FINAL REPORT

Assessing the Cost and Fuel Consumption of Off-Road Agricultural Equipment

Michael McCullough,
Lynn Hamilton,[1]
and
Cory Walters[2]
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[1] Drs. McCullough, mpmccull@calpoly.edu, and Hamilton, lhamilto@calpoly.edu, are Professors of Agribusiness at California Polytechnic State University, San Luis Obispo
[2] Dr. Walters is an Associate Professor in the Department of Agricultural Economics at University of Nebraska-Lincoln, cwalters@unl.edu.

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Executive Summary

Since 1995, U.S. Environmental Protection Agency (EPA) emission rules have mandated that off-road engine manufacturers gradually phase in lower emitting diesel engines across all tractor and other off-road equipment sold in the United States. Starting in 1996 with Tier 1 emission standards for tractors between 175-750 horsepower (hp), all tractors were scheduled to be rated as Tier 4 Final by 2015. During the transition period, emission credit agreements made between manufacturers and EPA allowed for nonattainment of some tractors such that several tractor models were produced post 2015 that did not meet Tier 4 Final standards. Tier 4 standards are primarily concerned with reducing nitrous oxide (NOx) and particulate matter (PM) pollutants, requiring a 90% emission reduction of both compared to Tier 3 standards. NOx contributes to formation of ground-level ozone, while particulate matter is implicated in respiratory illnesses.

With the new emission standards, manufacturers were required to implement emission reduction technologies. Emission reduction technologies such as diesel oxidation catalysts (DOC), diesel particulate filters (DPF), and/or selective catalyst reduction (SCR) systems on the exhaust were developed to break down NOx, resulting in cleaner burning engines. It is important to note that the emission targets do not dictate how manufacturers meet the standards. As a result, a wide array of emission reduction strategies were developed by manufacturers that affect engine fluids use, costs of ownership, and typical maintenance costs[3]. As tractor emission systems advanced through the stricter emission standards, anecdotal evidence from growers suggested a decrease in fuel efficiency.

Two primary questions drive this research: First, can Tier 4 tractors claim greater emission reductions via fuel efficiency? Second, do Tier 4 tractors have a higher cost of ownership via normal maintenance and repair?

To assess the change in fuel efficiency over time, we estimated the rate of change of fuel efficiency through Tier 4 Final emission standards and provide estimates for factors that have impacted fuel efficiencies using University of Nebraska Tractor Test Lab (NTTL) data from 1988 to 2021. To assess the costs of Tier 4 tractor ownership, we developed a grower survey sent to San Joaquin Valley producers. We asked specifically about the costs of ownership through repair and maintenance costs at various EPA emission tiers and horsepower. We also interviewed equipment repair businesses throughout the San Joaquin Valley to gain their perspectives on costs of repairs and maintenance and to assess whether any issues arose with Tier 4 equipment.

One important deliverable for the project was the development of a searchable database for hundreds of NTTL reports. The NTTL is the only third-party tractor test laboratory in North America, and all manufacturers who want access to the Nebraska and thus the U.S. tractor market must send their tractors there for testing. A partial database of NTTL reports can be found at https://tractortestlab.unl.edu.

The final project report is organized into two sections: the first reports on tractor fuel efficiencies and the second deals with differences in Tier 4 tractor repair and maintenance costs. The notable findings from each report are reported as follows:

Fuel Efficiency vs Emissions

- Tier 4 Final tractors are statistically more fuel efficient on average than earlier Tiers.

[3]Cost differences are discussed in the service provider final report. Fuel efficiency and fluid use is explicitly modeled as average differences between manufacturers here.

- The average percent change in fuel efficiency, measured as hp.hr/gal, in Tier 4 Final tractors has been 0.77% per year since 2015. This is compared to an average percent change in fuel efficiency of 0.55% per year across all tractors from 1987-2021.
- AGCO/Massey has produced the most fuel-efficient tractor, the AGCO Fendt/Challenger 1042 with a hp.hr/gal of 21.17, and John Deere has the highest average fuel efficiency throughout its tested tractors over the same period, 2001 to 2021.
- Fuel efficiency is consistently lower when tractors are not running at max power.
- We found statistically significant differences of average fuel efficiency at max power between tractor attributes for Time, Max power take-off (PTO) horsepower, and the interactions between Manufacturer, Chassis, and EPA Tier.

Tier 4 ownership and Maintenance Costs

Farm Survey

- Growers reported a wide variation in repair and maintenance hours across tractor emission tiers and horsepower.
- Growers reported paying an average of $20.39/hr for on-farm tractor repair by farm employees vs an average of $123.33/hr and $129.29/hr for independent mobile and in-shop repair services.
- The majority of respondents (likely those with newer tractors) had equipment still under warranty.
- Tractor manufacturer suggested retail prices (MSRP) are not available, nor are standard lease rates; industry contacts confirmed that dealers keep that information confidential.

Service Provider Interviews

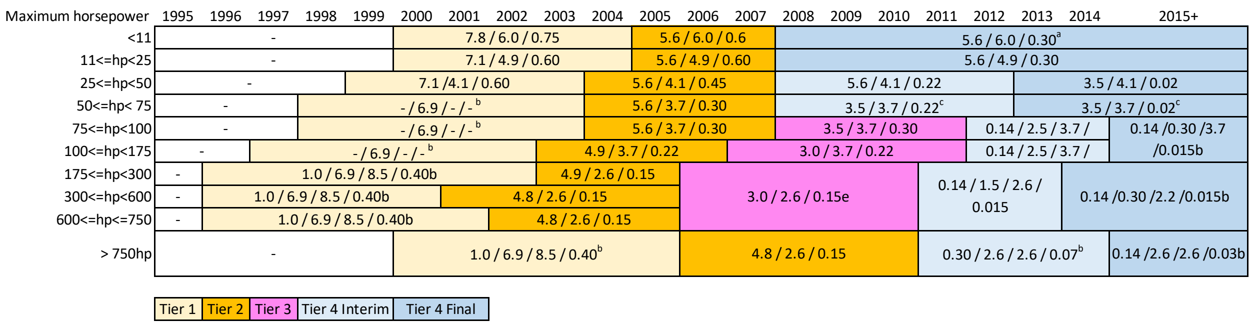
- All service managers reported both shop and mobile services.
- The average reported shop rate was $135/hr.
- The average reported field rate was $150/hr.
- Most service managers reported several thousand dollars of investment in computers/tablets/cell phones/hotspots and software per technician.
- Operator error is one of the most common reasons for emissions-related service calls. All service managers noted the need for more owner/operator education on emission system operation and maintenance.
- Common operator mistakes include:
    - Some operators will make simple but very expensive mistakes like putting diesel exhaust fluid (DEF) into a fuel tank;
    - Running tractors at low RPMs results in de-rating or re-gen modes, which require an expensive service call (minimum $200 - $300 to reset the system); and
    - Failing to refill the DEF tank.
- On average, service managers reported 30-35% of their calls were related to emissions systems.
- Most service managers noted that newer Tier 4 tractors are still under the manufacturer's emission warranties, so owners are not yet experiencing out of pocket costs for maintaining the emission systems.

Tractor Fuel Efficiencies 1988-2021: Evidence from the University of Nebraska Tractor Test Lab

Introduction

Since 1995, U.S. Environmental Protection Agency (EPA) emission rules have mandated that tractor engine manufacturers gradually phase in lower emitting diesel engines across all tractors sold in the United States. Figure 1 shows the phase in schedule and emission standard for each EPA Tier/hp bin. Starting in 1996 with Tier 1 emission standards for tractors between 175-750 horsepower (hp), manufactured tractors were scheduled to all be rated as Tier 4 Final by 2015. During the transition period, emission credit agreements made between manufacturers and EPA allowed for nonattainment of some tractors such that several tractors were produced post the 2015 that did not meet Tier 4 Final standards.

