.14	2.26	0.88	0.60	0.62	0.57	0.59	0.48	0.44	0.40	0.36	0.33	0.31	0.28	0.25	0.22	0.17	0.13	0.13	0.08	0.05
12	7.91	2.24	0.75	0.47	0.49	0.47	0.48	0.40	0.35	0.35	0.33	0.29	0.27	0.24	0.21	0.16	0.13	0.08	0.08	0.08	0.03
13	9.76	1.77	0.98	0.86	0.72	0.66	0.63	0.56	0.47	0.46	0.44	0.41	0.35	0.33	0.28	0.22	0.18	0.15	0.14	0.09	0.05
14	8.93	1.93	1.10	0.75	0.64	0.56	0.53	0.43	0.38	0.37	0.35	0.34	0.33	0.29	0.24	0.18	0.14	0.13	0.13	0.07	0.04
15	6.50	1.43	0.96	0.43	0.47	0.43	0.38	0.33	0.31	0.31	0.29	0.25	0.21	0.18	0.15	0.11	0.07	0.06	0.05	0.03	0.02
16	3.23	0.60	0.42	0.31	0.29	0.26	0.20	0.15	0.14	0.14	0.14	0.12	0.11	0.09	0.07	0.05	0.03	0.03	0.03	0.01	0.01
17	1.26	0.23	0.16	0.10	0.09	0.08	0.07	0.05	0.05	0.06	0.08	0.06	0.05	0.04	0.03	0.03	0.02	0.02	0.02	0.01	0.01
18	0.95	0.17	0.09	0.06	0.06	0.04	0.06	0.04	0.05	0.04	0.05	0.05	0.05	0.04	0.03	0.03	0.03	0.02	0.02	0.01	0.00
19	0.94	0.19	0.10	0.06	0.06	0.04	0.03	0.04	0.05	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.02	0.02	0.01	0.00
20	0.89	0.15	0.08	0.06	0.04	0.03	0.04	0.06	0.04	0.03	0.03	0.04	0.05	0.04	0.04	0.04	0.03	0.02	0.03	0.02	0.01
21	0.86	0.17	0.10	0.06	0.05	0.03	0.03	0.04	0.03	0.03	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.01	0.01
22	0.75	0.15	0.07	0.05	0.04	0.03	0.02	0.03	0.02	0.02	0.03	0.03	0.04	0.04	0.03	0.03	0.03	0.02	0.02	0.02	0.01
23	0.70	0.12	0.07	0.04	0.04	0.03	0.02	0.03	0.03	0.02	0.03	0.04	0.04	0.04	0.03	0.03	0.02	0.02	0.02	0.02	0.01

Figure 3-7. Percentage of Time as a function of Engine Load and Time of Day

3.1.3. Average Fuel Use per day and per hour

The average fuel use by crop type, engine power rating, and engine technology is presented in Figure 3-8 on a daily basis and in Figure 3-9 on an hourly basis. This information is also obtained from the ECU data from the data logger as well. It should be noted that the fuel use rates per day is a function of both the amount of fuel used per hour and the number of hours of operation during a day, whereas the fuel use per hour metric represents fuel use as a function of only hours when the tractor is operating. Hence, the fuel use per hour is a better metric in terms of understanding how much fuel is used during typical tractor work. The primary trend for fuel use is that it increases with increasing engine hp or engine size. This trend was readily seen for the Tier 3 and 4 tractors, which showed a consistent increase in going from the <175 hp to the 300 to 650 hp categories. The fuel use rates for the tree and row crops did not show significant differences for any of the hp categories. This suggests that work loads for the two different crop types are similar, which is consistent with the load factor results collected in section 3.1.2. Average daily fuel use rates were 20 gallons per day, with a maximum of about 43 to 47 gallons per day for the 300-650 hp categories, while tractors in the below 175 hp categories had fuel use rates below 10 gallons per day. Average fuel use rates were 4.2 gallons per hour, with a maximum of 7.7 to 8.6 gallons per hour for the 300-650 hp categories, while tractors in the below 175 hp categories had fuel use rates of about 2 gallons per hour. Some additional analyses were also done on daily fuel use as a function of farm size, as shown in Appendix D. Average daily fuel use for different farm size categories varied from 7.2 to 22.9 gallons per day. While average fuel rates tended to be higher for >2,000 acres farms, these differences were within the variability in the data.

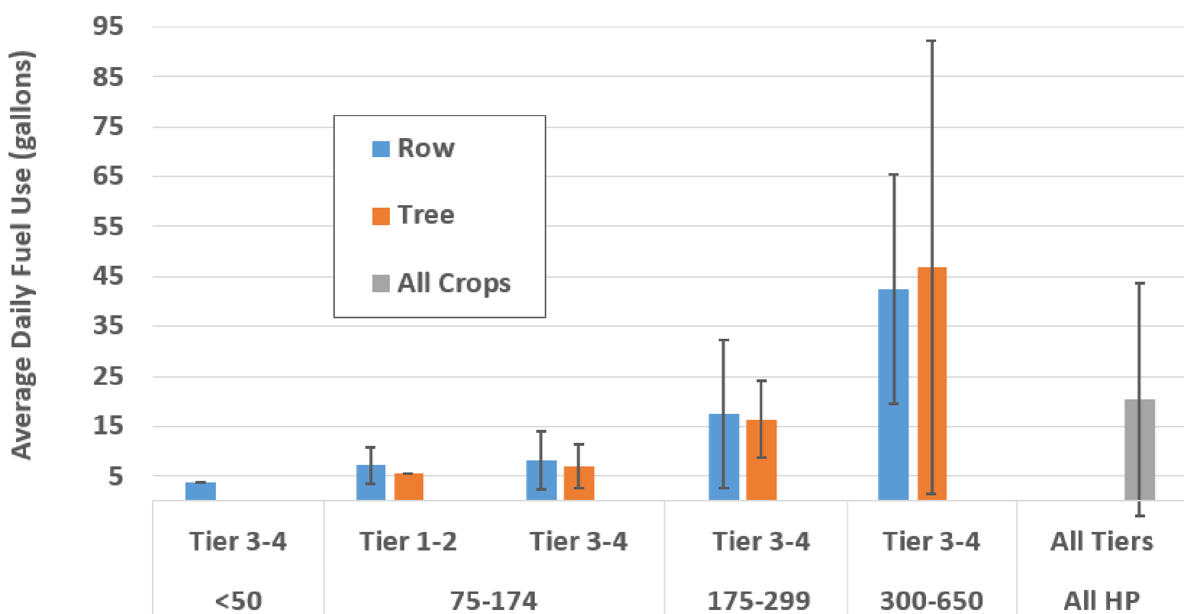

Figure 3-8. Average Fuel Use per Day by Crop Type, Engine Power Rating, and Engine Technology

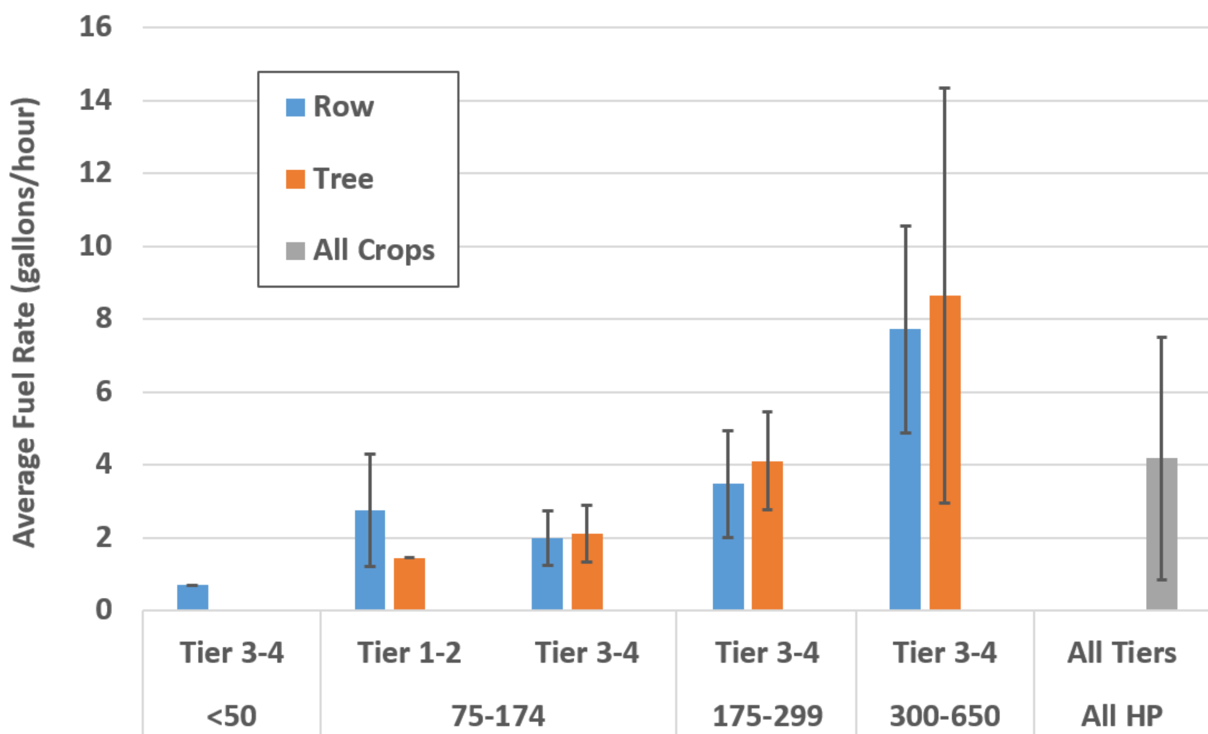

Figure 3-9. Average Fuel Use per Hour by Crop Type, Engine Power Rating, and Engine Technology

The fuel rate as a function of engine hp is shown in greater detail in a scatter plot in Figure 3-10, which includes all of the data from the data loggers. Overall, the data show a positive upward trend in fuel use in gals/hour as a function of increasing hp, as expected. The trend lines between the Tier 3 and 4 tractors and the Tier 2 tractors are comparable, but the data available for the older tractors was limited and only for lower hp tractors. Additional measurements for fuel consumption for four Tier 0 to Tier 2 tractors were also conducted by manually measuring fuel consumption over the period of a day. These tractors ranged in size from 76 to 105 hp, and showed fuel consumption ranging from 1.5 to 1.9 gals/hr, consistent with the results seen over longer periods of time for data collected by the data loggers.

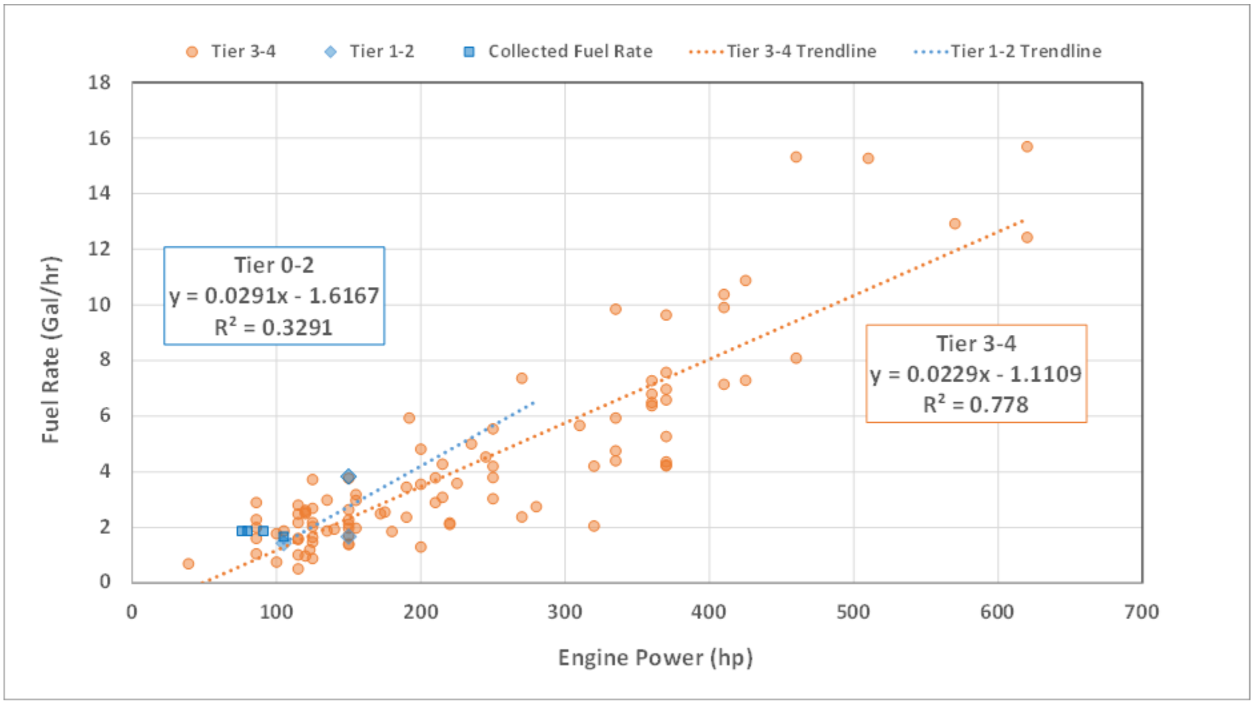

Figure 3-10. Average Fuel Use per Hour by Engine Power Rating

Fuel consumption as a function of engine work was also evaluated. Brake specific fuel consumption in gallons/kW-hr for the different horsepower categories is shown in Figure 3-11. Note that, as discussed in section 3.1.2, the Tier 1 and Tier 2 engines did not provide sufficient information to determine the work, so they are not included in the figure. The results are in the range of 0.07 to 0.08 gallons/kW-hr for all horsepower categories, with slightly higher fuel consumption for the 75-174 horsepower engines. This is again consistent with fuel consumption being a strong function of engine work, such that lower and higher hp tractors have a similar fuel consumption rate when it is normalized based on work.

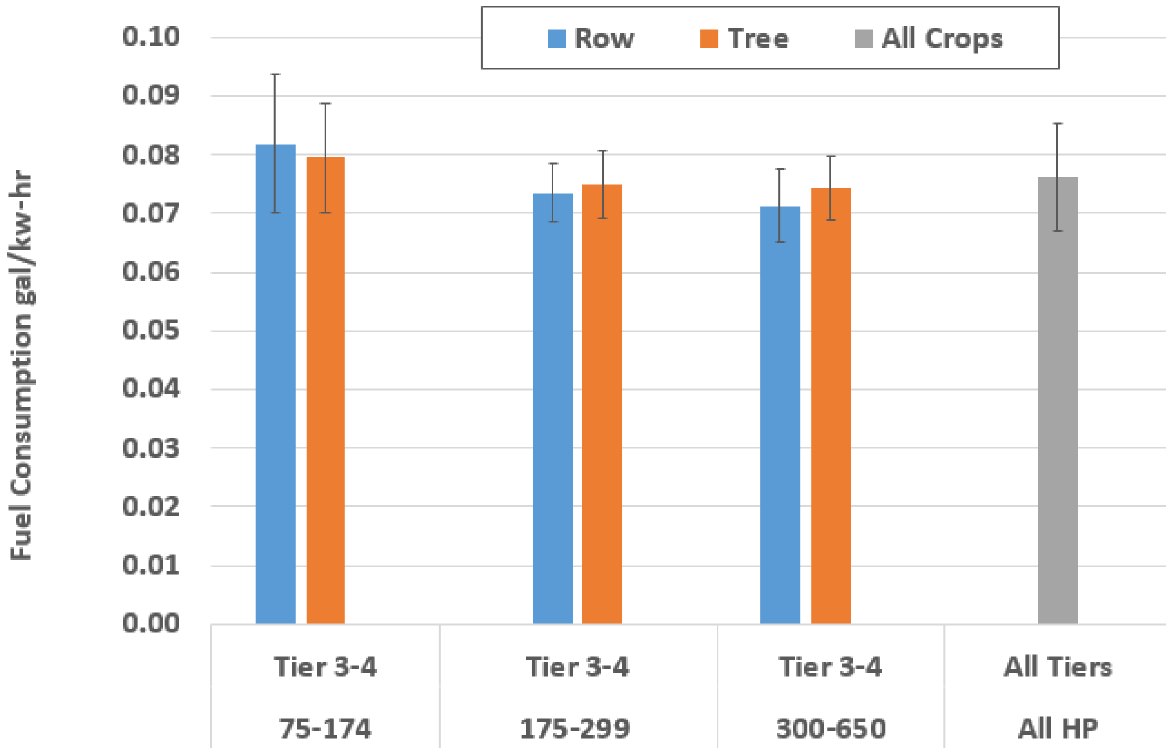

Figure 3-11. Brake Specific Fuel Consumption (g/kW-hr)

3.1.4. Average Exhaust/DPF Outlet Temperature

The average DPF outlet temperatures by crop type, engine power rating, and engine technology are presented in Figure 3-12. The DPF outlet temperature was selected as the primary metric for characterizing the exhaust temperature, because the DPF is the aftertreatment element that is immediately before the SCR in a typical DPF/SCR set, and because the ECU data files for these off-road engines typically did not include SCR exhaust temperatures. The results show similar average DPF outlet temperatures for the tree and row crops and the different hp categories. The average DPF outlet temperatures were at or above 250°C category for both the tree and row crops, for all of the different hp categories, and for the different farm sizes, as shown in Appendix D-2.