Figure 1. EPA emission tiers phase in schedule



a) The PM standard for hand-start, air cooled, direct injection engines below 11 hp may be delayed until 2010 and be set at 0.45 g/bhp-hr.
b) Standards given are NMHC/NOx/CO/PM in g/bhp-hr.
c) Engine families in this power category may alternately meet Tier 3 PM standards (0.30 g/bhp-hr) from 2008-2011 in exchange for introducing final PM standards in 2012.
d) The implementation schedule shown is the three-year alternate NOx approach. Other schedules are available.
e) Certain manufacturers have agreed to comply with these standards by 2005.
Source: CARB 2017

With the new emission standards, manufacturers were required to implement emission reduction technologies. Emission system technologies such as exhaust filters, diesel exhaust fluid (DEF) along with hotter burning engines were developed to break down NOx, resulting in cleaner burning engines. It is important to note that the emission targets do not dictate how attainment is met. With this there has been a wide array of emission reduction strategies adopted by manufacturers which have implications for tractor liquids use, costs, and typical maintenance costs today[4]. As tractor emission systems advanced through the stricter emission standards, anecdotal evidence from growers suggested a decrease in fuel efficiency.

Research focusing on the change in fuel efficiency throughout the implementation of emission standards is very limited. We identified only one study. Grisso et al., 2014, showed that even with slight drops in average fuel efficiency due to implementation of Tier 1 & Tier 2 standards,

[4]Cost differences are discussed in the service provider final report. Fuel efficiency and fluid use is explicitly modeled as average differences between manufacturers here.

fuel efficiency has been increasing significantly over the years. This study utilized tractor fuel use data obtained from the University of Nebraska Tractor Test Lab (NTTL) from 1979 to 2007 and utilized two methods for estimating tractor fuel consumption. Estimates suggested an average of 0.5% increase in fuel efficiency per year for a total of 14% fuel efficiency increase from 1979 to 2007.

This technical report aims to update the estimates of the rate of change of fuel efficiency through Tier 4 Final emission standards and provide estimates for factors that have impacted fuel efficiencies using NTTL data from 1988 to 2021. We find that, even though EPA Emission Tiers 1 and 2 showed an initial negative impact on fuel efficiency, on average Tier 4 Final tractors are statistically more fuel efficient than earlier Tier's. In addition, the rate of increase in average fuel efficiency over time has increased. A result indicating a greater gain in fuel efficiency from improved engine performance than the loss from emission systems.

Tractor Attributes

In 1919 the Nebraska Tractor Law was passed stating that any tractor sold in the state of Nebraska must undergo third-party unbiased testing to confirm manufacturer stated attributes (NTTL, 2022). Since, NTTL has tested over 2,000 tractors and has become one of a handful of Organization for Economic Co-operation and Development (OECD) certified agricultural tractor test centers, and the only one in the United States (OECD, 2022). In addition to testing tractors, NTTL also publishes other official OECD tractor test reports. Since 1959 OECD member countries along with notable non-members China, India, and the Russian Federation, adhere to the tractor test codes. It is common practice today for manufacturers to use the results of an OECD tractor test as certification of performance and nearly all tractors sold in California have an official OECD test, where most untested tractors are not intended for on-farm use.

Each year approximately two dozen new tractors are tested at NTTL under different operating conditions where important parameters such as power, speed, fuel use, and DEF use are recorded. Historically, the test reports have been made publicly available via the NTTL website and the University of Nebraska's digital commons. In cooperation with Rodney Rohrer and Roger Hoy at NTTL, this report utilizes reports compiled in a centralized dataset allowing for a detailed examination of fuel efficiencies across EPA Tiers, tractor manufacturers, horsepower, and chassis configurations.

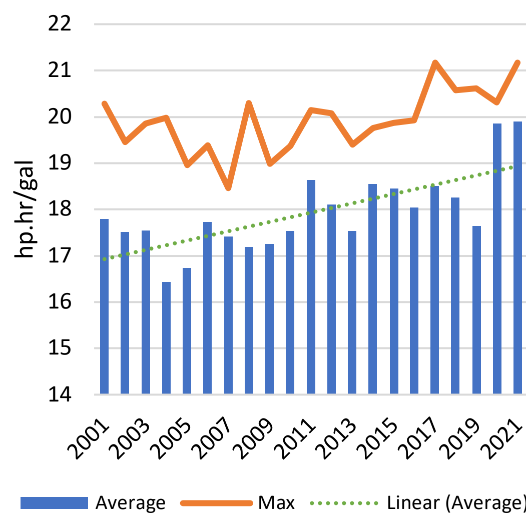
It is important to note that EPA emission tier is not explicitly reported for most tractors. In some cases, as is with John Deere, it can sometimes be found embedded in the tractor serial number. For purposes of this analysis, each tractor is assumed to adhere to the EPA Tier phase in schedule presented in Figure 1. This estimate is believed to be biased early for some tractors produced near the transition year. However, a cursory analysis of 100 John Deere tractors found only two tractors with a miss-assigned emission tier.

Fuel Efficiency

Fuel efficiency is measured here as horsepower hour per gallon of fuel use (hp.hr/gal). This specific volumetric fuel efficiency measure provides the energy efficiency of different tractors. NTTL measures the energy efficiency from different sources (i.e., power takeoff (PTO) and drawbar) across multiple power levels for a fixed amount of time. We focus on the PTO data as it best represents engine power from all measured sources. PTO power is measured at the engine's: maximum power, standard PTO speed, manufacture rated engine speed, and 85%, 75%, 50%, 25%, and 0% of power[5]. Table 1 shows descriptive statistics for fuel efficiency at max power over time since 2001 for all tested tractors with available data. Note all statistics reported in this analysis are at the tractor's maximum power where the tractor performs best in terms of both PTO horsepower and fuel efficiency.

Table 1/Figure 2. Fuel efficiency descriptive statistics at max power

	HP.HR/GAL			
YEAR	**Average**	**Max**	**Stdev**	**Tractors**
2001	17.8	20.3	1.3	37
2002	17.5	19.5	1.1	53
2003	17.5	19.9	1.1	52
2004	16.4	20.0	1.5	111
2005	16.7	19.0	1.3	58
2006	17.7	19.4	1.4	29
2007	17.4	18.5	0.7	90
2008	17.2	20.3	2.0	80
2009	17.3	19.0	0.9	64
2010	17.5	19.4	1.4	23
2011	18.6	20.1	1.0	66
2012	18.1	20.1	1.0	91
2013	17.5	19.4	0.8	54
2014	18.5	19.8	0.7	35
2015	18.5	19.9	0.9	60
2016	18.0	19.9	1.0	132
2017	18.5	21.2	1.3	28
2018	18.3	20.6	1.3	19
2019	17.6	20.6	2.3	13
2020	19.9	20.3	0.7	11
2021	19.9	21.2	1.0	17



It is clear from Table 1 that through the introduction of different emission Tiers, average fuel efficiency at max power increased from 2001 to 2021. However, due to the variability (measured by the standard deviation) in fuel efficiencies across tested tractors, it is not clear if tractors are becoming generally more fuel efficient as there could be other confounding factors affecting this trend. These potential confounding factors must be considered to identify the relation between fuel efficiency and emissions.

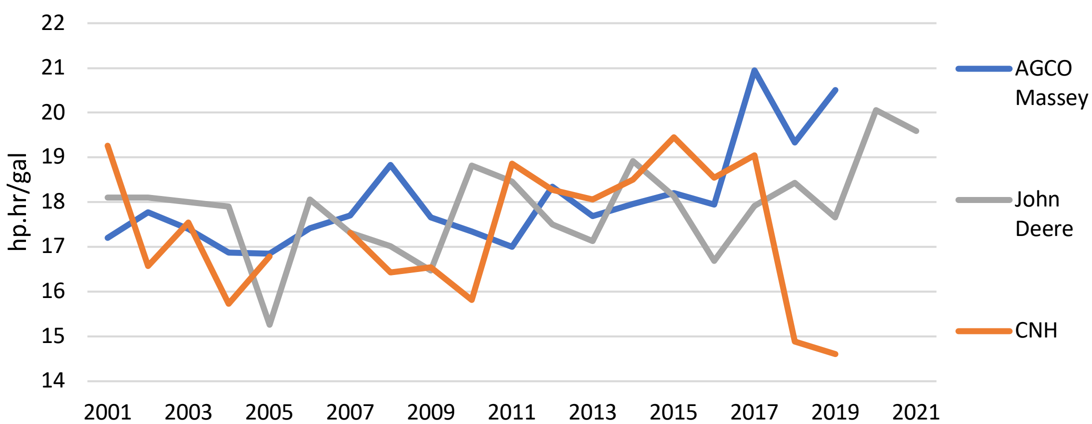
[5] Operating a tractor at a reduced rate, such as idling or a % of rated or maximum speed, is unfortunately not uncommon. As the analysis and discussions with manufacturers show, this potentially has a significant effect on fuel efficiency and emission systems. Most Tier 4 Final tractors are designed to operate at rated speeds and issues with active and passive regeneration can occur if not operated correctly.

To assess the change more accurately in fuel efficiency over time, multiple models that take into account important tractor attributes are estimated. We focus on five specific tractor attributes that relate to fuel efficiency: manufacturer, EPA emission tier, manufacturer reported tractor PTO horsepower, the year the tractor was tested, and chassis configuration. The following section describes each attribute individually and follows with a joint analysis using regression.

Manufacturer

There are 35 different manufacturers with available observations in the tractor test data. Of these, three parent companies produced the majority of tested tractors; AGCO/Massey, Case New Holland (CNH), and John Deere, with 536, 617, and 375 tractors tested since 1987, respectively. From 2001 to 2021, AGCO/Massey has produced the most fuel-efficient tractor, the AGCO Fendt/Challenger 1042 with a hp.hr/gal of 21.17, and John Deere has the highest average fuel efficiency over the same period, Figure 3. The variability in year-to-year fuel efficiencies across tractor manufacturers may also be due to other tractor attributes, such as chassis and emission systems. Indeed, a statistical model with interactions, as described below, provides more insight.

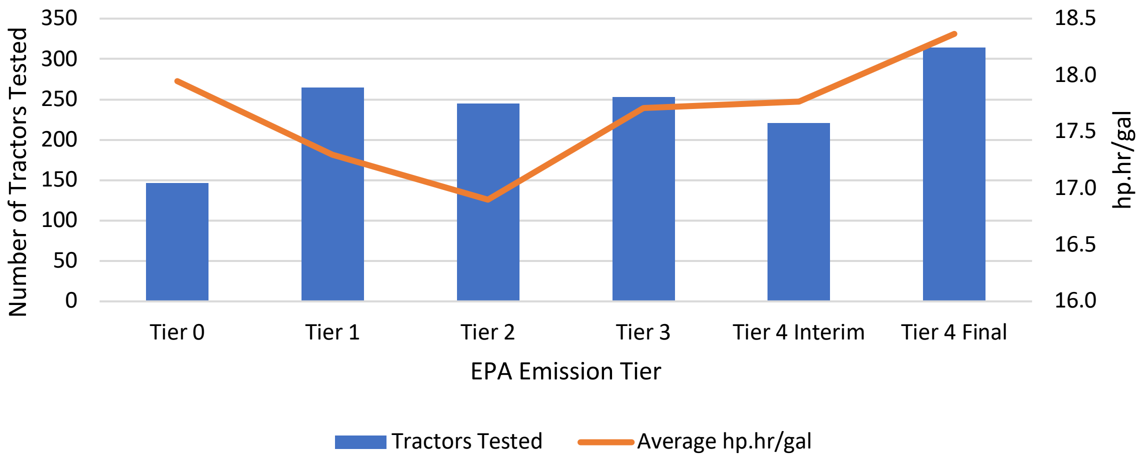
Figure 3. Average hp.hr/gal at max power for parent company manufacturers



EPA Emission Tier

As stated above, each manufacturer has achieved emission reductions utilizing different technologies such as diesel oxidation catalyst (DOC), diesel particulate filter (DPF), and/or selective catalyst reduction (SCR) systems on the exhaust. While examining average fuel efficiency across EPA emission tier provides general insight into changes in fuel efficiency over time, it does not tell the whole story in that the EPA emission tier is only a proxy for the specific emissions systems onboard the individual tractors. Table 2 shows the number of tested tractors and average hp.hr/gal at max power for tested tractors from 2001 to 2021. At face value it is difficult to interpret the effect on fuel efficiency by just examining emission standards. Indeed, the regressions show that while the emission tier does show an initial drop in fuel efficiency, as noted in Grisso et al., 2014, for Tier 1 and 2, this loss is far outweighed by the subsequent increases in fuel efficiency.

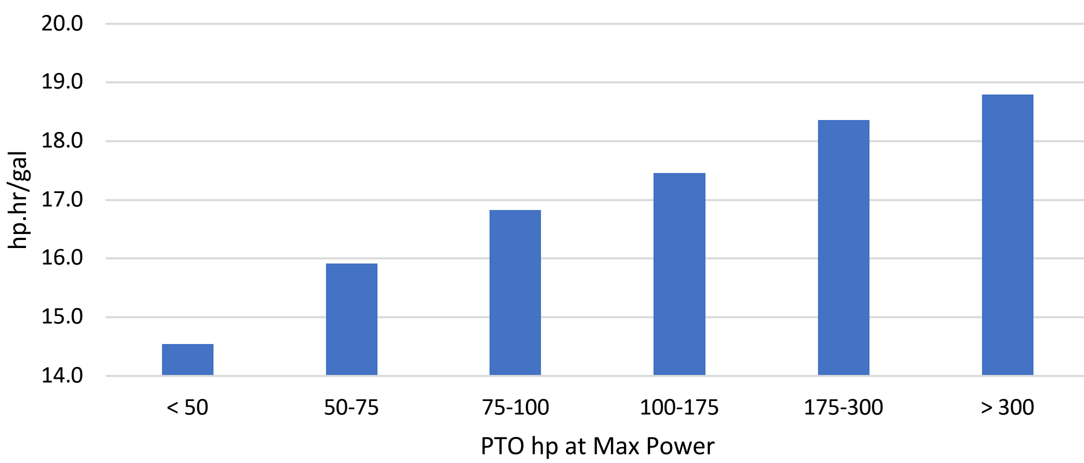
Figure 4. Tested tractors and hp.hr/gal at max power by EPA emission tier since 1987



Tractor Horsepower

The relationship between reported tractor PTO horsepower and hp.hr/gal at max power is of note. Specific volumetric fuel consumption should change very little for engine size. However, as shown in Figure 5, as engine size increases, average hp.hr/gal increases. While we make no claims as to the increased fuel efficiency for larger horsepower tractors, tractor size an important attribute to control for when estimating the impact of other factors on fuel efficiency.

Figure 5. Fuel efficiency at max power for different sized tractors



Chassis

The final tractor attribute examined to influence fuel efficiency is chassis. There are several different chassis in the database with front wheel assist (FWA) making up 72.78% of all tested tractors since 1987. Four-wheel drive comes in second with 9.56%, followed by two-wheel drive at 9%, crawlers at 6.3%, with a few other types making up the remainder. FWA tractors are essentially rear-wheel drive tractors with a steerable front axle that have a limited ability to engage the front wheels, as opposed to four-wheel drive that articulate in the middle. Crawlers have tracks instead of tires. As with EPA emission tiers, examining chassis' effect on fuel efficiency in isolation provides a mixed, and inaccurate, description. Furthermore, there have been only 42 four-wheel drive tractors tested since 2010 and six two-wheel tractors.

Regression Models

An initial Three-way Analysis of Variance (ANOVA) with continuous variables was fit to the entire available tractor data. Full results of the ANOVA and subsequent regression models can be found in Appendix 1. The ANOVA indicates statistically significance differences of average fuel efficiency at max power between tractor attributes for Time, Max PTO horsepower, and the interactions between Manufacturer, Chassis, and EPA Tier. The presence of significant interactions confirms the complex relationship between fuel efficiency and all tractor attributes. To further examine the differences between tractor attributes' impact on fuel efficiency a set of multiple linear regression models are estimated.

Table 2. 3-Way ANOVA with Interactions

Source	Wilks' lambda Statistic	df	F-Test	P-Value
Model	0.17	441	11.03	0.00
Residual		998		
Total		1,439		
Time	0.88	33	4.14	0.00
PTOHP	0.34	316	6.16	0.00
Manufacturer	0.99	6	1.53	0.17
Chassis	0.99	4	1.87	0.11
EPA Tier	0.99	5	1.21	0.30
Manufacturer by Chassis	0.95	15	3.16	0.00
Manufacturer by EPA Tier	0.90	24	4.74	0.00
Chassis by EPA Tier	0.96	18	2.29	0.00
Manufacturer by Chassis by EPA Tier	0.97	20	1.58	0.05

Three multiple linear regression models were estimated with hp.hr/gal at maximum power as the dependent variable. Differences in models are associated with the inclusion of different EPA emission tiers. As discussed above, the onset of emission standards saw a decrease in average hp.hr/gal. However, it was unclear as to whether there was a general increase in fuel efficiency over time. The estimated models isolate the fuel efficiency effect by estimating the average change in fuel efficiency over time (time coefficient measured in years) across three subsets of tractors in the data; Model 1: all tested tractors from 1987-2021, Model 2: Tier 1 to Tier 4 Final tractors, and Model 3: only Tier 4 Final tractors.