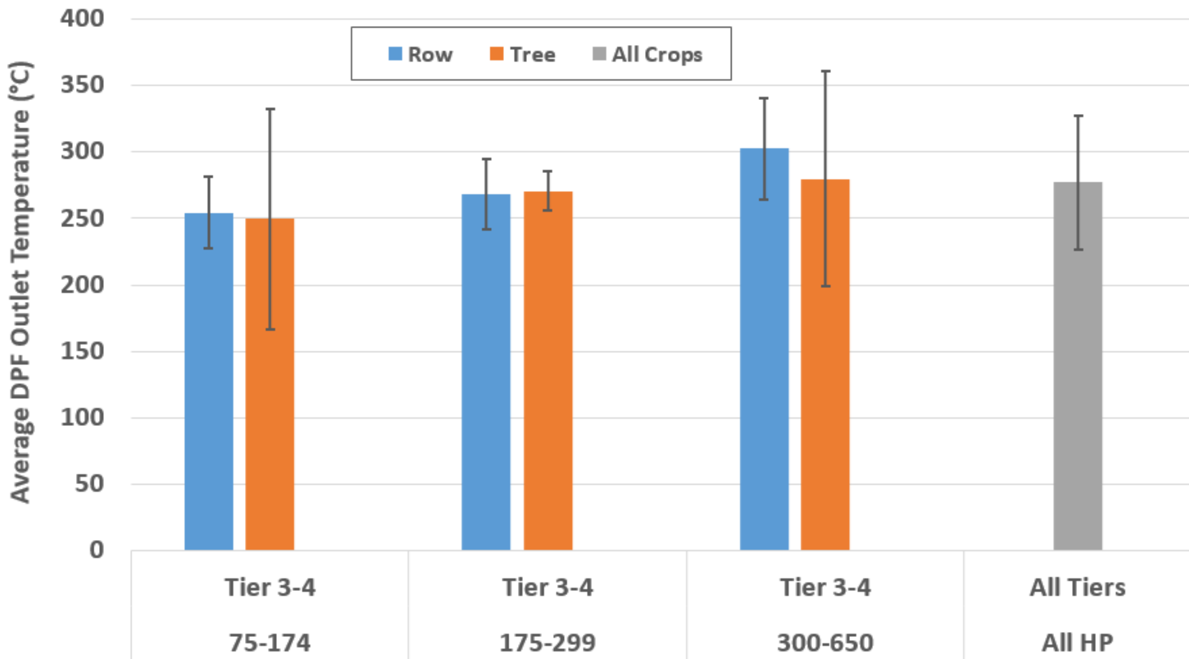

Figure 3-12. Average Exhaust/DPF Outlet Temperature by Crop Type, Engine Power Rating, and Engine Technology

The distribution of DPF outlet exhaust temperatures averaged over all tractors is shown in greater detail in Figure 3-13, which shows frequency distributions as a function of DPF outlet temperature bins from 0 to 600°C in 10°C bins. Additional DPF outlet temperature distributions for the different categories by hp and crop type are shown in Appendix D. This distribution shows that the DPF outlet temperature is above 200°C for 78.5% of the operational time, which in turn suggests that for 21.5% of the operating time, the DPF outlet temperature would not be sufficiently high to allow for the injection of urea into the SCR. This is due to the fact that urea injections at temperature below the 200°C can lead to deposit formation, so urea is typically not injected below this temperature threshold (M. Koebel et al., 2002). This is consistent with the distribution of the load data shown in Figure 3-7, showing that 34.2% of the operating time is at loads below 10%. DPF outlet distributions as a function of engine load are provided in Figure 3-14 for the Tier 3-4 tractors. The distribution in Figure 3-14 also shows that the DPF outlet temperature is below 200°C for about 21.5% of the operating time, with 17% of the operating time being below 200°C with the load percent being below 10%.

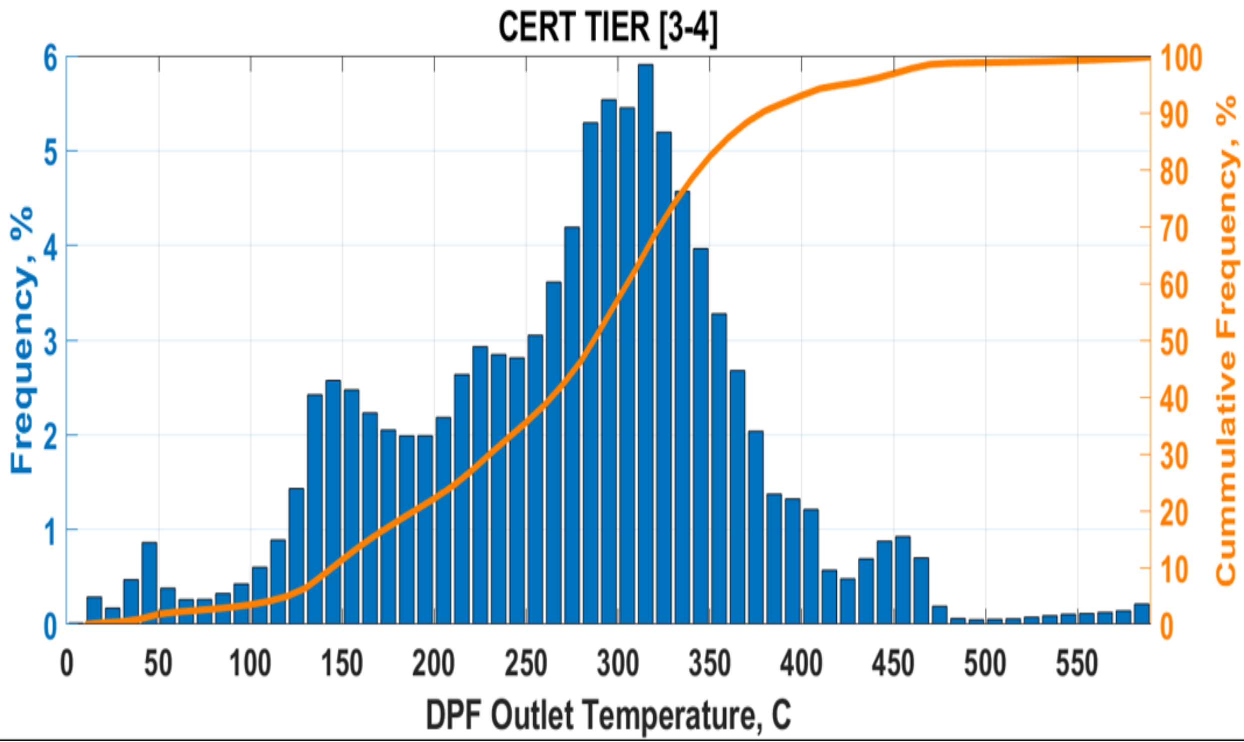

Figure 3-13. DPF Outlet Temperature Distributions for the Tractors.

Temperature Bins (°C)		0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	45-50	50-55	55-60	60-65	65-70	70-75	75-80	80-85	85-90	90-95	90-100
Load Bins (%)		22.80	11.58	6.58	6.77	6.12	5.71	5.06	4.31	4.08	4.30	4.11	3.96	3.41	2.88	2.29	1.79	1.42	1.37	1.13	0.32
575-600	0.52	0.12	0.03	0.03	0.02	0.03	0.03	0.03	0.04	0.04	0.04	0.03	0.03	0.02	0.01	0.01	0.01	0.00	0.00	0.00	0.00
550-575	0.31	0.07	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00
525-550	0.24	0.06	0.02	0.03	0.02	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00
500-525	0.15	0.03	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00
475-500	0.17	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
450-475	1.79	0.05	0.03	0.05	0.05	0.03	0.03	0.03	0.04	0.07	0.16	0.24	0.29	0.19	0.14	0.11	0.09	0.05	0.04	0.06	0.04
425-450	1.86	0.08	0.03	0.03	0.03	0.02	0.03	0.04	0.07	0.12	0.21	0.23	0.20	0.15	0.15	0.13	0.12	0.08	0.06	0.06	0.03
400-425	2.06	0.08	0.05	0.03	0.03	0.04	0.05	0.05	0.08	0.12	0.14	0.13	0.09	0.10	0.16	0.16	0.14	0.11	0.15	0.31	0.05
375-400	3.64	0.16	0.13	0.09	0.07	0.10	0.12	0.14	0.17	0.20	0.20	0.19	0.21	0.29	0.39	0.33	0.24	0.15	0.16	0.27	0.05
350-375	7.15	0.35	0.24	0.18	0.17	0.21	0.26	0.39	0.42	0.41	0.46	0.54	0.77	0.77	0.59	0.38	0.30	0.27	0.27	0.13	0.04
325-350	11.21	0.69	0.54	0.39	0.42	0.55	0.72	0.84	0.71	0.76	0.90	0.91	0.86	0.76	0.63	0.51	0.36	0.28	0.26	0.11	0.03
300-325	14.22	1.26	0.80	0.60	0.97	1.11	1.12	1.00	1.01	1.02	1.06	0.98	0.82	0.62	0.44	0.36	0.33	0.29	0.30	0.10	0.03
275-300	13.27	1.61	0.89	0.84	1.33	1.63	1.73	1.44	0.98	0.71	0.58	0.44	0.34	0.23	0.15	0.11	0.08	0.07	0.06	0.03	0.02
250-275	8.61	1.81	0.84	0.88	1.28	1.01	0.70	0.52	0.40	0.30	0.23	0.17	0.13	0.09	0.07	0.05	0.04	0.04	0.03	0.02	0.01
225-250	7.10	2.35	0.98	0.88	0.95	0.56	0.34	0.24	0.15	0.13	0.13	0.08	0.06	0.05	0.05	0.05	0.03	0.03	0.02	0.01	0.01
200-225	6.23	2.77	1.03	0.71	0.51	0.33	0.27	0.14	0.08	0.07	0.06	0.05	0.05	0.05	0.04	0.03	0.02	0.01	0.01	0.00	0.00
175-200	4.93	2.59	0.98	0.46	0.29	0.16	0.10	0.07	0.05	0.04	0.04	0.03	0.03	0.03	0.02	0.02	0.01	0.01	0.00	0.00	0.00
150-175	5.72	3.62	1.17	0.32	0.19	0.12	0.08	0.05	0.04	0.03	0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00
125-150	5.68	3.76	1.23	0.27	0.16	0.08	0.05	0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
100-125	1.97	0.98	0.64	0.19	0.06	0.04	0.02	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
75-100	0.83	0.17	0.42	0.13	0.06	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
50-75	0.75	0.09	0.43	0.11	0.07	0.03	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
25-50	1.38	0.10	0.97	0.21	0.06	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0-25	0.21	0.01	0.07	0.11	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Figure 3-14. DPF Outlet Temperature vs. Engine Load.

3.1.5. Average Idle Percentage

The average idle times by crop type and engine power rating are presented in Figure 3-15. Average idle times across different crops (tree and row) and the engine power ratings were in a range from 23% to 28%, with some exceptions. The overall average idle percentage was 26%. The <50 hp Tier 3-4 row tractors and the Tier 1-2 row tractors showed lower idle percentages of 14% and 12%, respectively, while the Tier 1-2 row tractors showed an idle percentage of 64%. The idle fractions for the NRTC and C1 cycles are also presented in figure, which were 4.5% and 15%, respectively. Overall, the data suggest that there is a higher fraction of idle in real world operation than is represented in the certification test cycles. Some additional analyses were also done on daily idle fractions use as a function of farm size, as shown in Appendix D. Average daily idle fractions for different farm size categories ranged from 10.8% to 36.5%. The average idle rates were highest for the 1,000 to 1,999 acres farms, and were lowest for the custom farm, with the idle fractions for the 2,000 to 9,999 and the 10,000 to 25,000 acre farms being 27.5% and 23.9%, respectively.

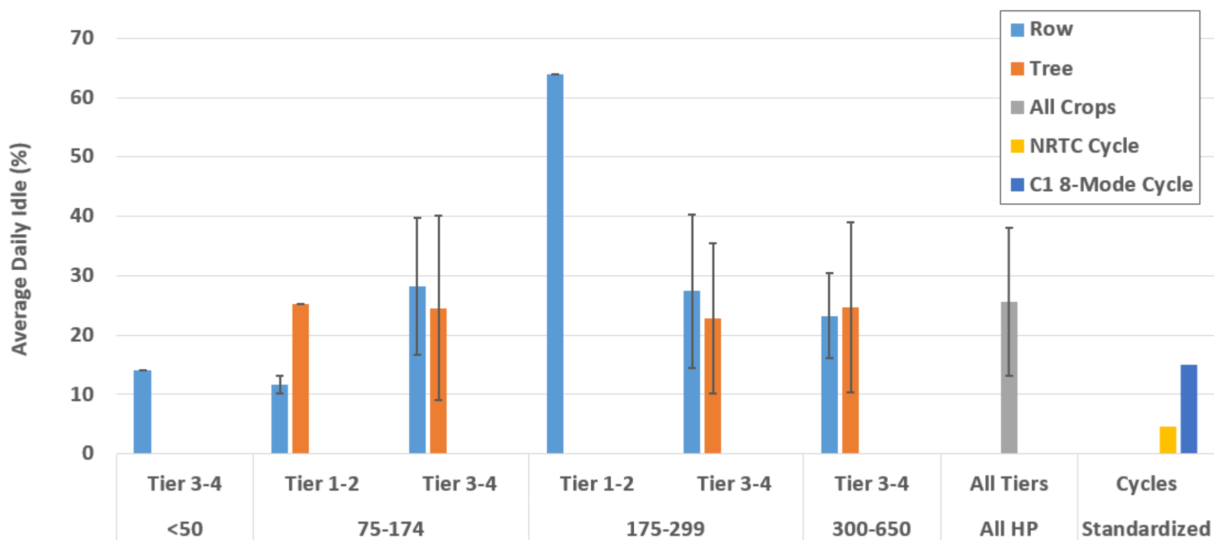

Figure 3-15. Average Idle Percentage by Crop Type, Engine Power Rating, and Engine Technology

3.1.6. Average Number of Engine Starts and Soak Durations

The average number of engine starts by crop type and engine power rating are presented in Figure 3-16. Average number of starts per day was approximate 3.5 starts, with a range from slightly less than 2 to 5 starts per day. The number of starts for most categories ranged between 2.5 and slightly more than 4 starts per day. There were differences between the different data crop/Tier/hp categories, but most of these were within the variability seen between different tractors in categories. There were somewhat fewer starts for the tree crops compared to the row crops for the 300 to 650 hp Tier 3-4 tractors.

The average number of engine starts by crop type and engine power rating is further broken down into hot starts and intermediate starts in Figure 3-17 and Figure 3-18, respectively. As discussed in section 2.3.2, hot starts are defined as starts with soaks with durations ≥ 30 seconds and ≤ 60 minutes, and intermediate starts are defined as starts with soaks with durations ≥ 60 minutes and ≤ 720 minutes. The data show that hot starts represented the highest fraction of starts per day, with an average of approximately 2.2 hot starts per day, with a range from slightly less than 1 to slightly greater than 3 hot starts between the different categories. The number of intermediate starts was on average about 0.4 per day, with the number of intermediate starts averaging 0.5 per day or less for all categories.

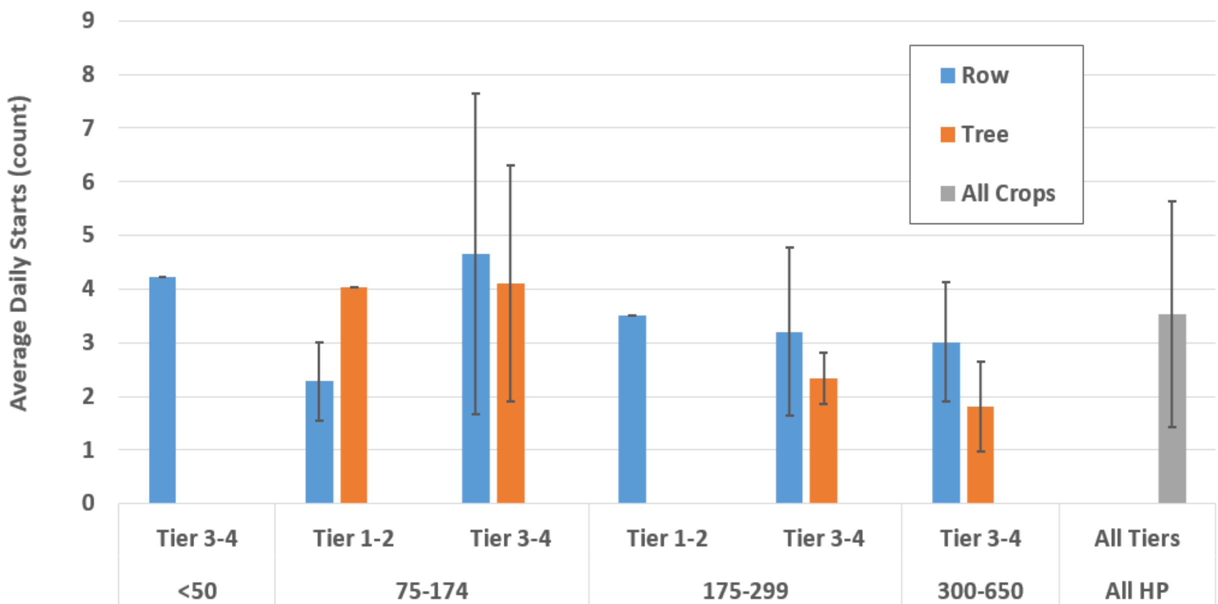

Figure 3-16. Average Number of Engine Starts by Crop Type, Engine Power Rating, and Engine Technology

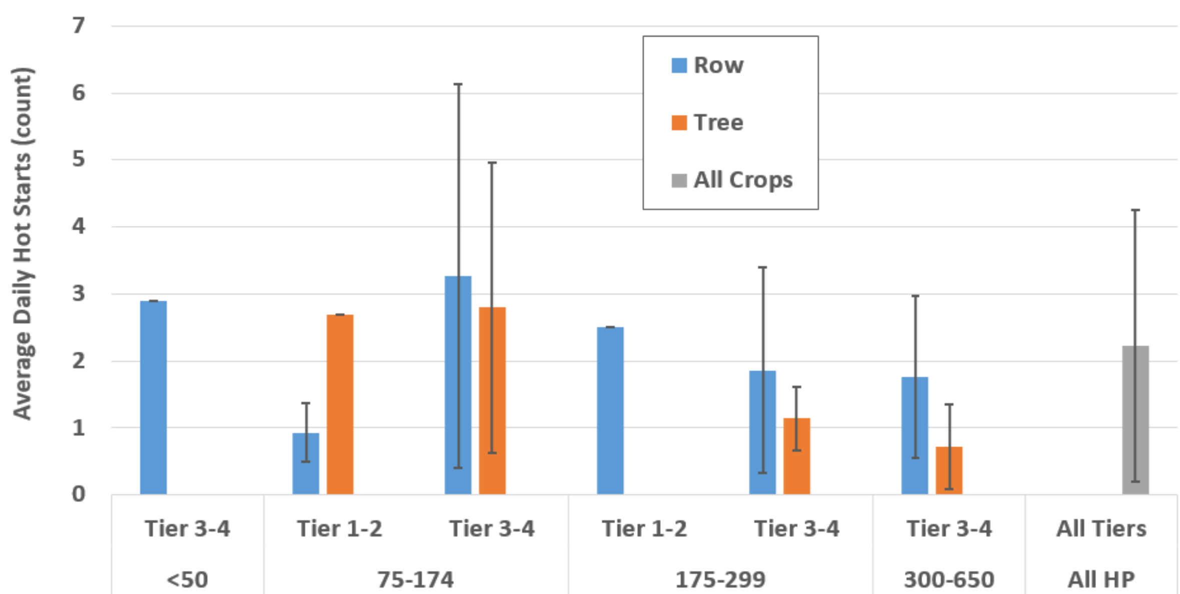

Figure 3-17. Average Number of Engine Hot Starts by Crop Type, Engine Power Rating, and Engine Technology