Each model contains the discussed tractors' attributes: max PTO HP as a continuous variable; chassis as a categorical variable; EPA emission tier in the applicable model as a categorical variable; and parent manufacturing company as a categorical variable. Due to data availability changes in manufacturer and chassis, discussed above, some sets of interactions are excluded from the respective models. Table 3 reports the results for Model 3: only Tier 4 Final tractors. Model 1 & 2 results can be found in Appendix 1. Note that for Model 3, Massey Ferguson is included in AGCO and New Holland in CNH for manufacturer, and 2WD in Other for Chassis.

Table 3. Estimated regression Model 3 (dependent variable: hp.hr/gal at maximum power)

Source	Sum of Squares	df	Mean Square
Model	301.95	14	21.57
Residual	168.29	299	0.56
Total	470.24	313	1.50

Number of observations	314
F(14,299)	38.32
Prob > F	0.00
R-squared	0.64
Adj. R-squared	0.63
Root MSE	0.75

		Coefficient	Std error	t-stat	P-Value	95% confidence interval Lower	Upper
Continuous	Constant	11.941	0.80	14.99	0.00	10.37	13.51
	PTOHP	0.011	0.00	19.30	0.00	0.01	0.01
	Time	0.141	0.03	5.27	0.00	0.09	0.19
Manufacturer	Case	0.028	0.54	0.05	0.96	-1.04	1.10
	CNH	0.688	0.13	5.48	0.00	0.44	0.94
	John Deere	0.091	0.12	0.74	0.46	-0.15	0.33
	Other	-0.487	0.20	-2.39	0.02	-0.89	-0.09
Chassis	Crawler	-1.658	0.27	-6.25	0.00	-2.18	-1.14
	4WD	-0.909	0.58	-1.56	0.12	-2.06	0.24
	Other	-0.720	0.26	-2.74	0.01	-1.24	-0.20

Manufacturer	Chassis	Coefficient	Std error	t-stat	P-Value	95% confidence interval Lower	Upper
Case	Other	-1.228	0.68	-1.81	0.07	-2.56	0.10
CNH	4WD	-1.323	0.60	-2.19	0.03	-2.51	-0.14
CNH	Other	-1.326	0.37	-3.61	0.00	-2.05	-0.60
John Deere	Crawler	1.014	0.36	2.85	0.01	0.31	1.71
John Deere	4WD	-0.104	0.65	-0.16	0.87	-1.38	1.18

PTO horsepower, time (annual change) and combinations of manufacturer, chassis, and EPA tiers are statistically significant at the α=0.05 level in all three models. Interpretations of the three categorical variables and the interaction terms are all relative to the factors left out of the model. For instance, in Table 3, results from Model 3, the interpretation of the manufacturer coefficients is the effect on fuel efficiency relative to AGCO, the base factor. On average across all Tier 4 Final tractors, CNH tractors are -1.857 less hp.hr/gal than the average AGCO tractor. For chassis, the base factor for comparison is FWA. For Tier 4 Final tractors, all other chassis are statistically less fuel efficient than FWA. For instance, the average crawler is -1.658 less hp.hr/gal than the average front wheel assist tractor.

Interaction coefficients are less straightforward to interpret. Table 4 shows the frequency of manufacturer and chassis combinations for all tested Tier 4 Final tractors with max hp.hr/gal observations. Gray highlighted cells are those that correspond to estimated coefficients in Table 3 and lined cells are estimates omitted from the regression due to collinearity. As was the case discussed above for manufacturer and chassis, AGCO and FWA are the base case for comparison, making direct comparisons difficult to interpret.

Table 4. Frequency table of manufacturer by chassis interaction observations for Tier 4 Final

Manufacturer	Chassis: FWA	Crawler	4WD	Other
AGCO	88	10	-	-
Case	2	-	-	5
CNH	66	-	14	9
John Deere	75	10	6	10
Massey Ferguson	-	-	-	-
New Holland	-	-	-	-
Other	17	-	2	-

Fortunately, for purposes of this analysis, our primary focus is the time variable, which shows the annual trend in fuel efficiency. Table 5 presents the annual change coefficient, average hp.hr/gal, number of tested tractors, and the average annual percent change in fuel efficiency for the three models.

Table 5. Regression model comparison

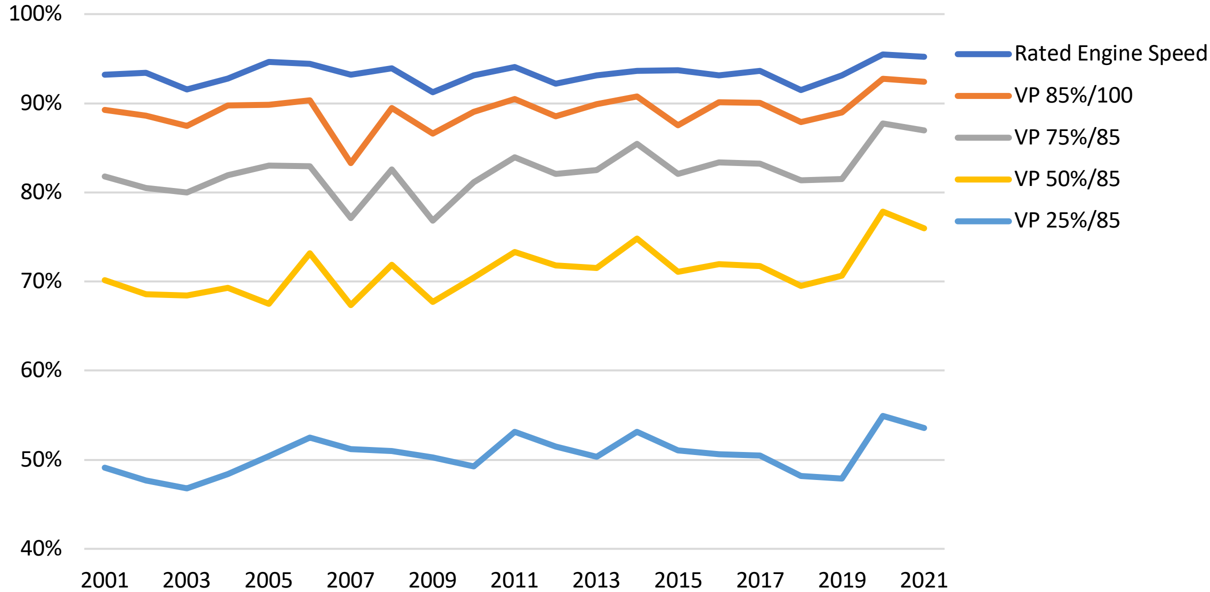
	Regression Model: Model 1: 1987-2021	Model 2: Tier 1 – Tier 4 Final	Model 3: Only Tier 4 Final
Average hp.hr/gal	17.67	17.64	18.37
Tested Tractors	1,440	1,297	314
Year Coefficient	0.097	0.105	0.141
Average %Change in hp.hr/gal per year	0.55%	0.60%	0.77%

The annual coefficient is statistically significant at the α=0.01 level in all three models. As the regression models are restricted in EPA emission Tiers, the time variable grows in impact. This indicates that the average annual increase in fuel efficiency has been increasing since the 1980's, and that the rate of increase in fuel efficiency is greatest for Tier 4 Final tractors. This statistical evidence is contrary to anecdotal belief that that lower emission tractors lead to lower fuel efficiency or higher fuel use. A plausible explanation for the anecdote may be driven by how tractors are used, which is described in the following section and the companion tractor cost reports.

Other Measures of Fuel Efficiency

The statistical models discussed here are all focused on fuel efficiency at maximum power. It is plausible to speculate that these results could differ at different power output. Figure 6 plots average hp.hr/gal for varying power as a percent of fuel efficiency at maximum power.

Figure 6. Hp.hr/gal for variable power tests as a percent of hp.hr/gal at max power



There are two points of interest to note. First, the ratios of fuel efficiencies are not constant over time. Second, and more importantly, fuel efficiency is consistently lower when not running at max power. As mentioned above, this has implications for fluid use and emissions if tractors are not appropriately sized for their intended use. For example, anecdotal discussions with farmers suggest it not uncommon to go with the "next size up" when purchasing a new tractor. Or that "more is better" when it comes to horsepower. This analysis suggests that that sentiment is not the case if the new tractor is not going to be ran at its maximum potential, i.e., at a variable power less than 100%.

Conclusions

Estimates show a statistically significant impact of the interaction between emission standards, manufacturer, and chassis on tractor fuel efficiencies. The results detail a complex story in the process of achieving emission standards and how that relates to fuel efficiency. It appears that any negative initial impacts, have been more than offset by an increasing trend in fuel efficiencies.

A logical next step in research would be to examine tractor inventory and typical use, especially for those tractors exchanged during government sponsored trade-in programs, to estimate the distribution of the more fuel-efficient tractors in use combined with their average use relative to tractors they replaced. In addition, specific emission system components could be included in the analysis to examine if they have different individual effects on fuel efficiency, instead of using the broader EPA emission tier.

Tractor Repair and Maintenance Costs: Grower and Service Provider Perspectives

Introduction

The San Joaquin Valley of California is the most productive agricultural region in the U.S., and arguably, the world. It is also home to some of the nation's worst air quality, and agriculture, as a leading industry in the region, is subject to strict emissions controls.

The Federal Clean Air Act requires states to develop and implement plans to meet health-based ambient air quality standards by 2023 and 2032. Reducing air pollution from off-road mobile agricultural equipment, such as tractors, combines, and harvesters, is one of the measures needed for California to meet federal air quality standards. Specifically, the San Joaquin Valley Air Pollution Control District (SJVAPCD) has committed, in a recently approved State Implementation Plan (SIP), to reduce 11 tons per day of oxides of nitrogen (NOx) from off-road agricultural equipment by 2024. Fine particulate matter, PM 2.5, is also a pollutant of concern because of its adverse effects on respiratory health. The SIP included incentive measures of $65 million to $212.6 million annually since 2017, totaling $535 million. These funds are provided as cost-shares to farmers who voluntarily upgrade equipment (mostly tractors) to lower emission models.

The primary initiative, CARB's Funding Agricultural Replacement Measures for Emission Reductions (FARMER) program, was funded by a $135 million allocation in September 2017 from Assembly Bill 134 and Assembly Bill 109. These bills allocated funding for reduced-emission replacement of heavy-duty agricultural equipment, trucks, pumps, and tractors. The program was developed between California Air Resources Board (CARB) staff and local air districts and agricultural groups to ensure that the projects funded would meet the emissions reduction goals. The funds are generated in part via the California Climate Investments cap-and-trade program. While farmers receive cost-shares that fund up to 80% of the initial cost of the equipment, they are responsible for the cost of ongoing maintenance and repairs for the duration of ownership.

Two primary questions drive this and concurrent research: First, can higher EPA emission tiered tractors claim greater emission reductions via fuel efficiency, addressed in the accompanied report; second, do higher EPA emission tiered tractors have a higher cost of ownership via normal maintenance and repair? To assess the costs of ownership, we developed a grower survey sent to San Joaquin Valley producers. We asked specifically about the costs of ownership through repair and maintenance costs at various EPA emission tiers and horsepower. We also interviewed equipment repair businesses throughout the San Joaquin Valley to gain their perspectives on costs of repairs and maintenance and to assess whether any issues arose with higher EPA emission tiered equipment.

Farm Survey

From June 2021 through November 2021 a survey to farmers was distributed online to assess the costs of normal maintenance and repairs on tractors. The survey was intended to support a concurrent assessment of service provider costs and of tractor fuel efficiency. The survey consisted of ten questions and was distributed via email from several agricultural associations representing various farmers across the San Joaquin Valley of California. It is included here as Appendix 2. The survey design was intended to facilitate a quick response while collecting necessary information regarding differences in costs between tractor designated EPA emission tiers and horsepower.

The survey was live for four months with multiple email reminders, and a total of thirty responses were collected. While this sample is quite small, it is in line with responses from the service provider assessment. The small sample size makes possible statistical tests of differences between tractor horsepower or EPA emission tier unreliable. Therefore, results for each question are presented in tabular form with number of responses per question. Averages are not representative of all farms within the San Joaquin Valley, CA.

Survey Results

Table 6 summarizes the responses collected in Question 1 of the survey, which asked farmers to indicate the horsepower and EPA emission tier bin for each tractor they owned, leased, or rented. Respondents had the option to choose all horsepower and EPA emission tier bins that applied to their operation. Most respondents indicated that they operated tractors between 75 and 300 horsepower.

Table 6. Values represent number of respondents who indicated the horsepower/EPA tier of tractors that they owned, leased, or rented

# of Respondents	Less than 25hp	Between 25hp and 50hp	Between 50hp and 75hp	Between 75hp and 100hp	Between 100hp and 175hp	Between 175hp and 300hp	Between 300hp and 600hp	Between 600hp and 750hp	Above 750hp
Tier 0	3	2	1	3	5	1	0	0	0
Tier 1	0	1	1	1	1	1	0	0	0
Tier 2	0	0	0	1	1	3	0	0	0
Tier 3	0	2	2	4	6	4	1	0	0
Tier 4 Interim	0	1	0	4	3	3	1	0	0
Tier 4 Final	0	1	2	6	3	3	2	0	0

Table 7 summarizes the responses collected in Question 2 of the survey, which asked farmers to indicate the brand of tractor(s) they owned, leased, or rented. Respondents were given the option to choose all brands that applied.

Table 7. Values represent number of respondents who indicated the manufacturer of owned, leased, or rented tractors

Brand	# of Respondents
Case IH	8
Challenger	1
John Deere	9
Kubota	4
Massey Ferguson	5
New Holland	4
Other	1

Table 8 summarizes the responses collected in Question 3 of the survey, which asked farmers to indicate the location in which maintenance and/or repair work was completed, and Table 9 summarizes the average, maximum, minimum, and number of respondents for the labor rates at the location of tractor maintenance/repair.

Table 8. Location of maintenance/repair work.

Location	# of Respondents
Offsite by service provider/dealer	14
Onsite by farm employee	14
Onsite by mobile mechanic	8

Table 9. Labor rates at different maintenance/repair locations

($/hour)	Average farm employee mechanic labor rate?	Average mobile mechanic labor rate?	Average offsite service provider labor rate?
Mean	$20.39	$123.33	$129.29
Max	$40.00	$180.00	$180.00
Min	$15.00	$100.00	$85.00
Count	9	6	7

Table 10 summarizes the responses collected in Question 4 of the survey, which asked farmers whether their purchase/lease/rental agreement included some kind of warranty The bulleted list below presents the descriptions of warranty terms that were provided by the respondents who indicated that their purchase/lease/rental agreement included a warranty.

Table 10. Warranty responses.

Response	# of Respondents
Yes	8
No	4

Please describe the terms of your maintenance and/or repair(warranty) plan(s).

- 2-year warranties
- 250 deductible, 6 year or 2,500 hours
- 5-year, 5,000 hours
- Basic warranty plus extended warranty with a $250 deductible for six years or 2,500 hours
- John Deeres are warrantied for 2 years or 2,000 hours whichever comes first.... I've purchased extended warranty on Massey Ferguson swathers for bumper-to-bumper coverage for 3,000 hours or 3 years, that cost me $6,000
- Pays for repairs/parts for a certain number of hours such as 2,000 hours or 4 years
- Rentals are serviced and maintained by provider. Owned equipment warranties vary by dealer and options.

Table 11 summarizes the responses collected in Question 5 of the survey, which asked farmers to indicate the average number of hours per year maintenance is performed on a single tractor. Similar to Question 1, respondents were asked to provide this information based on horsepower and EPA emission tier of each tractor they owned, leased, or rented. Note the wide variability in hours across all bins. While some respondents reported have regular maintenance performed over 500 hours a year, the average response was 67 hours across all tractor bins, with a median and mode of 20 hours per year.

Table 11. Average hours per year (number of respondents) of tractor maintenance.