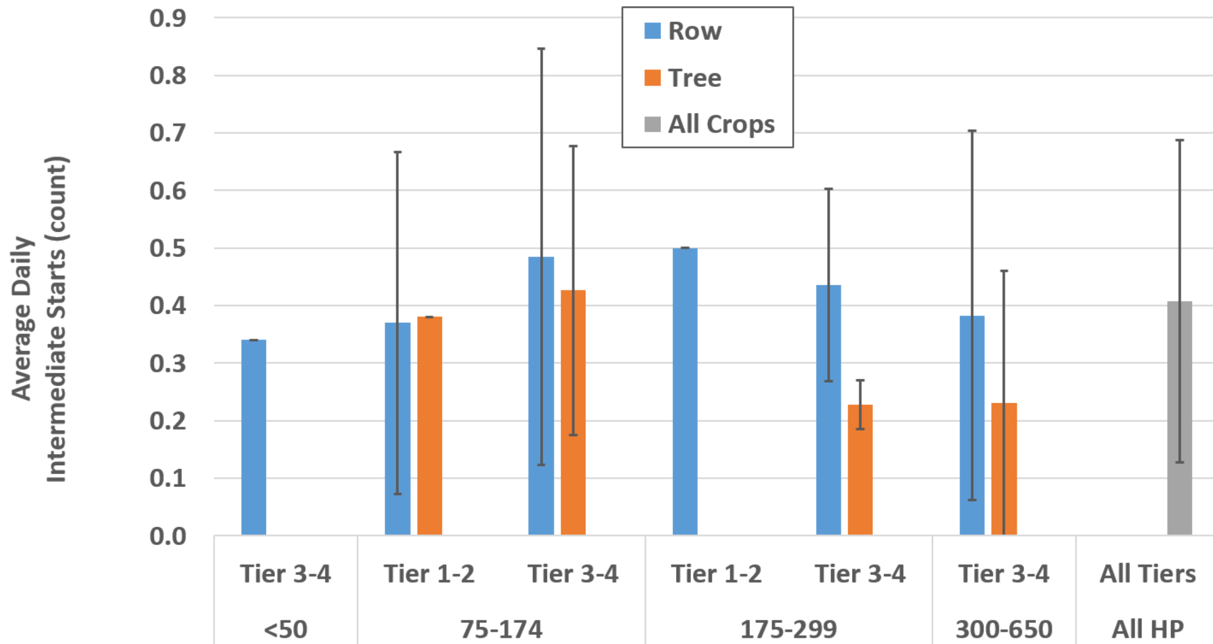

Figure 3-18. Average Number of Engine Intermediate Starts by Crop Type, Engine Power Rating, and Engine Technology

The average soak durations for hot starts and intermediate starts are shown in Figure 3-19 and Figure 3-20, respectively. The average hot start soak duration was approximately 15 minutes, with a range from approximately 10 to 20 minutes between different categories. The average intermediate start soak duration was approximately 200 minutes, with a range from approximately 150 to 250 minutes between different categories.

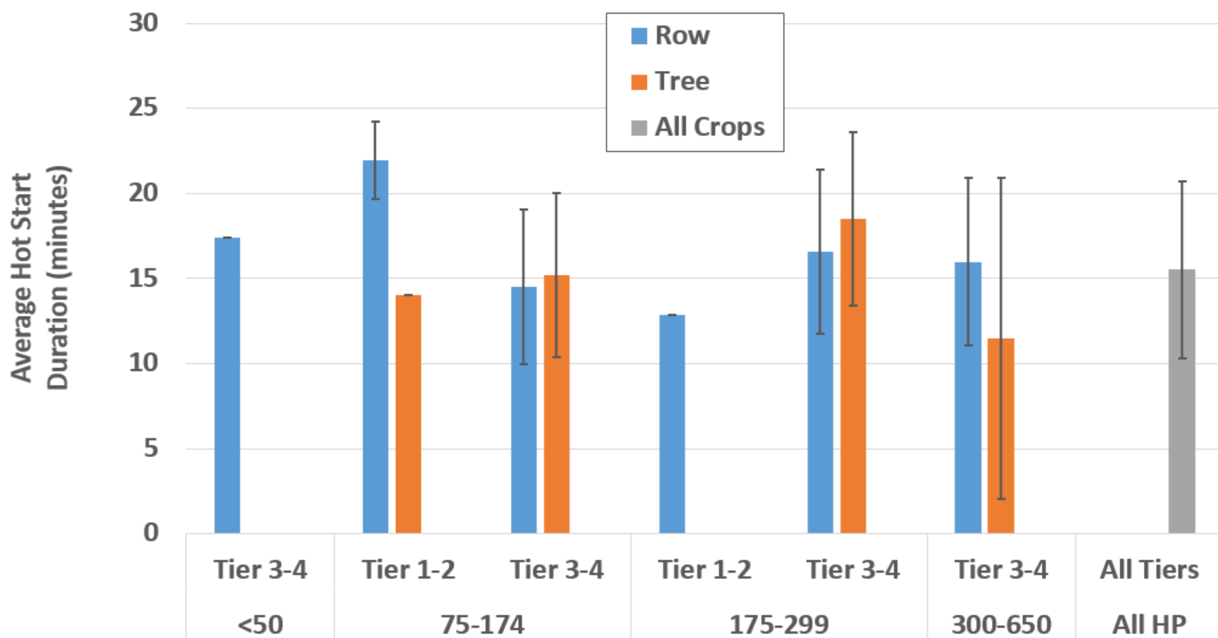

Figure 3-19. Average Hot Start Soak Duration by Crop Type, Engine Power Rating, and Engine Technology

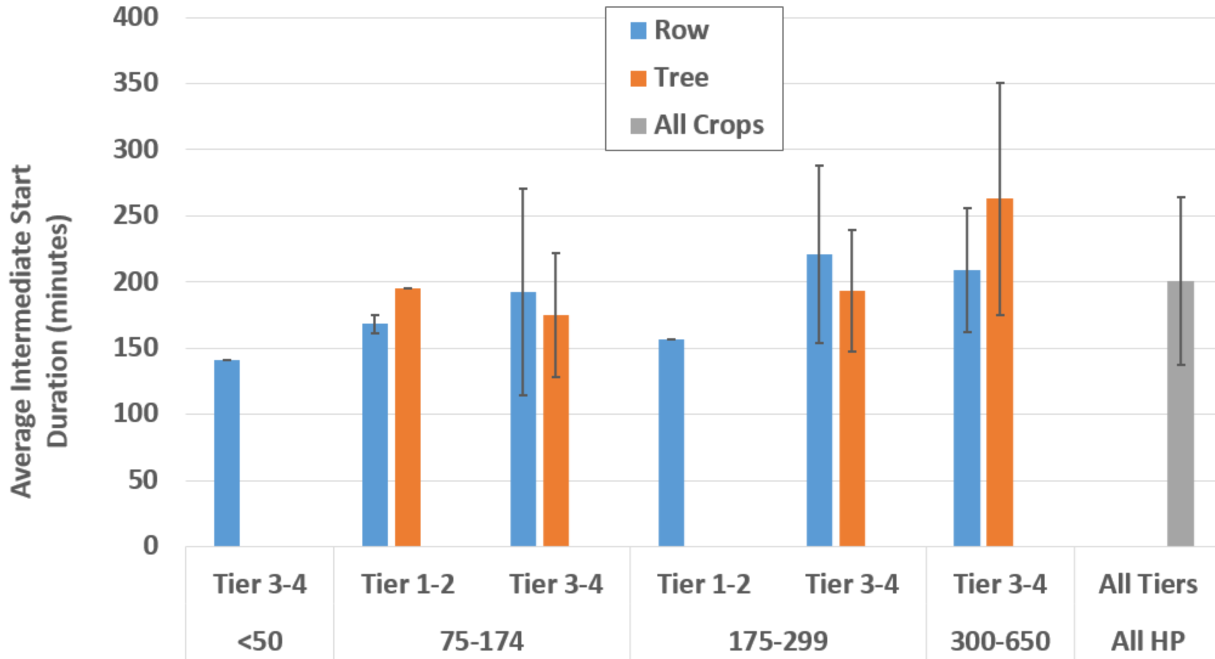

Figure 3-20. Average Intermediate Start Soak Duration by Crop Type, Engine Power Rating, and Engine Technology

3.2. Test Cycle Comparisons and Duty Cycles

In this section, comparisons are made between the in-use activity data and the certification cycles and the in-use activity data were used to develop more representative duty cycles. The comparison of the in-use engine operation characteristics from the activity data to two of the off-road certification cycles (the NRTC and C1 cycles) is presented in section 3.2.1. Example duty cycles based on the in-use agriculture data are presented in section 3.2.2.

3.2.1. Activity vs. Certification Cycle Lug Curve Comparisons

For this subsection, the data were analyzed by category to show the load profile in terms of engine rpm and torque distributions. The distributions are shown for the overall average, and for each agriculture tractor category based on the normalized profiles. The individual categories for the agriculture tractor were separated into 6 groups based on the different crop types (tree vs. row crop) and engine hp ratings (75 to 174 hp, 175 to 299 hp, and 300 to 650 hp). Note these comparisons were made for the Tier 3 and 4 tractor data, as the Tier 0-2 tractor data was limited, and as Tier 0-2 agriculture tractor engines are not currently being certified.

Figure 3-21 and Figure 3-22 show the normalized torque and speed patterns for the NRTC and C1 cycles, respectively. Figure 3-23 shows the frequency distribution of the continuous torque and engine speed data for the collected in-use data for the overall average of the Tier 3 and 4 agriculture tractor data. Figure 3-24 to Figure 3-29 show the distributions of the continuous torque and engine speed data for the individual agriculture tractor categories. For these plots, the data was binned in 1% intervals for both normalized engine speed and normalized engine torque relative to the normalized maximum torque and speed values for the NRTC cycle. Note that the normalized engine speed values are based on the calculation in 40 CFR Part 1065.610, which is close to the speed at the peak rated power for the engine, as opposed to the maximum speed for the engine itself. As such, some portion of the activity occurs above the 100% reference speed. The normalized torque values are based on the maximum output torque at the given speed, as opposed to the absolute maximum torque value for the engine. In general, the in-use data covers a much broader range of operating conditions than are found in the engine certification cycles. Specifically, the distributions for the in-use data show that there is a more significant contribution at low load conditions than is captured in the certification cycles. 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.

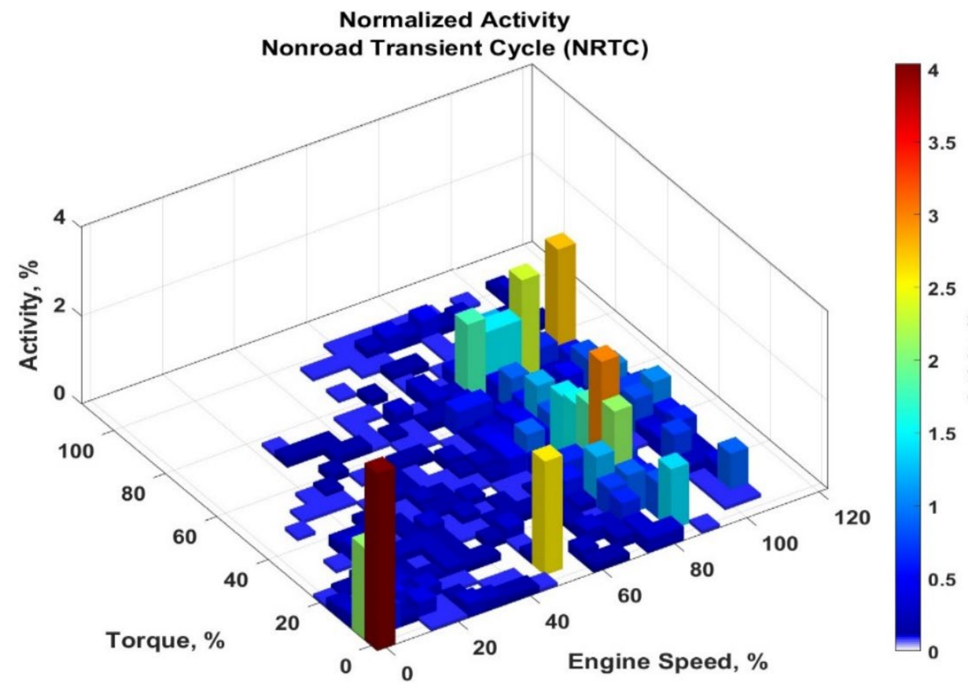

Figure 3-21. Frequency distribution of normalized torque and engine speed for the NRTC cycle.

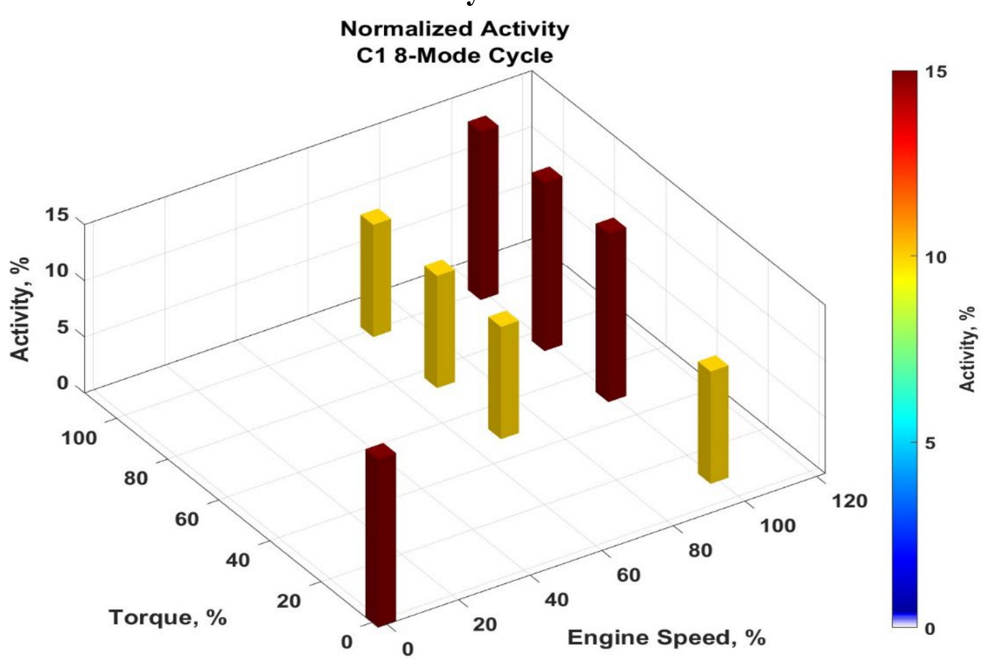

Figure 3-22. Frequency distribution of normalized torque and engine speed for the C1 cycle.

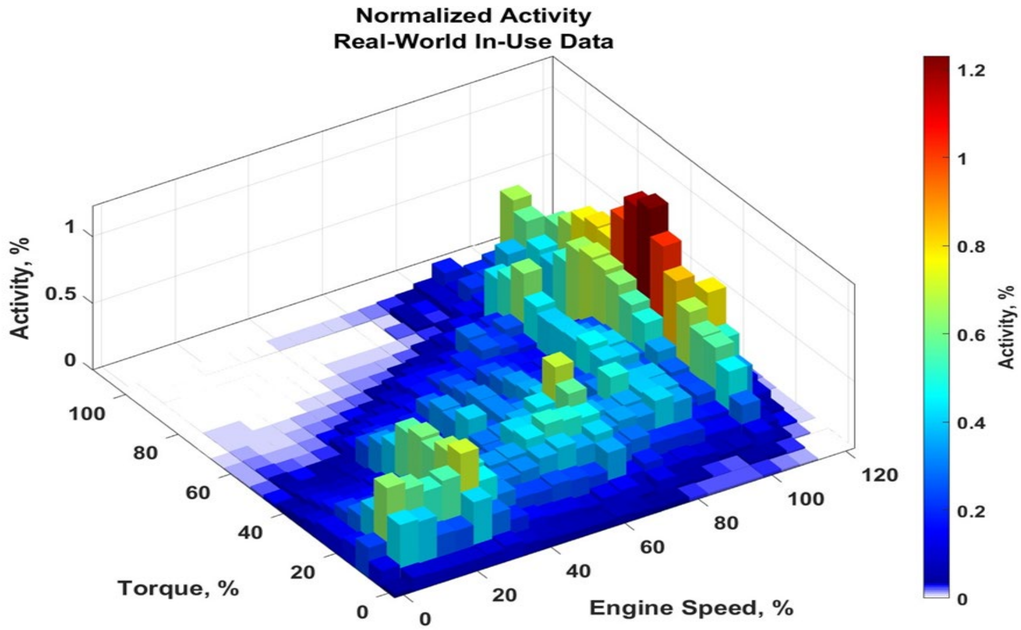

Figure 3-23. Frequency distribution of normalized torque and engine speed for the overall average of the in-use agriculture tractor data.

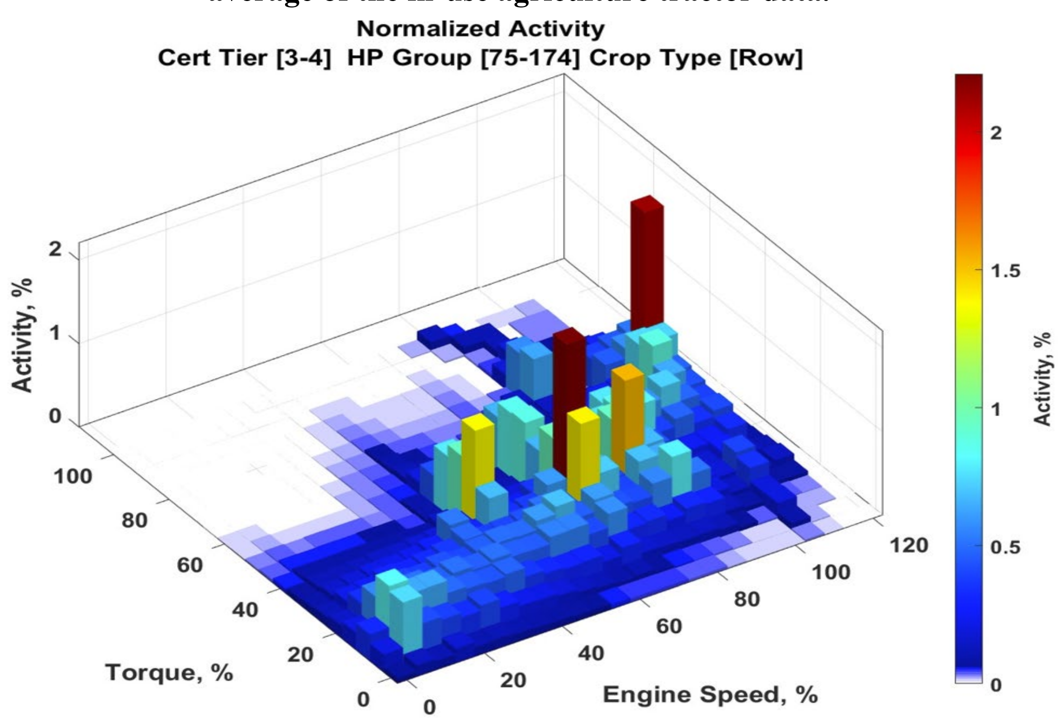

Figure 3-24. Frequency distribution of normalized torque and engine speed between for the in-use data for the 75 to 174 hp row crop agriculture tractor category.

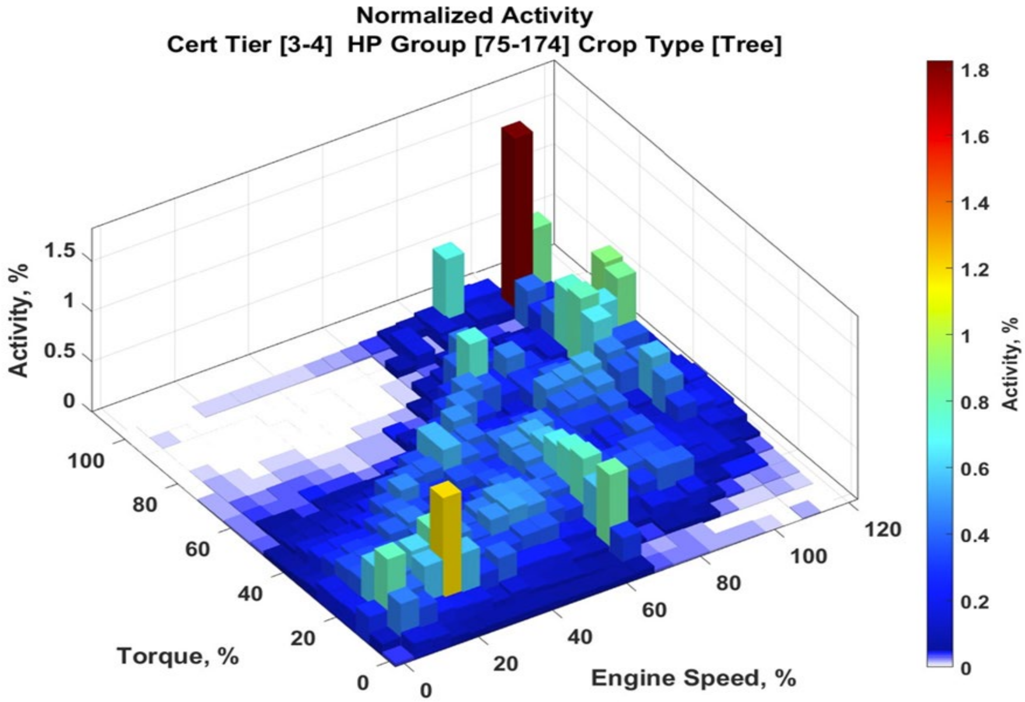

Figure 3-25. Frequency distribution of normalized torque and engine speed for the in-use data for the 75 to 174 hp tree crop agriculture tractor category.

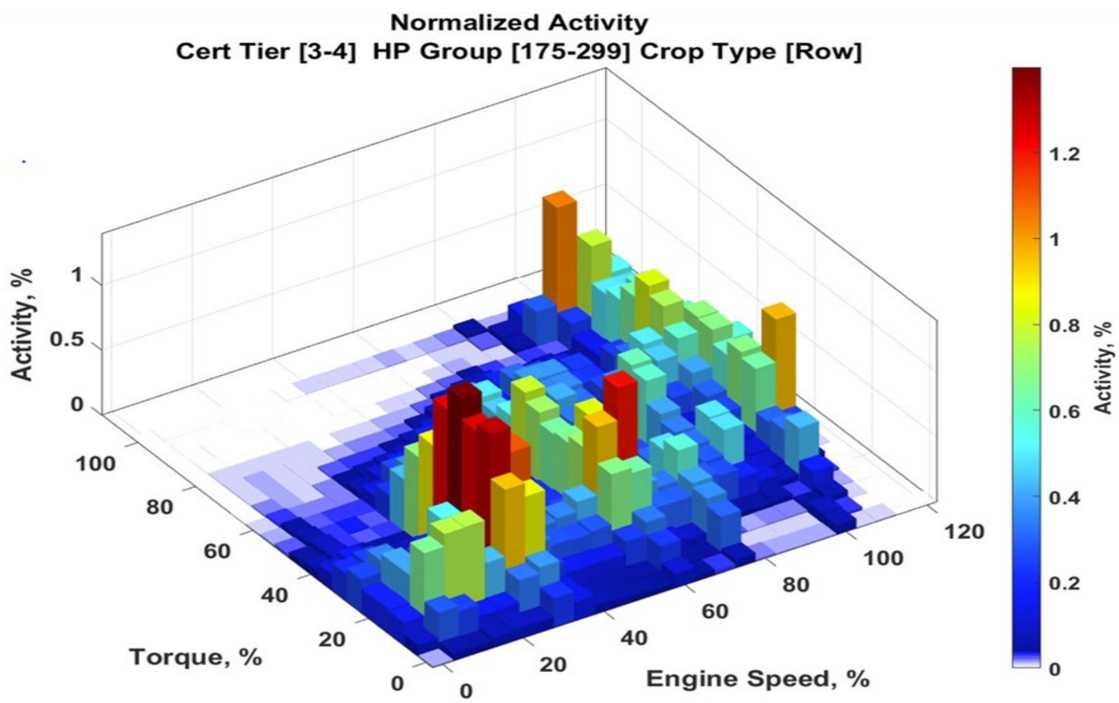

Figure 3-26. Frequency distribution of normalized torque and engine speed for the in-use data for the 175 to 299 hp row crop agriculture tractor category.

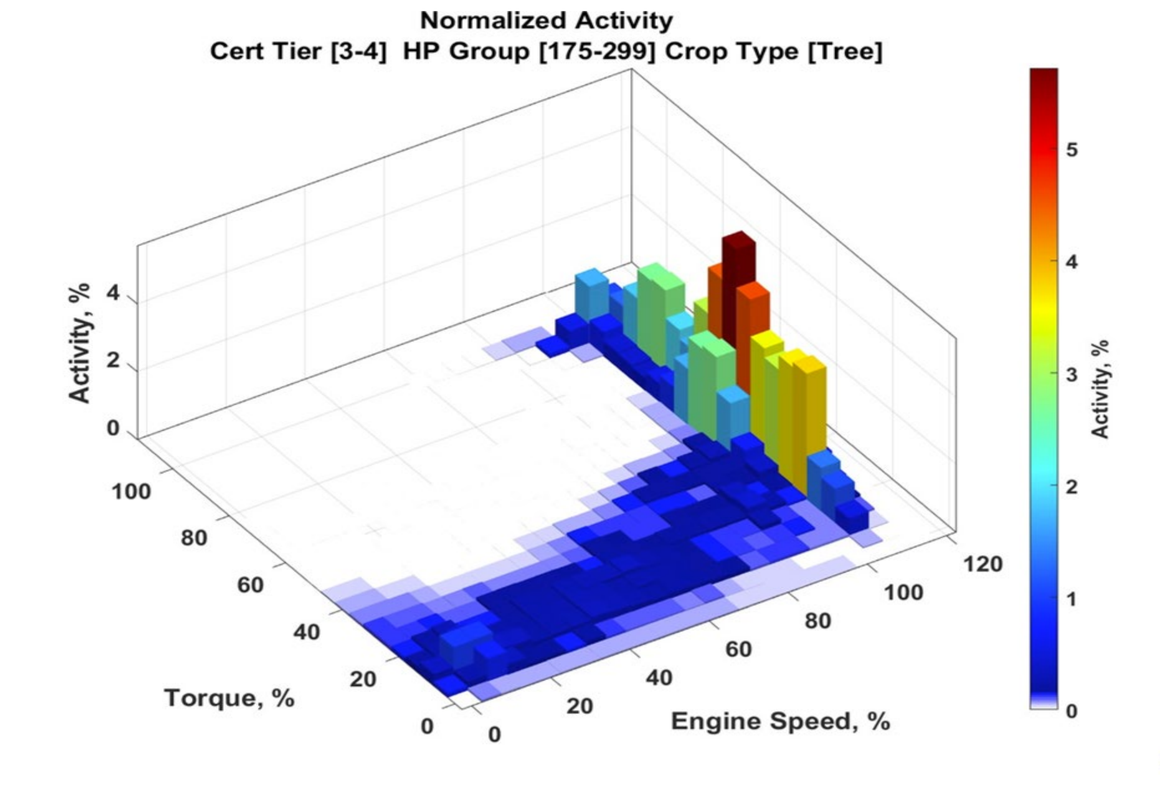

Figure 3-27. Frequency distribution of normalized torque and engine speed for the in-use data for the 175 to 299 hp tree crop agriculture tractor category.

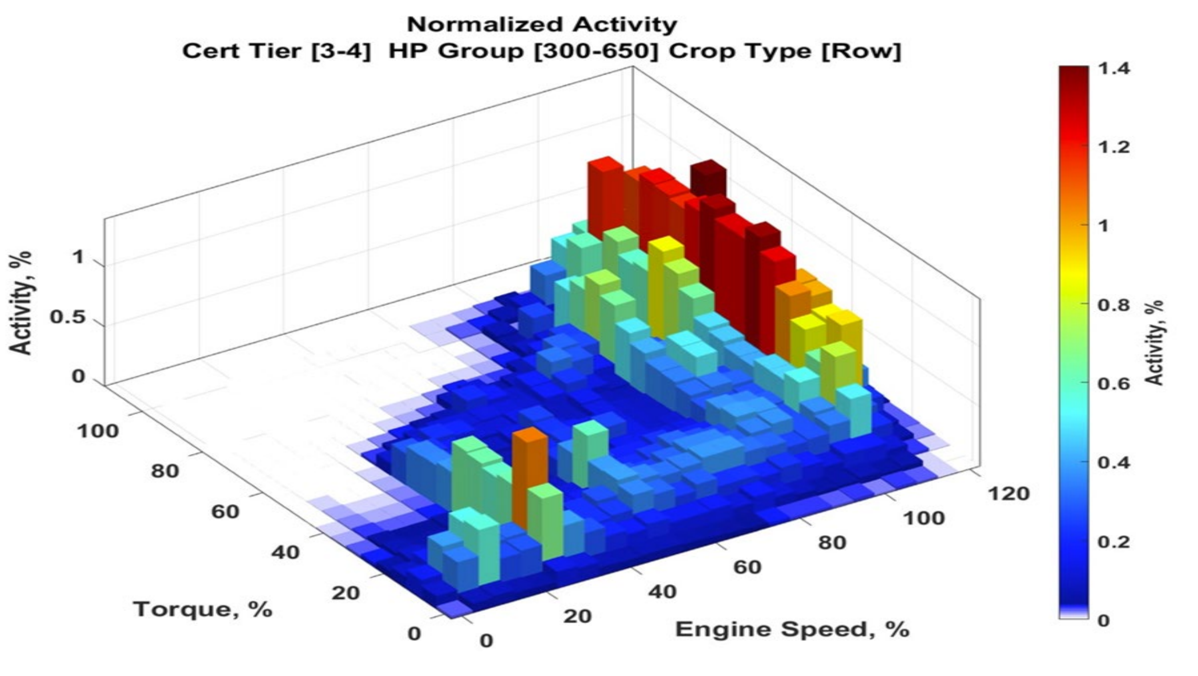

Figure 3-28. Frequency distribution of normalized torque and engine speed for the in-use data for the 300 to 650 hp row crop agriculture tractor category.

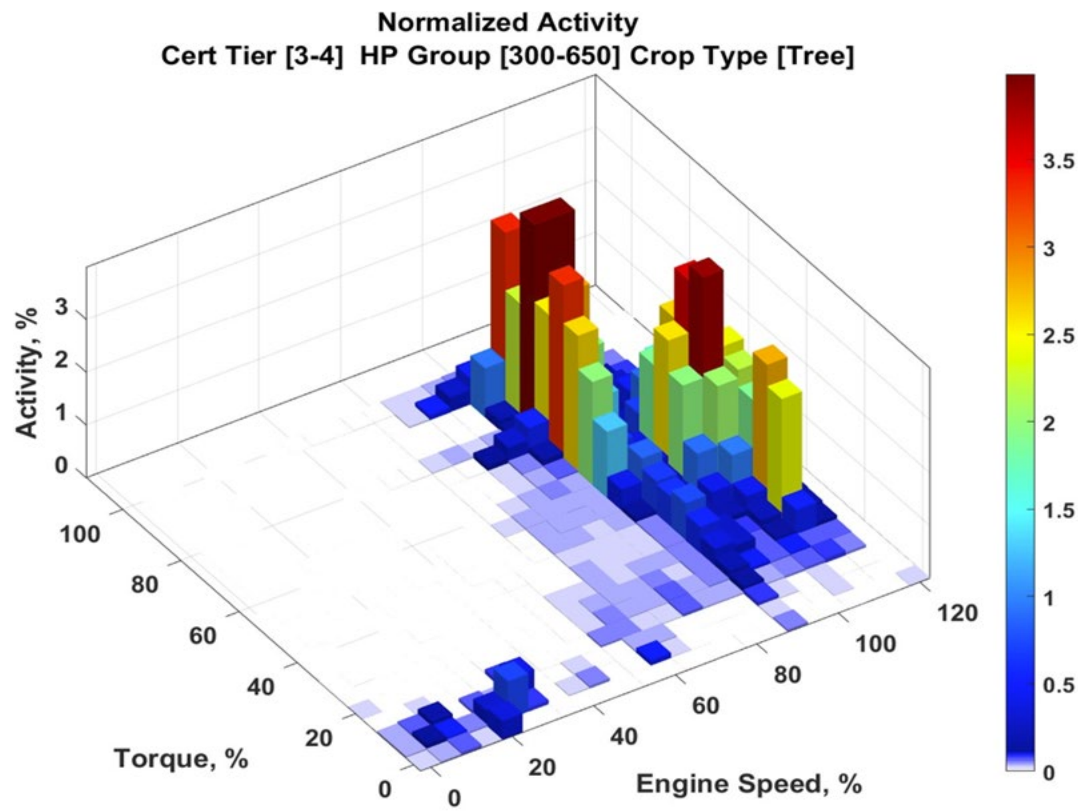

Figure 3-29. Frequency distribution of normalized torque and engine speed for the in-use data for the 300 to 650 hp tree crop agriculture tractor category.

3.2.2. Duty Cycles for Different Equipment Categories

For this subsection, the data were analyzed to develop duty cycles representative of the operation of the equipment data logged in the different equipment categories. These duty cycles were developed based on the methodologies discussed in section 2.3.3. The representative duty cycles are shown in Figure 3-30 for all agriculture tractors, Figure 3-31 for 75<x<175 hp row crop agriculture tractors, Figure 3-32 for 75<x<175 hp tree crop agriculture tractors, Figure 3-33 for 175<x<300 hp row crop agriculture tractors, Figure 3-34 for 175<x<300 hp tree crop agriculture tractors, Figure 3-35 for 300<x<650 hp row crop agriculture tractors, Figure 3-36 for 300<x<650 hp tree crop agriculture tractors.

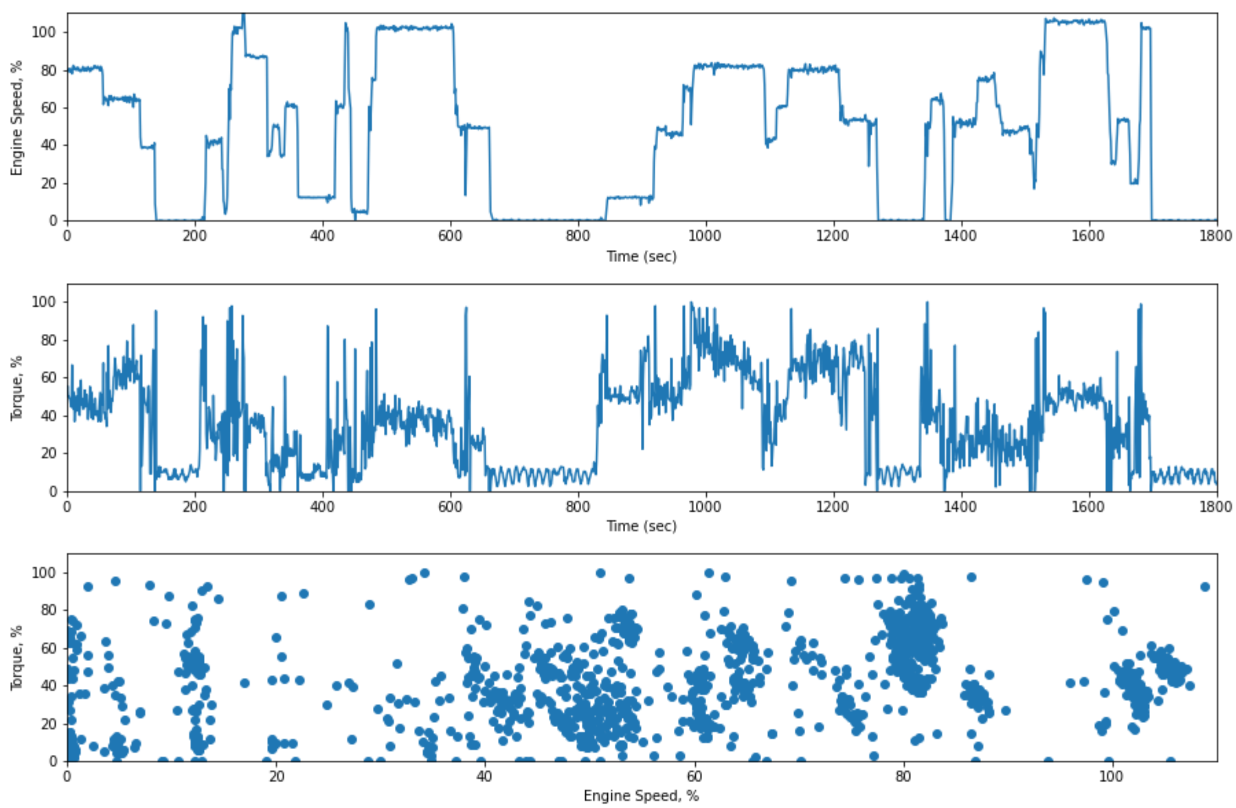

Figure 3-30. Engine Speed % and Torque % for the Duty Cycle for all agriculture tractors