On average, how many hours per year do you have maintenance performed on a single tractor?									
Average Hours (# of respondents)	**Less than 25hp**	**Between 25hp and 50hp**	**Between 50hp and 75hp**	**Between 75hp and 100hp**	**Between 100hp and 175hp**	**Between 175hp and 300hp**	**Between 300hp and 600hp**	**Between 600hp and 750hp**	**Above 750hp**
Tier 0	1.17 (3)	1.75 (2)	-	1.00 (1)	28.75 (4)	-	-	-	-
Tier 1	-	11.00 (2)	2.00 (1)	-	20.00 (1)	-	-	-	-
Tier 2	-	-	-	-	30.00 (1)	20.00 (2)	-	-	-
Tier 3	-	1.00 (1)	1.00 (1)	2.33 (3)	140.00 (4)	260.00 (2)	-	-	-
Tier 4 Interim	-	-	-	2.00 (2)	18.33 (3)	25.00 (3)	25.00 (1)	-	-
Tier 4 Final	-	1.00 (1)	5.33 (1)	127.75 (4)	438.33 (3)	37.50 (2)	25.00 (1)	-	-

Table 12 summarizes the responses from Questions 6, 7, 9 and 10 of the survey, which asked farmers to indicate whether increased annual usage on a given tractor required additional maintenance and/or repair. If respondents answered with a "yes," they were asked to indicate the average additional hours of maintenance and repair associated with each additional 100 hours of annual tractor usage.

Table 12. Number of responses and average time per 100 hours.

Does average maintenance hours/year change for hours of use per year?	**# of Respondents**
Yes	8
No	2
Average change per 100 hrs.	2.83

Does average repair hours/year change for hours of use per year?	**# of Respondents**
Yes	6
No	4
Average change per 100 hrs.	3.20

Finally, Table 13 summarizes the responses collected in Question 8 of the survey, which asked farmers to indicate the average number of hours per year repairs are performed on a single tractor. Similar to Questions 1 and 5, respondents were asked to provide this information based on horsepower and EPA emission tier of each tractor they owned, leased, or rented. Again, note the wide variability in hours across all bins. Again, the number of responses for each bin is too small to statistically test for significant difference and make inferences on actual hours of work each year.

Table 13. Average hours per year (number of respondents) of tractor repair.

On average, how many hours per year do you have repairs performed on a single tractor?									
Average Hours (# of respondents)	**Less than 25hp**	**Between 25hp and 50hp**	**Between 50hp and 75hp**	**Between 75hp and 100hp**	**Between 100hp and 175hp**	**Between 175hp and 300hp**	**Between 300hp and 600hp**	**Between 600hp and 750hp**	**Above 750hp**
Tier 0	1.17 (3)	2.75 (2)	-	5.25 (2)	18.50 (2)	-	-	-	-
Tier 1	-	2.00 (1)	-	-	30.00 (1)	-	-	-	-
Tier 2	-	-	-	-	16.00 (2)	-	-	-	-
Tier 3	-	0.50 (1)	2.00 (1)	8.75 (4)	15.00 (2)	15.00 (2)	-	-	-
Tier 4 Interim	-	-	-	3.00 (1)	17.50 (2)	45.00 (2)	40.00 (1)	-	-
Tier 4 Final	-	0.50 (1)	1.00 (1)	1.40 (5)	35.00 (3)	13.00 (2)	40.00 (1)	-	-

Farm Survey Remarks

Unfortunately, response rates were too low to make any reliable conclusions on differences in operating costs between emission tiers and/or horsepower. However, general work rates are in line with results for the service provider assessment. It is unclear if a different survey administration would have increased response rates. Farm surveys are becoming quite common and anecdotal discussions indicate a general weariness of filling them out.

Service Provider Interviews

In the summer of 2021, we met with Joani Woelfel, CEO of the Far West Equipment Dealer Association, a not-for-profit trade association representing agricultural, among other industrial equipment dealers in Arizona, California, Colorado, Hawaii, Nevada, Utah, and Wyoming, to discuss the project and to get permission to use the member list for service providers. She granted permission to call service providers from her member list and seemed very interested in the project and was hopeful that they would participate. Though we originally planned to investigate tractor retail prices and lease rates, she confirmed that dealers keep that information confidential, and that no MSRP existed for agricultural and construction equipment. In December 2020, our team made calls to nine new equipment dealers in the San Joaquin Valley and were told by each sales manager we contacted that they did not discuss pricing outside of a customer deal. Dealer pricing depends on customization of the equipment, and price lists are not published on new equipment for public use.

We contacted a dozen service providers, from Bakersfield to Merced, and covered all major brands of equipment – John Deere, Case IH, New Holland, Massey Ferguson, and Kubota. Some businesses also carried and serviced smaller brands like Kioti. Each brand was represented by at least two of the contacted service providers. In all cases, we interviewed the service manager. Several of the companies had multiple branches throughout the valley, but to get a better overview of the costs, we only contacted one branch of each business.

We asked a variety of questions regarding the types of equipment (primary use and horsepower) that were most common in their shop, their shop and field rates, technology investment and training costs for their technicians, and the most common issues they experienced with Tier 4 Final equipment. The results of these interviews are summarized and presented as follows:

Type of Equipment

Each service provider serviced a wide variety of equipment but depending on the prevailing agricultural production in their region, they usually specialized in a particular size range. Dealers located in tree and vine areas reported the smallest tractors, around 35 hp in some cases, but the most common reported types of equipment were in the 90 – 130 hp range. Dealers who worked with dairy feed tractors reported 250 hp equipment and those working with field crop equipment noted they commonly worked on 300 – 600 hp tractors. The type of agriculture as well as soil conditions were the primary determinants of tractor size.

Services and Rates

All shops reported both in-shop and field services. The smallest dealer had three technicians and the largest reported 15. Most were split nearly evenly between shop and field technicians. All billed time on a time and parts basis, with some noting that their billable time for some jobs was determined by the manufacturer or warranty guidelines. The lowest rate reported for shop service was $120 per hour, and highest was $150 (that business had one rate for both in-shop and field services), with the average being about $135 per hour. Field rates were higher, usually about $15 per hour more than shop rates, with the highest reported at $160 per hour. It is common practice for service providers to call their competitors annually to check on rates to be sure that they’re in the ballpark and not over or underpricing their services. Average field rates were about $147 per hour and all businesses started billing the time from the moment the tech left either the shop or another job site to travel to the customer. The clock stopped when the job was finished, and the tech was on the road to another job.

Technology investment

Nearly all service managers reported several thousand dollars of investment in computers/tablets/cell phones/hotspots and software for their technicians. The average cost reported was about $3,000; the lowest value report was $1,500, and the highest value reported was up to $7,000 per technician. Some brands require specific fuel injection test kits that cost

$500 to $600 each. Service providers that work with multiple brands noted that they must provide separate cabling appropriate to each brand of tractor – each brand has its own specific diagnostic portal; there is no universal attachment like the standard On-Board Diagnostics (OBD) system found in cars. All techs must have all the types of cables available to do their work.

Training

All service managers reported additional training required for their techs, particularly for emissions systems. However, all systems on new tractors are very complex, so the training is not just for the emissions systems. Some service managers reported a very low level of additional training, as low as 5 – 10 hours per year, but some reported up to 300 hours of training required annually by the manufacturer. If a technician attends an in-person training, the fees and travel costs can add up to $3,000 per class. The training costs also vary depending on the technician's skill level. New trainees who are not a Level 1 tech and do not own their own tools can be paid minimum wage, so their training is relatively less expensive. However, more experienced technicians who own their own tools are paid at least double the minimum wage to start. Once a service manager has invested in training a technician, they have an incentive to keep them, so the technician gets pay raises. Senior technicians commonly make up to $40 per hour. Overall, training and technology investment are quite expensive for service providers.

Common maintenance and repair issues with Tier 4 final equipment

All service providers reported that, while newer equipment was mechanically more sound, the electronic systems governing the emissions is very complex and required a high level of operator understanding and education to run properly. All new tractors have more electrical components, and owners must have more knowledge both to operate and to repair/maintain tractors from older models. They all reported more maintenance issues and more points of failure with Tier 4 final emissions systems.

A common theme among all interviews was the problem of operator error. Some operators will make simple but very expensive mistakes like putting diesel exhaust fluid (DEF) into a fuel tank because there are now two fill points that are close to each other on some tractor models. That mistake crystallizes the whole engine and results in a $13,000 repair. Emission sensors cost around $1,000 a unit, and tractors typically have multiple sensors. If a filter is clogged or a DEF sensor is triggered, the engine will go into a re-gen or de-rate mode. That requires a service call, which costs a minimum of $200 - $300 if the issue is just a simple system re-set. If a DEF sensor needs replacing, the service call can cost nearly $2,000, as some managers reported the cost of the sensor at $1,800.