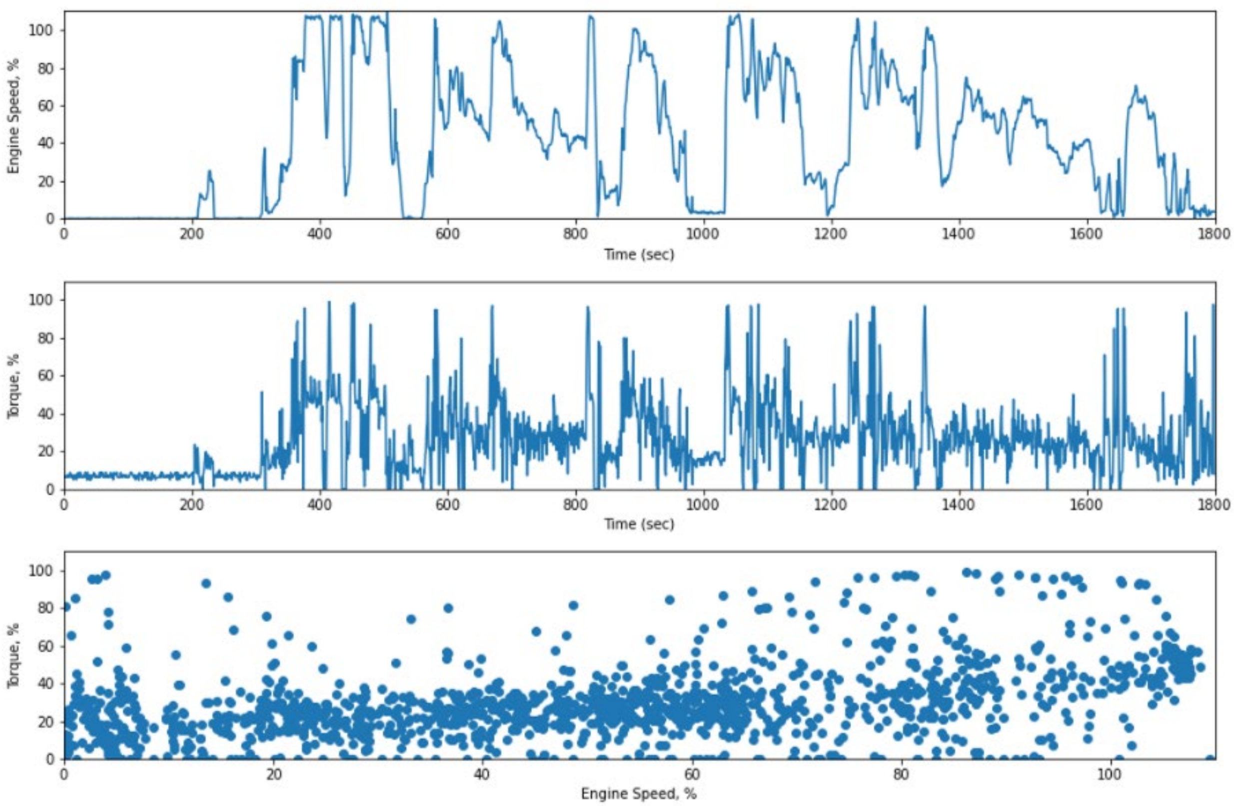

Figure 3-31. Engine Speed % and Torque % for the Duty Cycle for 75<x<175 hp Row Crop Agriculture Tractors

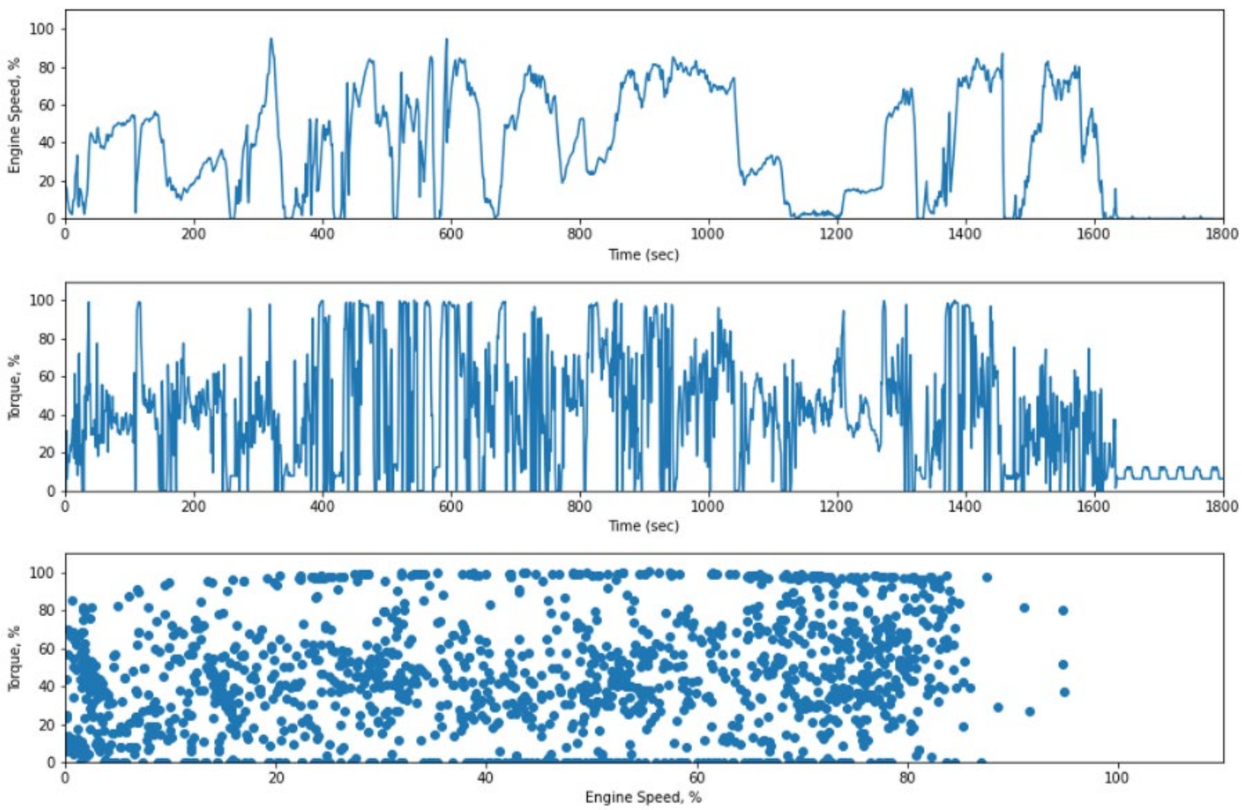

Figure 3-32. Engine Speed % and Torque % for the Duty Cycle for 75<x<175 hp Tree Crop Agriculture Tractors

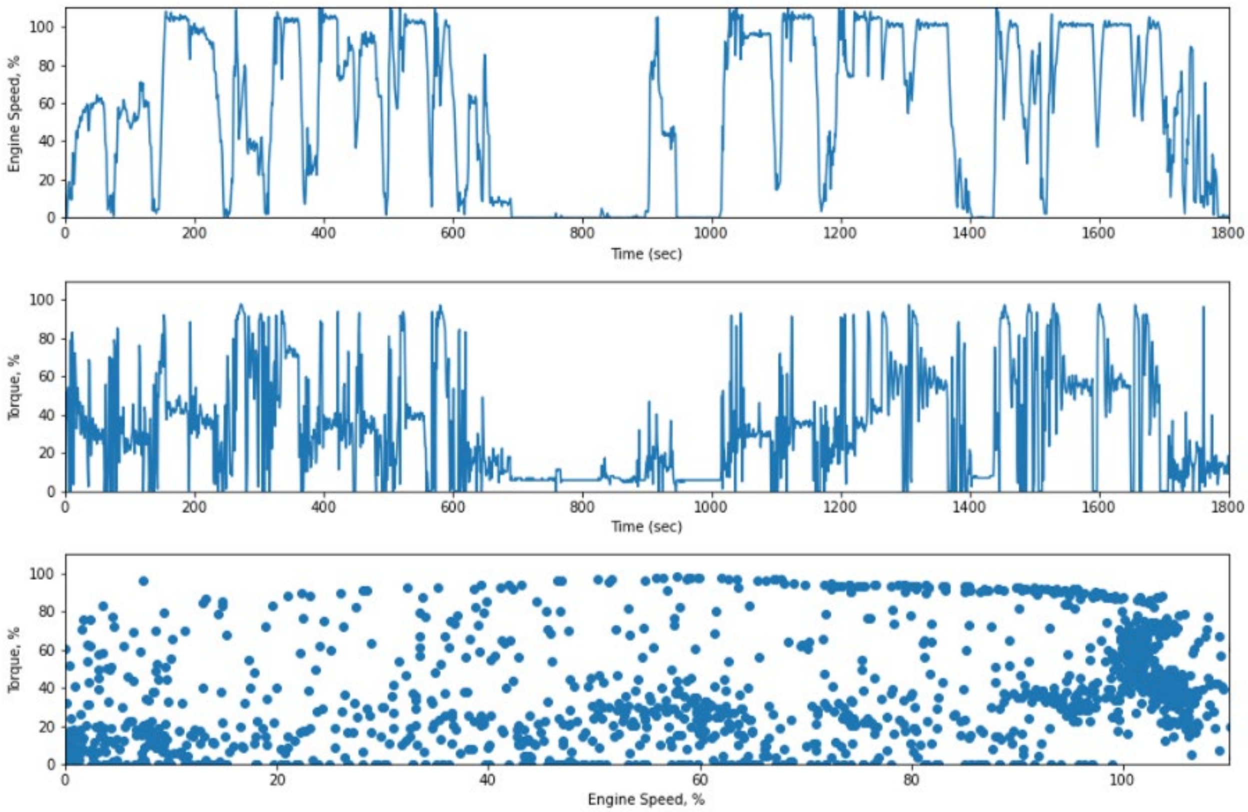

Figure 3-33. Engine Speed % and Torque % for the Duty Cycle for 175<x<300 hp Row Crop Agriculture Tractors

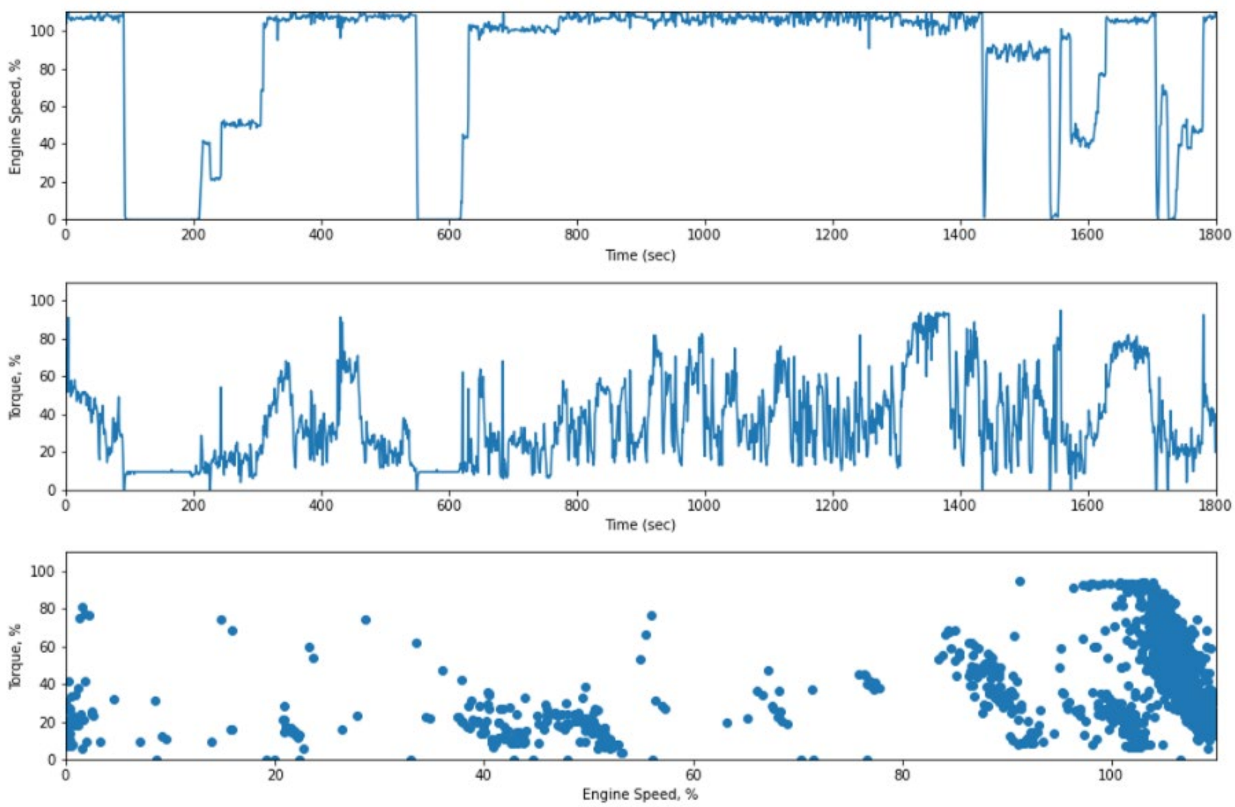

Figure 3-34. Engine Speed % and Torque % for the Duty Cycle for 175<x<300 hp Tree Crop Agriculture Tractors

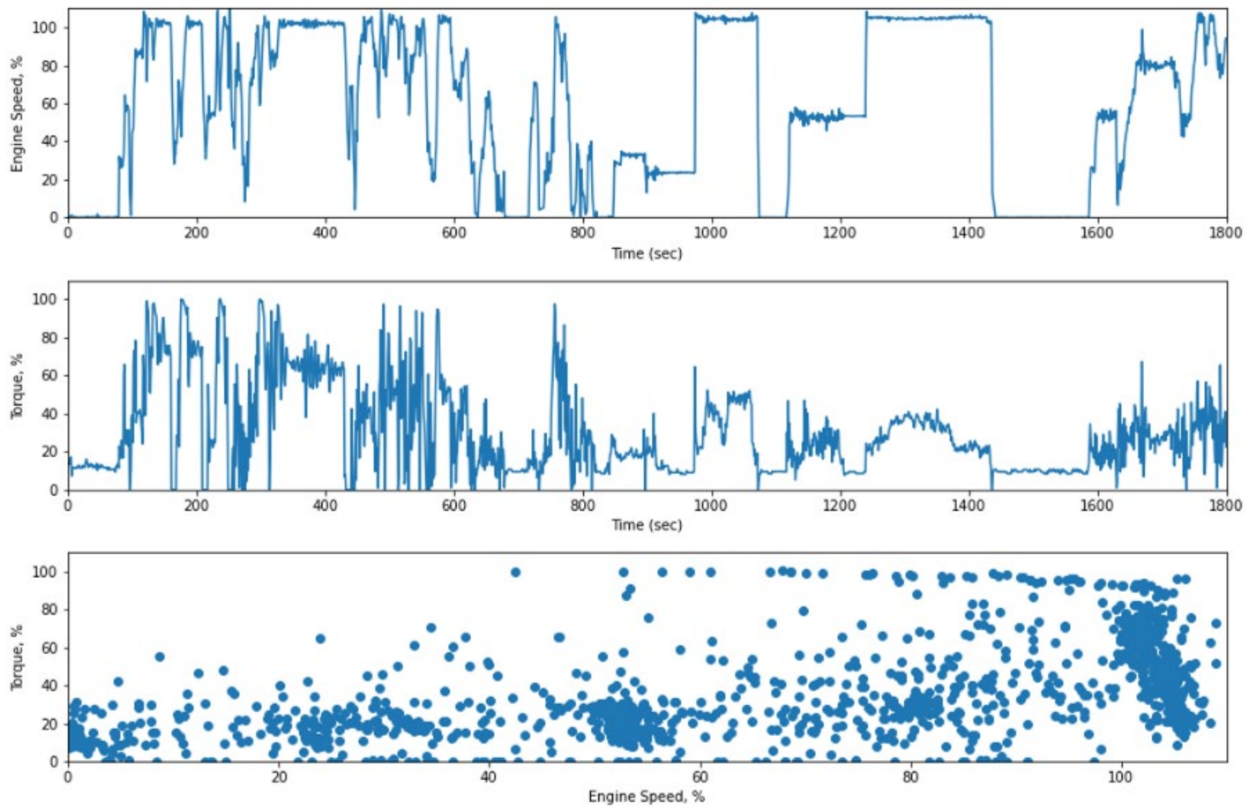

Figure 3-35. Engine Speed % and Torque % for the Duty Cycle for 300<x<650 hp Row Crop Agriculture Tractors

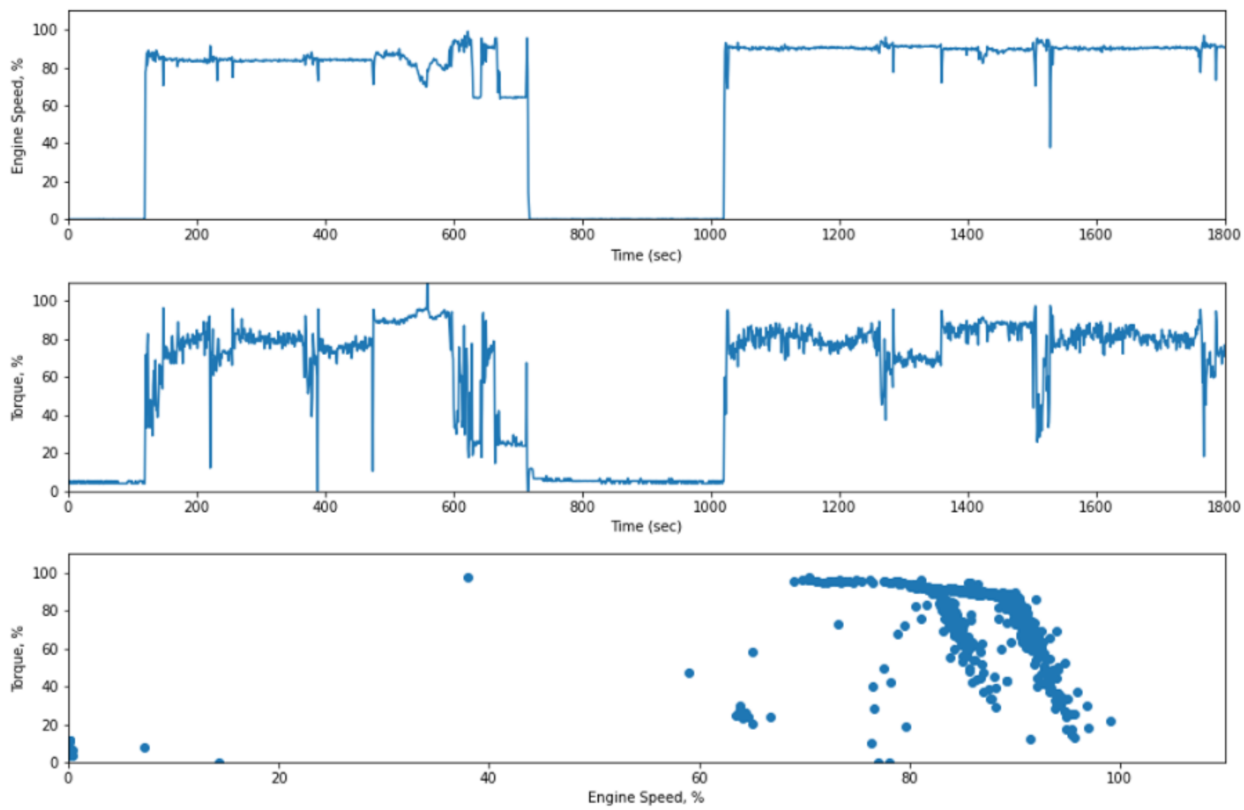

Figure 3-36. Engine Speed % and Torque % for the Duty Cycle for 300<x<650 hp Tree Crop Agriculture Tractors

4. Conclusions

Agriculture is a key industrial sector and employer in California where diesel engines are widely used in the tractors used to plant and harvest crops. In order to understand the impact of these agriculture tractors on air quality in California, it is important to develop accurate inventories of their activity patterns and associated emissions. The objective of this research was to collect real-world activity data from agricultural equipment that could be used to improve the emission inventory and to inform policies and incentive programs in California. For this research, ECU data were collected under actual working conditions related to engine and aftertreatment performance, such as engine load, engine speed, engine torque, fuel economy, and aftertreatment temperatures. Additional data were collected from monitoring the engine hours of tractors to determine their level of use over an annual cycle of agriculture operations. The study results will help ensure that the future development of emission inventories, policies, and incentive programs can reflect more information collected from real-world farm activities.