Operators are also not used to running tractor engines at the higher RPMs necessary for emission systems to operate correctly. This improper engine use also results in de-rating or re-gen modes, which, as noted above, require an expensive service call. Service managers noted that Tier 4 engine issues are more urgent when they do happen. The emission system overrides all others and the engine de-rates to the point where the tractor is essentially unusable until it is diagnosed and fixed.

One provider made some interesting observations about the longevity of the Tier 4 systems. He thought the emissions systems seem like a stopgap technology. There has to be a better technology to satisfy ever increasing emissions regulations. He thought the emissions systems, at least the ones with a DEF system, will eventually become obsolete and probably render some of these tractors useless before they are really worn out. Some of the emissions parts are very complex, and he didn't see the company manufacturing replacement parts forever.

Service Calls related to emissions

All service providers noted an increase in calls related to emissions systems. The lowest reported was about 20% of all service calls related to emissions, while the highest was 75% The average reported percentage across service providers was about 30- 35% of service calls related to emissions. The percentage reported seemed to be related to who was operating the equipment. Some providers noted that larger growers who employed many workers had higher call incidents because the workers may not have gone through proper training on how to operate the new equipment. More operator error was likely in those cases, with mistakes with DEF maintenance (proper fluid levels and/or filling the right tank) as well as engine operation.

Warranty

All Tier 4 tractors have a federal 5-year or 3,000-hour warranty on the emissions systems for both parts and labor. Most of the new tractors are only two or three years into this, so perhaps after two more years, dealers will start seeing more issues. Also, since a significant proportion of growers in the San Joaquin Valley purchased tractors under a cost-share program, most providers noted that growers don't mind the higher maintenance costs at this point. That may change in a few years if these tractors are still in service.

References

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Appendix 1: Model Results

Model 1: All tested tractors with Max hp.hr/gal estimates from 1987-2021

Source	Sum of Squares	df	Mean Square		
				Number of observations	1,440
				F(76,1363)	26.53
Model	1,513.85	76	19.92	Prob > F	0.00
Residual	1,023.53	1,363	0.75	R-squared	0.60
Total	2,537.38	1,439	1.76	Adj. R-squared	0.57
				Root MSE	0.87

		Coefficient	Std error	t-stat	P-Value	[95% confidence interval] Lower	Upper
Continuous	Constant	14.599	0.47	30.80	0.00	13.67	15.53
	PTOHP	0.011	0.00	28.98	0.00	0.01	0.01
	Time	0.095	0.02	6.09	0.00	0.06	0.13
Manufacturer	Case	1.140	0.50	2.28	0.02	0.16	2.12
	CNH	1.418	0.35	4.04	0.00	0.73	2.11
	John Deere	1.820	0.44	4.12	0.00	0.95	2.69
	Massey Ferguson	1.087	0.43	2.54	0.01	0.25	1.93
	New Holland	0.619	0.46	1.34	0.18	-0.28	1.52
	Other	1.034	0.94	1.10	0.27	-0.81	2.88
Chassis	4WD	-3.064	0.66	-4.67	0.00	-4.35	-1.78
	Crawler	-2.101	0.95	-2.22	0.03	-3.96	-0.24
	FWA	0.120	0.40	0.30	0.76	-0.66	0.90
	Other	-0.038	1.50	-0.03	0.98	-2.99	2.91
EPA Tier	Tier 1	-0.411	0.46	-0.89	0.37	-1.31	0.49
	Tier 2	-1.033	0.46	-2.24	0.03	-1.94	-0.13
	Tier 3	-1.357	0.64	-2.13	0.03	-2.61	-0.11
	Tier 4 Interim	-1.246	0.65	-1.92	0.06	-2.52	0.03
	Tier 4 Final	-4.608	0.73	-6.31	0.00	-6.04	-3.18

Manufacturer	Chassis	Coefficient	Std error	t-stat	P-Value	[95% confidence interval] Lower	Upper
Case	4WD	2.540	0.66	3.83	0.00	1.24	3.84
Case	Crawler	-	-	-	-	-	-
Case	FWA	-0.179	0.42	-0.42	0.67	-1.01	0.65
Case	Other	1.081	1.23	0.88	0.38	-1.34	3.50
CNH	4WD	0.651	0.50	1.30	0.20	-0.33	1.64
CNH	Crawler	-	-	-	-	-	-
CNH	FWA	-0.757	0.33	-2.33	0.02	-1.40	-0.12
CNH	Other	0.987	1.50	0.66	0.51	-1.95	3.92
John Deere	4WD	1.134	0.58	1.94	0.05	-0.01	2.28
John Deere	Crawler	-0.144	0.43	-0.34	0.74	-0.98	0.69
John Deere	FWA	-0.602	0.37	-1.62	0.10	-1.33	0.12
John Deere	Other	1.755	1.49	1.18	0.24	-1.17	4.68
Massey Ferguson	4WD	-	-	-	-	-	-
Massey Ferguson	Crawler	-	-	-	-	-	-
Massey Ferguson	FWA	-0.172	0.30	-0.56	0.57	-0.77	0.43
Massey Ferguson	Other	-	-	-	-	-	-
New Holland	4WD	2.143	0.65	3.28	0.00	0.86	3.42
New Holland	Crawler	-	-	-	-	-	-
New Holland	FWA	0.114	0.29	0.39	0.70	-0.46	0.69
New Holland	Other	-	-	-	-	-	-
Other	4WD	1.521	0.91	1.67	0.10	-0.27	3.31
Other	Crawler	1.111	0.81	1.37	0.17	-0.48	2.70
Other	FWA	-0.788	0.68	-1.16	0.25	-2.12	0.54
Other	Other	-	-	-	-	-	-

Manufacturer	EPA Tier	Coefficient	Std error	t-stat	P-Value	[95% confidence interval] Lower	Upper
Case	Tier 1	-0.638	0.34	-1.86	0.06	-1.31	0.03
Case	Tier 2	-1.298	0.40	-3.21	0.00	-2.09	-0.51
Case	Tier 3	-	-	-	-	-	-
Case	Tier 4 Interim	-	-	-	-	-	-
Case	Tier 4 Final	-1.076	0.68	-1.58	0.12	-2.41	0.26

CNH	**Tier 1**	-1.801	0.38	-4.68	0.00	-2.56	-1.05
CNH	**Tier 2**	-1.379	0.24	-5.78	0.00	-1.85	-0.91
CNH	**Tier 3**	-0.948	0.20	-4.68	0.00	-1.35	-0.55
CNH	**Tier 4 Interim**	-0.660	0.21	-3.18	0.00	-1.07	-0.25
CNH	**Tier 4 Final**	-	-	-	-	-	-
John Deere	**Tier 1**	-0.120	0.32	-0.38	0.70	-0.74	0.50
John Deere	**Tier 2**	-1.084	0.32	-3.34	0.00	-1.72	-0.45
John Deere	**Tier 3**	-1.158	0.31	-3.68	0.00	-1.77	-0.54
John Deere	**Tier 4 Interim**	-1.456	0.31	-4.72	0.00	-2.06	-0.85
John Deere	**Tier 4 Final**	-0.933	0.30	-3.15	0.00	-1.51	-0.35
Massey Ferguson	**Tier 1**	-1.171	0.37	-3.14	0.00	-1.90	-0.44
Massey Ferguson	**Tier 2**	-0.570	0.38	-1.49	0.14	-1.32	0.18
Massey Ferguson	**Tier 3**	-0.452	0.41	-1.10	0.27	-1.26	0.36
Massey Ferguson	**Tier 4 Interim**	-	-	-	-	-	-
Massey Ferguson	**Tier 4 Final**	-	-	-	-	-	-
New Holland	**Tier 1**	-0.319	0.41	-0.78	0.44	-1.12	0.49
New Holland	**Tier 2**	-0.509	0.41	-1.23	0.22	-1.32	0.30
New Holland	**Tier 3**	-1.085	0.43	-2.51	0.01	-1.93	-0.24
New Holland	**Tier 4 Interim**	-0.933	0.88	-1.06	0.29	-2.66	0.79
New Holland	**Tier 4 Final**	-	-	-	-	-	-
Other	**Tier 1**	-0.784	0.72	-1.09	0.28	-2.20	0.63
Other	**Tier 2**	0.117	0.72	0.16	0.87	-1.30	1.53
Other	**Tier 3**	-0.937	0.79	-1.19	0.24	-2.49	0.61
Other	**Tier 4 Interim**	-1.317	0.74	-1.78	0.08	-2.77	0.14
Other	**Tier 4 Final**	-0.610	0.69	-0.88	0.38	-1.96	0.74