In total, 208 tractors were monitored through either engine hour records or data loggers, with 103 of these tractors monitored with data loggers. This included 168 Tier 3 and 4 tractors, with 99 monitored with HEM data loggers and 69 monitored from engine hour records. A total of 40 Tier 0 to 2 tractors were monitored, with 36 of these monitored from engine hour records and 4 monitored with HEM data loggers. The tractors monitored for this program came from a total of 22 individual farms.

The results of the data analysis for the agriculture tractors are summarized below:

- The overall average use for all tractors was about 4 hours per day. The data show a few trends of note. The results show that for the newer Tier 3-4 tractors, row crops show higher hours of use per day with the tractors for the row crops averaging about 5 hours per day for the 175-299 hp and 300-650 hp categories, and about 4 hours for the 75-174 hp category. For the tree crops for the Tier 3-4 tractors, the average hours of use per day was about 4 hours for the 175-299 hp and 300-600 hp categories, and 3 hours for the 75-174 hp category. The Tier 1-2 tractors generally showed lower operating hours per day, with averages of around 2.5 hours per day for the 75-174 hp and 1 hour per day for the 175-299 hp categories row crops, but did have higher average hours, at nearly 4 hours per day for the 75-174 hp tree crop tractors.
- The average annual hours of usage were 60 hours, 130 hours, 143 hours, 741 hours, and 739 hours, respectively, for Tier 0, Tier 1, Tier 2, Tier 3, and Tier 4 tractors. The Tier 3 and Tier 4 tractors showed similar patterns of annual use. The results show that there is a large drop-off in annual engine hours for the older Tier 0 and 1 equipment, with a much smaller drop-off for the Tier 2 tractors.
- Typical average loads for the tractors are similar, as a function of the engine's hp level. The data show relatively consistent load levels with the loads between 22 and 35% for the different tractor categories, with an overall average load percent of 28%. The data did not show significant differences between tractors for tree or row crops, or for different engine hp categories. It should be noted that the average load factors include idle time, so it does not necessarily represent the typical load for tractor during the working portion of their operation.

- Fuel consumption data showed a positive upward trend in fuel use in gals/hour as a function of increasing hp, as expected. The trend lines between the Tier 3 and 4 tractors and the Tier 2 tractors were comparable, but the data available for the older tractors was limited and only for lower hp tractors. Average daily fuel use rates were 20 gallons per day, with a maximum of about 40 gallons per day for the 300-650 hp categories, while tractors in the below 175 hp category had fuel use rates below 10 gallons per day. Average fuel use rates were 4.2 gallons per hour, with a maximum of about 8 gallons per hour for the 300-650 hp categories, while tractors in the below 175 hp categories had fuel use rates of about 2 gallons per hour. Additional measurements for fuel consumption for four Tier 0 to Tier 2 tractors were also conducted by manually measuring fuel consumption over the period of a day. These tractors ranged in size from 76 to 105 hp, and showed fuel consumption ranging from 1.5 to 1.9 gals/hr, consistent with the results seen over longer periods of time for data collected by the data loggers.
- Average DPF outlet temperatures for the tree and row crops and the different hp categories were similar. The average DPF outlet temperatures were at or above 250°C category for both the tree and row crops and for all of the different hp categories. Frequency distributions of DPF outlet temperatures show that that the DPF outlet temperature is above 200°C for 78.5% of the operational time, which in turn suggests that for 21.5% of the operating time, the DPF outlet temperature would not be sufficiently high to allow for the injection of urea into the SCR.
- Average idle times are relatively consistent for different crops (tree and row) and the engine power ratings. The overall average idle percentage was 26%. Across the engine power ratings, idle emissions showed a range from 23% to 28% for most power ratings, with some higher and lower exceptions.
- The average number of starts per day was approximately 3.4 starts, with a range from slightly less than 2 to 5 starts per day. Hot starts (with soak durations ≥ 30 seconds and ≤ 60 minutes) represented the highest fraction of starts per day, with an average of approximately 2.2 hot starts per day, with a range from < 1 to slightly greater than 3 hot starts between the different categories. The number of intermediate starts (with soak durations ≥ 60 minutes and ≤ 720 minutes) was on average about 0.4 per day, with the number of intermediate starts averaging 0.5 per day or less for all categories. The average hot start soak duration was approximately 15 minutes, with a range from approximately 10 to 20 minutes between different categories. The average intermediate start soak duration was approximately 200 minutes, with a range from approximately 150 to 250 minutes between different categories.
- The in-use activity data covers a much broader range of operating conditions than are found in the certification cycles. In general, the distributions for the in-use data show that there could be a more significant contribution at low load conditions than is captured in the certification cycles.
- As next steps, we recommend that air quality agencies consider these findings alongside other datasets to update official emissions inventories and other data used to support air quality programs, such as FARMER. Specifically, such agencies should consider longitudinal assessments using this study design to assess long-term trends of the in-use agricultural fleet. For example, follow-up studies could assess how the distribution of engine loads and idling times measured today change for the in-use fleet of agricultural equipment in the 2030 timeframe. Near-term, CARB should consider supplementing

results of this study using a broader survey collecting information on the distribution of engine population by tier and annual activity levels of such equipment. Overall, the assessment of 208 pieces of equipment in this study, and particularly the subset that had real-time activity logged during the study, provides a strong foundation upon which CARB and other air quality agencies can construct updates to their emissions inventories and inform incentive and other air quality programs.

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Appendix A. Equipment Data Collection Sheet

Equipment Type	
Year/Make/Model	/ /
Type of fuel (diesel, biodiesel, renewable diesel, other specify)	
HP	
Tier (1, 2, 3, 4)	
After-Treatment Configuration	
Engine Serial Number	
Main tractor tasks (cultivation, transport, pruning etc.)	
Main crop that the tractor will be used for	
Approximate Original Equipment Cost	

The information collected under this Survey Form and any associated data logging, such as the Agency name, Address, Contact Person and Phone Number/Email, is considered under this CARB Contract to be Personally Identifiable Information and protected by California Civil Code Sections 1798, et seq. and shall not be disclosed unless required by law. Please confirm that you acknowledge that the information provided under this survey will be deidentified and utilized by the university in reports and publications, in order to meet the university's contractual obligations with CARB. □ I accept.

Equipment Information
Tractor and Engine Related Documentation (photos)

□	1	Fleet equipment ID
□	2	Vehicle
□	2a	Front right angle
□	2b	Front left angle
□	2c	Rear right angle
□	2d	Rear left angle
□	3	OBD connection
□	4	HEM logger ID
□	5	Engine Hours

□	6	Tire type
□	7	SCR tank cap
□	8	Engine and Vehicle Labels
□	8a	Engine family
□	8b	Emissions control equipment
□	8c	Rated engine information
□	8d	In Vehicle Labels
□	9	Engine body
□	10	HEM Installation

Agricultural Operation Information

Tractor ID

Comments	Crop	Agricultural Operation	Tool Attachments	Soil Type	Date start	Date end	Acres (per day)	Acres (per month)

Month 3 Odometer (with picture) _______________

Service records Maintenance Type:

Maintenance Frequency:

Cost:

Length of time non-operational:

Month 6 Odometer (with picture) _______________

Service records Maintenance Type:

Maintenance Frequency:

Cost:

Length of time non-operational:

Month 9 Odometer (with picture) _______________

Service records Maintenance Type:

Maintenance Frequency:

Cost:

Length of time non-operational:

Month 12 Odometer (with picture) _______________

Service records Maintenance Type:

Maintenance Frequency:

Cost:

Length of time non-operational:

Comments:

Appendix B. ECU Parameters for Agriculture Tractors

Table B-1. ECU Parameters for Agriculture Tractors.

Column Index	Parameter Name	Source
1	Time	HEM Logger
2	File	CE-CERT
3	VehNum	CE-CERT
4	Accelerator_Pedal_Position_1_per	ECU
5	Eng_Percent_Load_At_Current_Speed_per	ECU
6	DPF_Thermal_Management_Act_bit	ECU
7	SCR_Thermal_Management_Act_bit	ECU
8	Actual_Maximum_Available_Eng_Percent_Torque_per	ECU
9	Actual_Eng_Percent_Torque_513_per	ECU
10	Eng_Speed_190_rpm	ECU
11	Trans_Actual_Gear_Ratio_Ratio	ECU
12	ATS_1_DEF_Actual_Dosing_Quantity_g_h	ECU
13	ATS_1_SCR_Sys_1_State_bit	ECU
14	ATS_1_DEF_Actual_Quantity_of_Integrator_g	ECU
15	ATS_1_DEF_Doser_1_Abs_Pressure_kPa	ECU
16	ATS_1_DEF_Actual_Dosing_Quantity_High_Range_g_min	ECU
17	ATS_DPF_Passive_Regen_Stat_bit	ECU
18	ATS_DPF_Act_Regen_Stat_bit	ECU
19	ATS_DPF_Stat_bit	ECU
20	DPF_Act_Regen_Inhib_Due_to_Low_Exhaust_Temp_bit	ECU
21	DPF_Act_Regen_Forced_Stat_bit	ECU
22	ATS_1_DPF_Conditions_Not_Met_for_Act_Regen_bit	ECU
23	ATS_1_DPF_Intermediate_Temp_3250_C	ECU
24	ATS_1_DPF_Diff_Pressure_3251_kPa	ECU
25	ATS_1_DPF_Outlet_Temp_C	ECU
26	ATS_1_Exhaust_Temp_1_3241_C	ECU
27	ATS_1_DPF_Intake_Temp_3242_C	ECU
28	ATS_1_DEF_Tank_Volume_per	ECU
29	ATS_1_DEF_Tank_Temp_1_C	ECU
30	ATS_DEF_Tank_Low_Level_Indicator_bit	ECU
31	ATS_SCR_Operator_Inducement_Severity_bit	ECU
32	Eng_Intake_Manifold_1_Temp_High_Res_C	ECU
33	Fan_Drive_State_bit	ECU
34	Nominal_Friction_Percent_Torque_per	ECU
35	Engines_Desired_Operating_Speed_rpm	ECU
36	Engines_Desired_Operating_Speed_Asymmetry_Adjustment_Ratio	ECU
37	Estimated_Eng_Parasitic_Losses_Percent_Torque_per	ECU
38	ATS_1_Exhaust_Gas_Mass_Flow_Rate_kg_h	ECU
39	Eng_Percent_Torque_At_Idle_Point_1_per	ECU
40	Eng_Percent_Torque_At_Point_2_per	ECU
41	Eng_Percent_Torque_At_Point_3_per	ECU
42	Eng_Percent_Torque_At_Point_4_per	ECU
43	Eng_Percent_Torque_At_Point_5_per	ECU

44	Eng_Reference_Torque_Nm	ECU
45	Eng_Moment_of_Inertia_kgm	ECU
46	Eng_Default_Torque_Limit_Nm	ECU
47	Eng_Total_Hours_of_Operation_h	ECU
48	Eng_Total_Revolutions_r	ECU
49	Total_Veh_Hours_h	ECU
50	Eng_Coolant_Temp_C	ECU
51	Eng_Fuel_1_Temp_1_C	ECU
52	Eng_Oil_Temp_1_C	ECU
53	Eng_Fuel_Rate_l_h	ECU
54	Eng_Instantaneous_Fuel_Economy_km_L	ECU
55	Eng_Throttle_Valve_1_Position_1_per	ECU
56	Barometric_Pressure_kPa	ECU
57	Cab_Interior_Temp_C	ECU
58	Ambient_Air_Temp_C	ECU
59	Eng_Intake_Manifold_num1_Pressure_kPa	ECU
60	Eng_Intake_Manifold_1_Temp_C	ECU
61	Eng_Intake_Air_Pressure_kPa	ECU
62	Eng_Exhaust_Temp_C	ECU
63	Battery_Potential_Power_Input_1_V	ECU
64	Fuel_Level_1_per	ECU
65	calculated_power_kw	CE-CERT
66	Eng_Fuel_Rate_gal_h	ECU (Converted Units)

Appendix C. Test Cycle Information

Traditional Engine Dynamometer Test Cycles

Engine dynamometer test cycles represent the gold standard to which off-road and on-highway engines are certified to for emissions compliance prior to sale. For engine dynamometer testing, cycles are typically defined in terms of a normalized engine speed and a normalized engine torque % that can be translated into actual engine speed and torque values using an engine map that is specific for each engine. The normalized engine speed is defined as a percentage for the engine speed between the engine idle speed and that maximum speed from the engine map. The normalized engine torque is defined as the percentage of the maximum torque at the given engine speed, as determined from the engine map.

For off-road equipment, the standard transient cycle that is used for testing is the non-road transient cycle (NRTC) [Dieselnet, 2024a]. The NRTC contains a series of transient modes, and is designed to closely match engine work during normal operation. The cycle is 1,238 seconds in duration, which is defined based on normalized engine speed and torque as depicted in Figure C-1. 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. The NRTC was based on segments of activity that were representative of a broad range of equipment types, including backhoe loaders, rubber-tire loaders, crawler dozers, agricultural tractors, excavators, arc welders, and skid steer loaders. A breakdown of how the individual segments is provided in Table C-1.

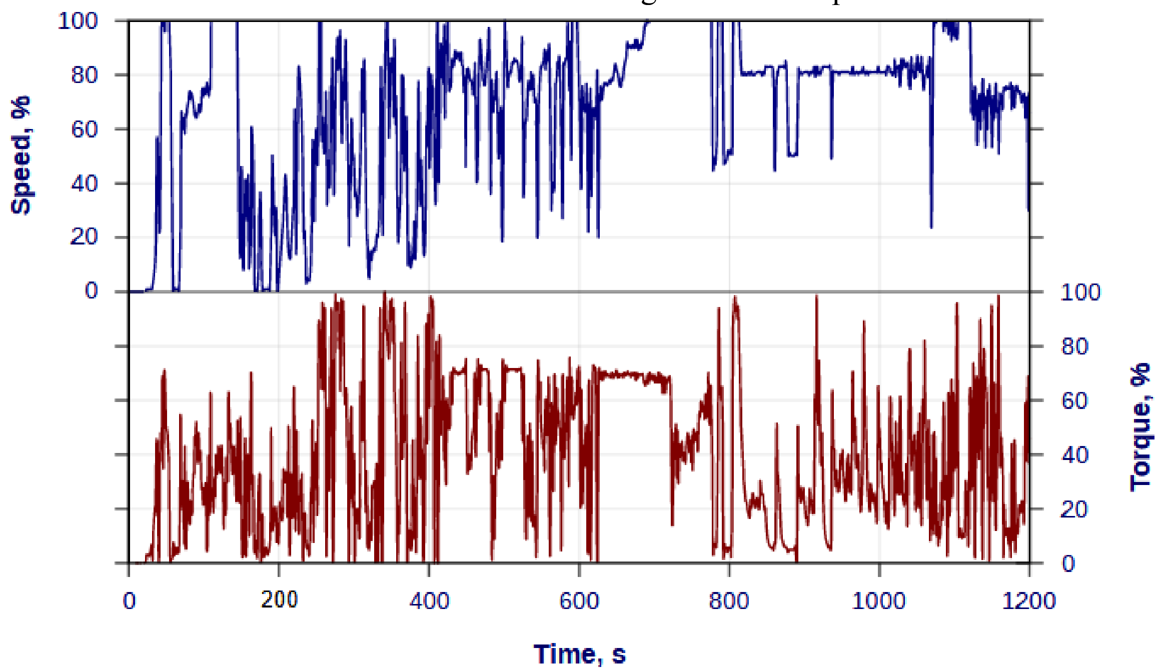


Figure C-1. Non-road transient cycle (NRTC)

Table C-1. Description of the Individual Segments of the NRTC Cycle

Supplemental NRTC (Nonroad Transient Composite) Cycle

Application Number	Nonroad Application	Application Duration (seconds)	Application in Cycle Position (#seconds)	Segments from Application Cycle (#seconds)	Segment Name	Segment Duration (seconds)	Cumulative Cycle Time (seconds)	Segment in Cycle Position (#seconds)
					Start/Transition	28	28	0-28
1	Backhoe Loader	206	29-234	52-86	Roading	35	63	29-63
				108-141	Trenching	34	97	64-97
				174-218	Loading	45	142	98-142
				351-442	Grade/Level	92	234	143-234
2	Rubber-Tire Loader	184	235-418	746-822	Typical Operation	77	311	235-311
				531-637	Hi-Spd Transient	107	418	312-418
3	Crawler-Dozer	209	419-627	85-206	Road Bed Prep	122	540	419-540
				376-462	Clearing	87	627	540-627
4	Agricultural Tractor	150	628-777	265-414	AgTractor	150	777	628-777
5	Excavator	35	778-812	319-338	LowerHp (128Hp)	20	797	778-797
				431-445	HigherHp (208Hp)	15	812	798-812
					Transition	3	815	813-815
6	Arc Welder	204	816-1019	1007-1103	Typical Operation	97	912	816-912
				544-650	Hi-Spd Transient	107	1019	913-1019
7	Skid Steer Loader	185	1020-1204	264-365	Typical Operation	102	1121	1020-1121
				150-232	Hi-Trq Transient	83	1204	1122-1204
					Idle/Transition/End	34	1238	1215-1238

Steady state cycles are also used during the certification process for non-road engines. 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 State Cycle (NRSC). The engine speed and torque levels that make up of the 8-mode cycle are given in Table 2-3. Also given in Table C-2 are weighting factors, which are used to weight the measured emissions in each mode.

Table C-2. 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	-	0.15

Appendix D. Additional Activity Data Analysis

Section D-1. Summary Tables for Agriculture Tractors Statistics.

Average Daily Use (hr)

Crops	HP Group	Tier Group	Count	Average	Median	Stdev	Avg-Stdev	Avg+Stdev
Row	<50	Tier 3-4	1	5.59	5.59	0	5.59	5.59
Row	75-174	Tier 1-2	2	2.64	2.64	0.16	2.48	2.8
Row	75-174	Tier 3-4	24	3.76	3.3	1.94	1.82	5.7
Row	175-299	Tier 1-2	1	1.08	1.08	0	1.08	1.08
Row	175-299	Tier 3-4	19	4.85	5.14	2.43	2.42	7.28
Row	300-650	Tier 3-4	23	5.16	5.32	1.62	3.54	6.79
Row	All HP	All Tiers	70	4.47	4.67	2.07	2.4	6.54
Tree	<50	Tier 3-4	0	-	-	-	-	-
Tree	75-174	Tier 1-2	1	3.79	3.79	0	3.79	3.79
Tree	75-174	Tier 3-4	18	2.94	3.04	1.48	1.46	4.42
Tree	175-299	Tier 1-2	0	-	-	-	-	-
Tree	175-299	Tier 3-4	5	4.03	3.68	1.49	2.54	5.52
Tree	300-650	Tier 3-4	7	3.98	4.43	2.63	1.35	6.61
Tree	All HP	All Tiers	31	3.38	3.26	1.79	1.59	5.17
All Crops	<50	Tier 3-4	1	5.59	5.59	0	5.59	5.59
All Crops	75-174	Tier 1-2	3	3.02	2.75	0.67	2.35	3.7
All Crops	75-174	Tier 3-4	42	3.41	3.25	1.79	1.62	5.19
All Crops	175-299	Tier 1-2	1	1.08	1.08	0	1.08	1.08
All Crops	175-299	Tier 3-4	24	4.68	4.82	2.26	2.42	6.94
All Crops	300-650	Tier 3-4	30	4.89	5.08	1.92	2.97	6.81
All Crops	All HP	All Tiers	101	4.14	3.91	2.04	2.09	6.18

Average Load (%)

Crops	HP Group	Tier Group	Count	Average	Median	Stdev	Avg-Stdev	Avg+Stdev
Row	<50	Tier 3-4	0	-	-	-	-	-
Row	75-174	Tier 1-2	0	-	-	-	-	-
Row	75-174	Tier 3-4	21	22.09	22.49	8.57	13.52	30.66
Row	175-299	Tier 1-2	0	-	-	-	-	-
Row	175-299	Tier 3-4	17	26.41	22.75	9.52	16.89	35.93
Row	300-650	Tier 3-4	23	32.4	32.88	8.64	23.76	41.04
Row	All HP	All Tiers	61	27.18	25.65	9.78	17.4	36.96
Tree	<50	Tier 3-4	0	-	-	-	-	-
Tree	75-174	Tier 1-2	0	-	-	-	-	-
Tree	75-174	Tier 3-4	18	29.27	28.12	10.03	19.23	39.3
Tree	175-299	Tier 1-2	0	-	-	-	-	-
Tree	175-299	Tier 3-4	4	29.03	26.15	6.26	22.77	35.3
Tree	300-650	Tier 3-4	7	35.12	32.74	13.16	21.96	48.28
Tree	All HP	All Tiers	29	30.65	28.09	10.44	20.21	41.09
All Crops	<50	Tier 3-4	0	-	-	-	-	-
All Crops	75-174	Tier 1-2	0	-	-	-	-	-
All Crops	75-174	Tier 3-4	39	25.4	25.08	9.84	15.56	35.24
All Crops	175-299	Tier 1-2	0	-	-	-	-	-
All Crops	175-299	Tier 3-4	21	26.91	25.6	8.91	18	35.82
All Crops	300-650	Tier 3-4	30	33.03	32.81	9.69	23.35	42.72
All Crops	All HP	All Tiers	90	28.3	26.67	10.07	18.23	38.37

Average Daily Fuel Use (gal)

Crops	HP Group	Tier Group	Count	Average	Median	Stdev	Avg-Stdev	Avg+Stdev
Row	<50	Tier 3-4	1	3.91	3.91	0	3.91	3.91
Row	75-174	Tier 1-2	2	7.16	7.16	3.61	3.55	10.77
Row	75-174	Tier 3-4	24	8.19	6.78	5.83	2.36	14.03
Row	175-299	Tier 1-2	1	0	0	0	0	0
Row	175-299	Tier 3-4	19	17.36	14.87	14.85	2.51	32.2
Row	300-650	Tier 3-4	23	42.55	34.35	23	19.55	65.55
Row	All HP	All Tiers	70	21.76	14.32	21.65	0.11	43.41

Tree	<50	Tier 3-4	0	-	-	-	-	-
Tree	75-174	Tier 1-2	1	5.45	5.45	0	5.45	5.45
Tree	75-174	Tier 3-4	18	6.87	7.17	4.37	2.5	11.24
Tree	175-299	Tier 1-2	0	-	-	-	-	-
Tree	175-299	Tier 3-4	5	16.4	14.76	7.77	8.63	24.17
Tree	300-650	Tier 3-4	7	46.84	19.47	45.49	1.34	92.33
Tree	All HP	All Tiers	31	17.39	8.19	26.58	-9.19	43.96

All Crops	<50	Tier 3-4	1	3.91	3.91	0	3.91	3.91
All Crops	75-174	Tier 1-2	3	6.59	5.45	2.73	3.86	9.32
All Crops	75-174	Tier 3-4	42	7.63	6.91	5.24	2.39	12.87
All Crops	175-299	Tier 1-2	1	0	0	0	0	0
All Crops	175-299	Tier 3-4	24	17.16	14.81	13.53	3.63	30.69
All Crops	300-650	Tier 3-4	30	43.55	34.03	28.86	14.69	72.41
All Crops	All HP	All Tiers	101	20.42	11.18	23.23	-2.81	43.65

Fuel Use (gal/hr)

Crops	HP Group	Tier Group	Count	Average	Median	Stdev	Avg-Stdev	Avg+Stdev
Row	<50	Tier 3-4	1	0.7	0.7	0	0.7	0.7
Row	75-174	Tier 1-2	2	2.75	2.75	1.53	1.22	4.28
Row	75-174	Tier 3-4	24	1.99	1.96	0.75	1.24	2.74
Row	175-299	Tier 1-2	0	-	-	-	-	-
Row	175-299	Tier 3-4	19	3.47	3.09	1.46	2.01	4.93
Row	300-650	Tier 3-4	23	7.72	7.15	2.84	4.88	10.56
Row	All HP	All Tiers	69	4.31	3.19	3.11	1.2	7.42

Tree	<50	Tier 3-4	0	-	-	-	-	-
Tree	75-174	Tier 1-2	1	1.44	1.44	0	1.44	1.44
Tree	75-174	Tier 3-4	18	2.11	2.24	0.79	1.32	2.9
Tree	175-299	Tier 1-2	0	-	-	-	-	-
Tree	175-299	Tier 3-4	5	4.1	3.8	1.35	2.75	5.45
Tree	300-650	Tier 3-4	7	8.65	6.49	5.68	2.96	14.33
Tree	All HP	All Tiers	31	3.88	2.56	3.8	0.08	7.68

All Crops	<50	Tier 3-4	1	0.7	0.7	0	0.7	0.7
All Crops	75-174	Tier 1-2	3	2.31	1.67	1.32	0.99	3.63
All Crops	75-174	Tier 3-4	42	2.04	1.99	0.76	1.28	2.8
All Crops	175-299	Tier 1-2	0	-	-	-	-	-
All Crops	175-299	Tier 3-4	24	3.6	3.5	1.43	2.17	5.03
All Crops	300-650	Tier 3-4	30	7.94	7.06	3.6	4.33	11.54
All Crops	All HP	All Tiers	100	4.18	2.94	3.33	0.85	7.51

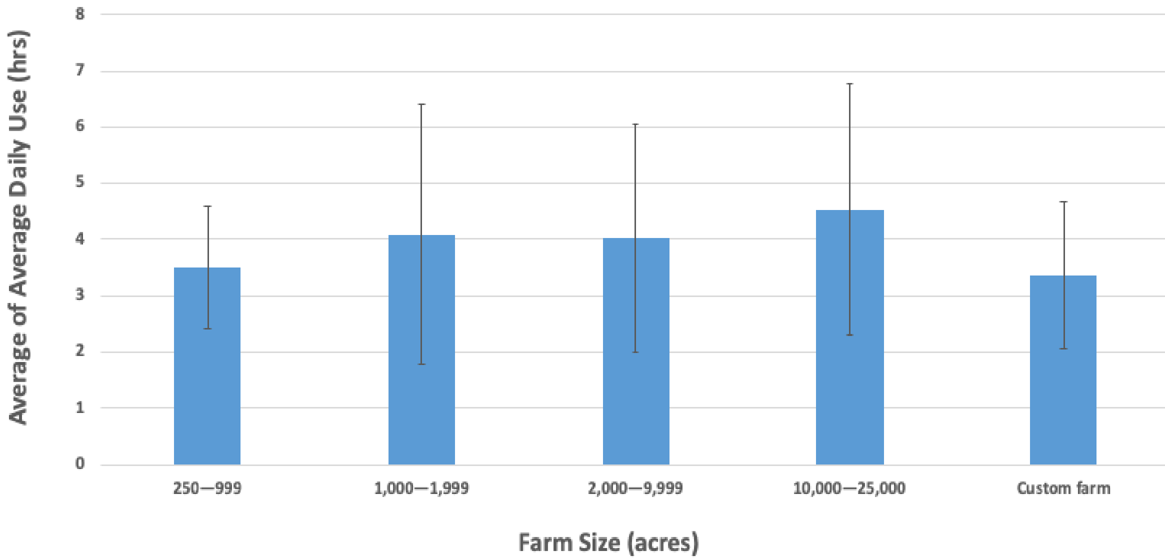
Average Outlet DPR (°C)

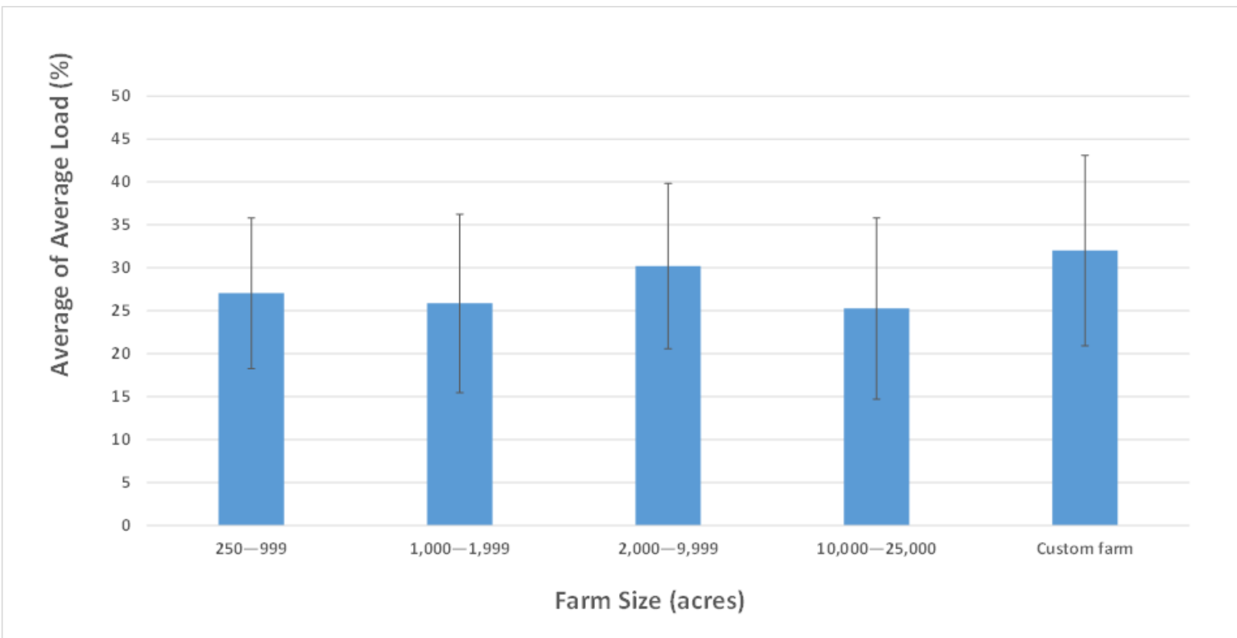
Crops	HP Group	Tier Group	Count	Average	Median	Stdev	Avg-Stdev	Avg+Stdev
Row	<50	Tier 3-4	0	-	-	-	-	-
Row	75-174	Tier 1-2	0	-	-	-	-	-
Row	75-174	Tier 3-4	9	254.21	264.2	26.76	227.45	280.98
Row	175-299	Tier 1-2	0	-	-	-	-	-
Row	175-299	Tier 3-4	12	268.4	272.29	26.39	242.01	294.8
Row	300-650	Tier 3-4	20	302.35	297.33	37.7	264.64	340.05
Row	All HP	All Tiers	41	281.85	278.16	38.03	243.82	319.87
Tree	<50	Tier 3-4	0	-	-	-	-	-
Tree	75-174	Tier 1-2	0	-	-	-	-	-
Tree	75-174	Tier 3-4	7	249.46	272.86	83.09	166.38	332.55
Tree	175-299	Tier 1-2	0	-	-	-	-	-
Tree	175-299	Tier 3-4	4	270.49	266.25	14.84	255.65	285.33
Tree	300-650	Tier 3-4	7	279.81	288.1	80.64	199.17	360.46
Tree	All HP	All Tiers	18	265.94	277.3	70.47	195.46	336.41
All Crops	<50	Tier 3-4	0	-	-	-	-	-
All Crops	75-174	Tier 1-2	0	-	-	-	-	-
All Crops	75-174	Tier 3-4	16	252.14	266.67	56.12	196.02	308.25
All Crops	175-299	Tier 1-2	0	-	-	-	-	-
All Crops	175-299	Tier 3-4	16	268.93	270.88	23.57	245.35	292.5
All Crops	300-650	Tier 3-4	27	296.5	296.84	51.39	245.12	347.89
All Crops	All HP	All Tiers	59	276.99	278.16	50.08	226.92	327.07

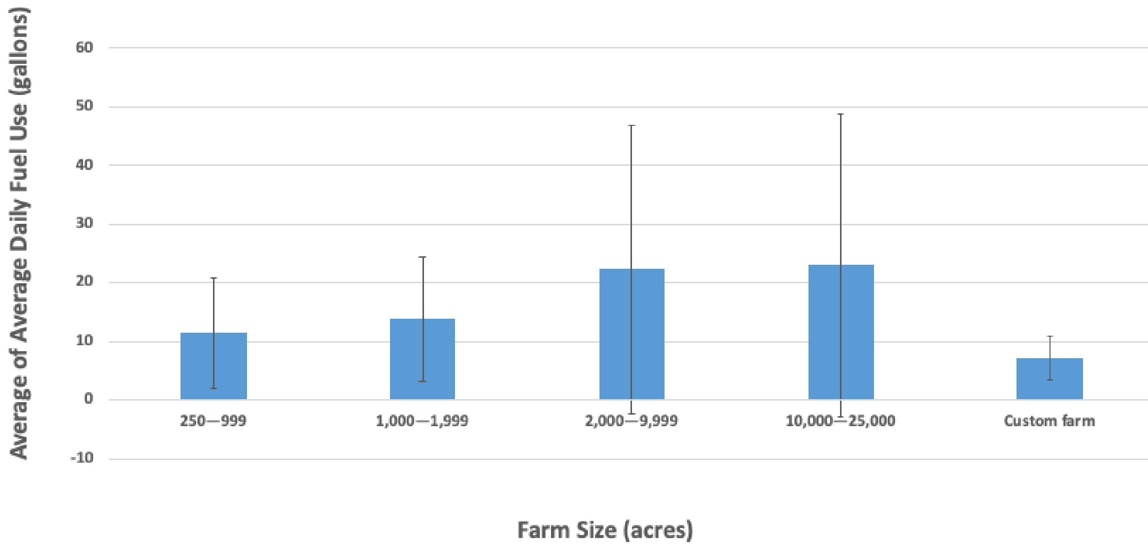
Average Daily Idle (%)

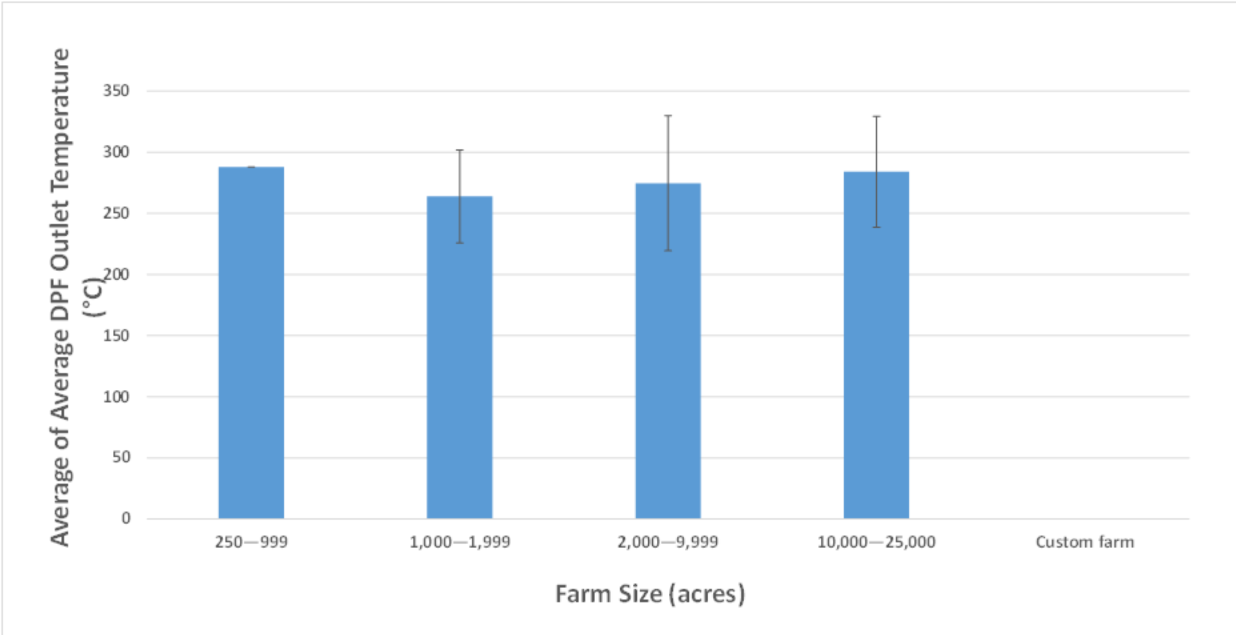
Crops	HP Group	Tier Group	Count	Average	Median	Stdev	Avg-Stdev	Avg+Stdev
Row	<50	Tier 3-4	1	14.08	14.08	0	14.08	14.08
Row	75-174	Tier 1-2	2	11.59	11.59	1.53	10.06	13.13
Row	75-174	Tier 3-4	24	28.12	28.79	11.54	16.58	39.66
Row	175-299	Tier 1-2	1	63.91	63.91	0	63.91	63.91
Row	175-299	Tier 3-4	19	27.36	26.24	12.94	14.42	40.31
Row	300-650	Tier 3-4	23	23.23	24.94	7.15	16.09	30.38
Row	All HP	All Tiers	70	26.15	26.34	11.74	14.4	37.89
Tree	<50	Tier 3-4	0	-	-	-	-	-
Tree	75-174	Tier 1-2	1	25.17	25.17	0	25.17	25.17
Tree	75-174	Tier 3-4	18	24.56	22.7	15.49	9.07	40.06
Tree	175-299	Tier 1-2	0	-	-	-	-	-
Tree	175-299	Tier 3-4	5	22.77	24.26	12.69	10.08	35.46
Tree	300-650	Tier 3-4	7	24.62	23.18	14.33	10.3	38.95
Tree	All HP	All Tiers	31	24.31	23.47	14.11	10.2	38.41
All Crops	<50	Tier 3-4	1	14.08	14.08	0	14.08	14.08
All Crops	75-174	Tier 1-2	3	16.12	12.68	7.91	8.21	24.03
All Crops	75-174	Tier 3-4	42	26.59	26.3	13.32	13.27	39.91
All Crops	175-299	Tier 1-2	1	63.91	63.91	0	63.91	63.91
All Crops	175-299	Tier 3-4	24	26.4	25.66	12.76	13.65	39.16
All Crops	300-650	Tier 3-4	30	23.56	23.49	9.03	14.53	32.59
All Crops	All HP	All Tiers	101	25.58	25.17	12.47	13.11	38.06

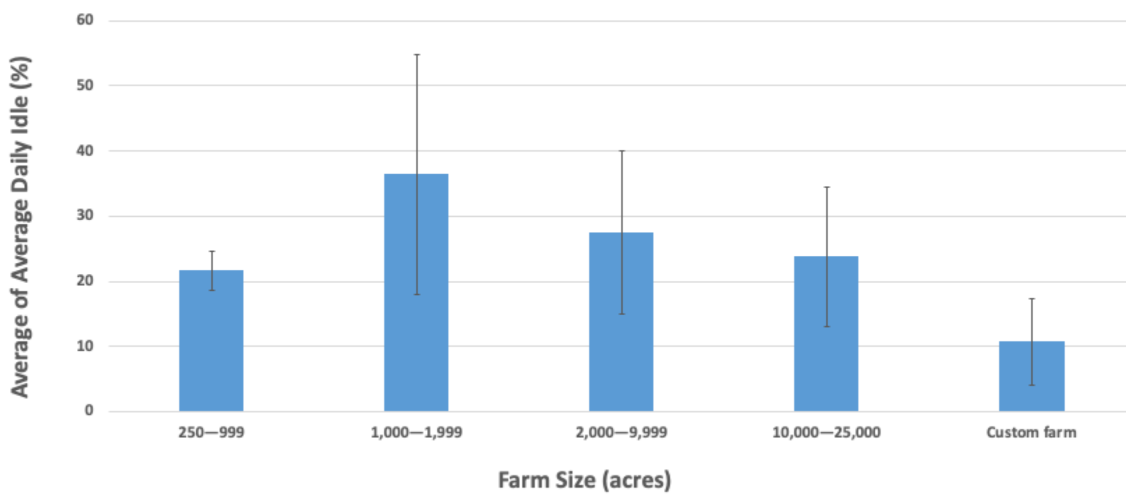
Section D-2. Figures of Activity Statistics as a Function of Farm Size



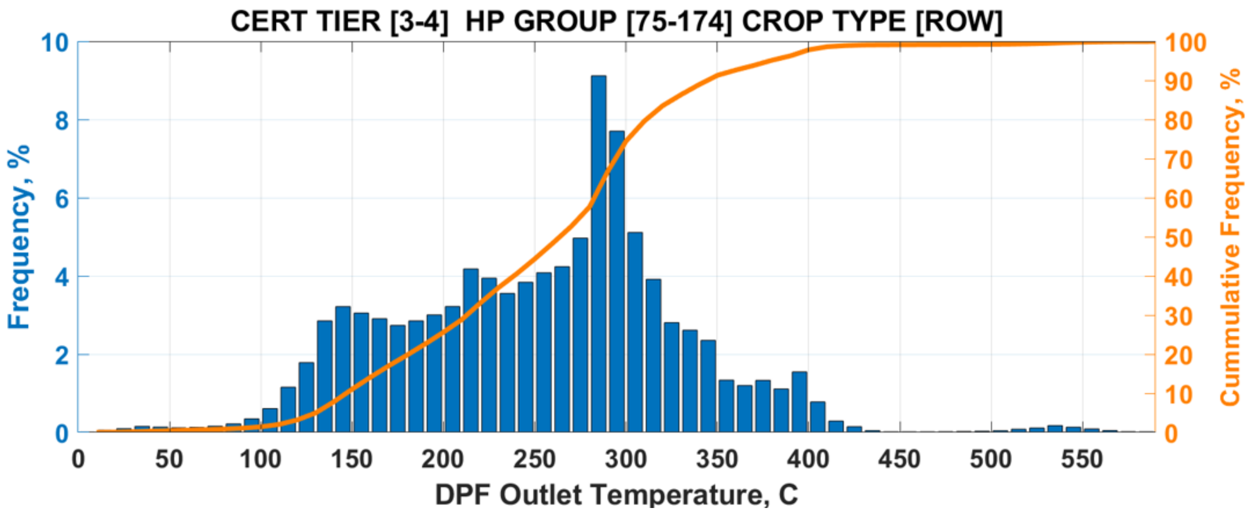


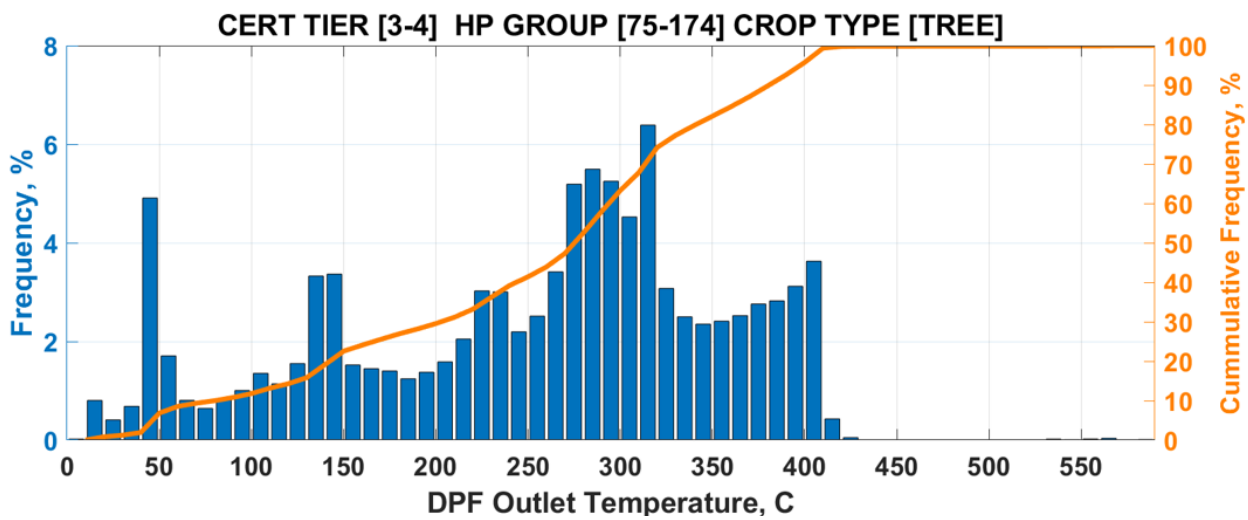

Average of Average Daily Fuel Use (gallons)
60
50
40
30
20
10
0
-10
250—999
1,000—1,999
2,000—9,999
10,000—25,000
Custom farm
Farm Size (acres)

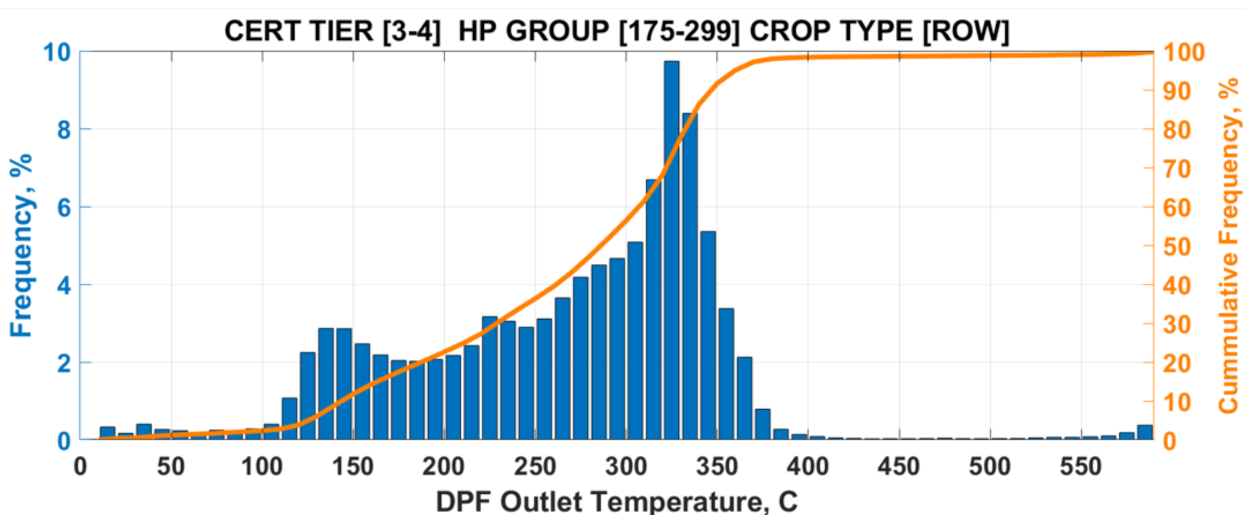

Average of Average DPF Outlet Temperature (°C)
350
300
250
200
150
100
50
0
250—999
1,000—1,999
2,000—9,999
10,000—25,000
Custom farm
Farm Size (acres)

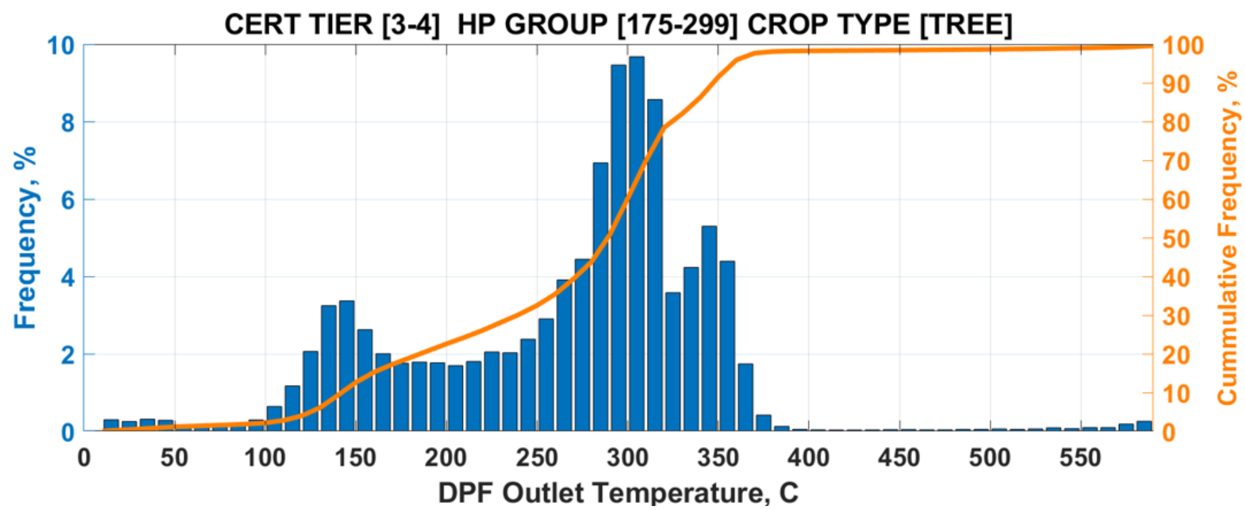

Average of Average Daily Idle (%)
60
50
40
30
20
10
0
250—999
1,000—1,999
2,000—9,999
10,000—25,000
Custom farm
Farm Size (acres)

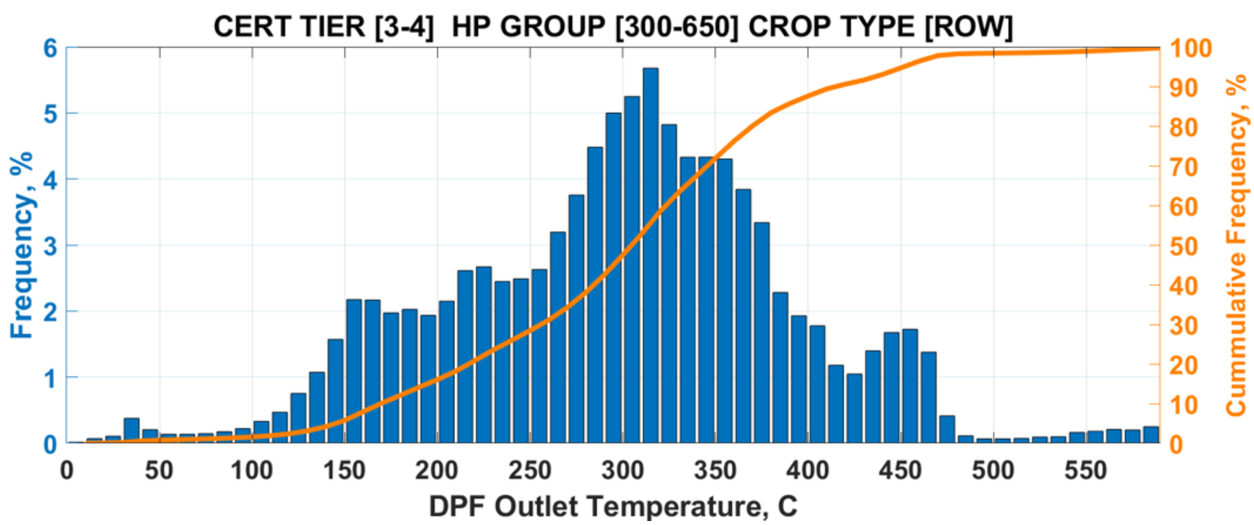
Section D-3. DPF Outlet Temperature Profiles for Different Crop Types and hp ratings

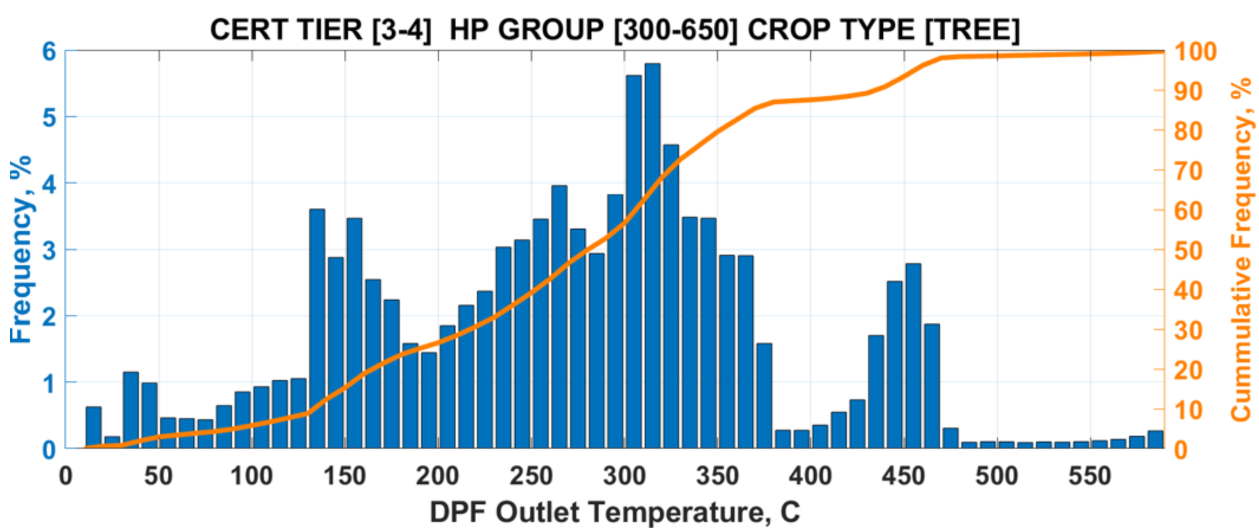







CERT TIER [3-4] HP GROUP [175-299] CROP TYPE [TREE]
Frequency, %
Cummulative Frequency, %
DPF Outlet Temperature, C
0
50
100
150
200
250
300
350
400
450
500
550
0
2
4
6
8
10
0
10
20
30
40
50
60
70
80
90
100


CERT TIER [3-4] HP GROUP [300-650] CROP TYPE [ROW]
Frequency, %
Cummulative Frequency, %
DPF Outlet Temperature, C
0
50
100
150
200
250
300
350
400
450
500
550
0
1
2
3
4
5
6
0
10
20
30
40
50
60
70
80
90
100


CERT TIER [3-4] HP GROUP [300-650] CROP TYPE [TREE]
Frequency, %
Cummulative Frequency, %
DPF Outlet Temperature, C
0
50
100
150
200
250
300
350
400
450
500
550
0
1
2
3
4
5
6
0
10
20
30
40
50
60
70
80
90
100