						[95% confidence interval]	
Chassis	**EPA Tier**	**Coefficient**	**Std error**	**t-stat**	**P-Value**	**Lower**	**Upper**
4WD	**Tier 1**	0.020	0.46	0.04	0.96	-0.88	0.92
4WD	**Tier 2**	1.129	0.51	2.22	0.03	0.13	2.12
4WD	**Tier 3**	0.384	0.65	0.59	0.56	-0.90	1.67
4WD	**Tier 4 Interim**	0.087	0.66	0.13	0.90	-1.20	1.38
4WD	**Tier 4 Final**	2.653	0.67	3.99	0.00	1.35	3.96
Crawler	**Tier 1**	1.136	0.88	1.29	0.20	-0.60	2.87
Crawler	**Tier 2**	1.518	0.95	1.60	0.11	-0.34	3.38
Crawler	**Tier 3**	0.982	1.03	0.95	0.34	-1.04	3.01
Crawler	**Tier 4 Interim**	1.180	1.04	1.14	0.26	-0.86	3.22
Crawler	**Tier 4 Final**	3.741	1.04	3.61	0.00	1.71	5.78
FWA	**Tier 1**	-0.101	0.37	-0.27	0.79	-0.83	0.63
FWA	**Tier 2**	0.072	0.35	0.21	0.84	-0.62	0.76
FWA	**Tier 3**	0.556	0.54	1.04	0.30	-0.50	1.61
FWA	**Tier 4 Interim**	0.200	0.55	0.37	0.72	-0.87	1.27
FWA	**Tier 4 Final**	3.046	0.57	5.38	0.00	1.94	4.16
Other	**Tier 1**	-1.327	1.25	-1.06	0.29	-3.79	1.13
Other	**Tier 2**	-0.139	1.26	-0.11	0.91	-2.62	2.34
Other	**Tier 3**	-3.711	0.91	-4.09	0.00	-5.49	-1.93
Other	**Tier 4 Interim**	-3.228	0.79	-4.07	0.00	-4.78	-1.67
Other	**Tier 4 Final**	-	-	-	-	-	-

Model 2: All tested tractors with Max hp.hr/gal estimates for Tier 1 to Tier 4 Final

Source	Sum of Squares	df	Mean Square
Model	1,466.91	67	21.89
Residual	975.22	1,229	0.79
Total	2,442.13	1,296	1.88

Number of observations	1,297
F(67,1229)	27.59
Prob > F	0.00
R-squared	0.60
Adj. R-squared	0.58
Root MSE	0.89

		Coefficient	Std error	t-stat	P-Value	[95% confidence interval] Lower	Upper
Continuous	Constant	14.037	0.37	37.53	0.00	13.30	14.77
	PTOHP	0.011	0.00	27.81	0.00	0.01	0.01
	Time	0.105	0.02	5.84	0.00	0.07	0.14
Manufacturer	Case	0.496	0.44	1.12	0.26	-0.37	1.37
	CNH	-0.394	0.41	-0.97	0.34	-1.19	0.41
	John Deere	1.924	0.46	4.19	0.00	1.02	2.82
	Massey Ferguson	-0.150	0.33	-0.46	0.65	-0.79	0.49
	New Holland	0.324	0.30	1.07	0.28	-0.27	0.91
	Other	0.250	0.70	0.36	0.72	-1.12	1.62
Chassis	4WD	-2.852	0.64	-4.48	0.00	-4.10	-1.60
	Crawler	-1.005	0.42	-2.38	0.02	-1.83	-0.18
	FWA	-0.009	0.26	-0.03	0.97	-0.52	0.50
	Other	-1.396	1.55	-0.90	0.37	-4.43	1.64
EPA Tier	Tier 1	-	-	-	-	-	-
	Tier 2	-0.685	0.26	-2.60	0.01	-1.20	-0.17
	Tier 3	-1.057	0.51	-2.07	0.04	-2.06	-0.06
	Tier 4 Interim	-1.018	0.55	-1.84	0.07	-2.10	0.07
	Tier 4 Final	-4.488	0.64	-6.97	0.00	-5.75	-3.23

Manufacturer	Chassis	Coefficient	Std error	t-stat	P-Value	[95% confidence interval] Lower	Upper
Case	4WD	2.313	0.72	3.23	0.00	0.91	3.72
Case	Crawler	-	-	-	-	-	-
Case	FWA	-0.133	0.44	-0.30	0.76	-0.99	0.72
Case	Other	1.063	1.27	0.84	0.40	-1.43	3.55
CNH	4WD	0.654	0.52	1.27	0.21	-0.36	1.67
CNH	Crawler	-	-	-	-	-	-
CNH	FWA	-0.776	0.33	-2.32	0.02	-1.43	-0.12
CNH	Other	0.919	1.54	0.60	0.55	-2.10	3.94
John Deere	4WD	0.924	0.63	1.46	0.15	-0.32	2.17
John Deere	Crawler	-0.361	0.48	-0.75	0.46	-1.31	0.59
John Deere	FWA	-0.851	0.43	-1.96	0.05	-1.70	0.00
John Deere	Other	1.459	1.55	0.94	0.35	-1.58	4.50
Massey Ferguson	4WD	-	-	-	-	-	-
Massey Ferguson	Crawler	-	-	-	-	-	-
Massey Ferguson	FWA	-0.065	0.33	-0.20	0.84	-0.71	0.58
Massey Ferguson	Other	-	-	-	-	-	-
New Holland	4WD	1.692	0.71	2.37	0.02	0.29	3.09
New Holland	Crawler	-	-	-	-	-	-
New Holland	FWA	0.166	0.30	0.55	0.58	-0.43	0.76
New Holland	Other	-	-	-	-	-	-
Other	4WD	1.531	0.94	1.63	0.10	-0.31	3.37
Other	Crawler	1.142	0.83	1.37	0.17	-0.49	2.78
Other	FWA	-0.779	0.70	-1.11	0.27	-2.15	0.59
Other	Other	-	-	-	-	-	-

Manufacturer	EPA Tier	Coefficient	Std error	t-stat	P-Value	[95% confidence interval] Lower	Upper
Case	Tier 1	-	-	-	-	-	-
Case	Tier 2	-0.651	0.35	-1.85	0.07	-1.34	0.04
Case	Tier 3	-	-	-	-	-	-
Case	Tier 4 Interim	-	-	-	-	-	-
Case	Tier 4 Final	-0.470	0.68	-0.70	0.49	-1.80	0.86
CNH	Tier 1	-	-	-	-	-	-
CNH	Tier 2	0.453	0.40	1.14	0.25	-0.32	1.23
CNH	Tier 3	0.885	0.40	2.21	0.03	0.10	1.67
CNH	Tier 4 Interim	1.186	0.40	2.94	0.00	0.39	1.98

CNH	**Tier 4 Final**	1.841	0.40	4.65	0.00	1.06	2.62
John Deere	**Tier 1**	-	-	-	-	-	-
John Deere	**Tier 2**	-0.999	0.26	-3.78	0.00	-1.52	-0.48
John Deere	**Tier 3**	-1.015	0.25	-4.04	0.00	-1.51	-0.52
John Deere	**Tier 4 Interim**	-1.304	0.25	-5.31	0.00	-1.79	-0.82
John Deere	**Tier 4 Final**	-0.796	0.23	-3.51	0.00	-1.24	-0.35
Massey Ferguson	**Tier 1**	-	-	-	-	-	-
Massey Ferguson	**Tier 2**	0.592	0.27	2.19	0.03	0.06	1.12
Massey Ferguson	**Tier 3**	0.684	0.32	2.17	0.03	0.07	1.30
Massey Ferguson	**Tier 4 Interim**	-	-	-	-	-	-
Massey Ferguson	**Tier 4 Final**	-	-	-	-	-	-
New Holland	**Tier 1**	-	-	-	-	-	-
New Holland	**Tier 2**	-0.228	0.27	-0.83	0.40	-0.76	0.31
New Holland	**Tier 3**	-0.826	0.32	-2.56	0.01	-1.46	-0.19
New Holland	**Tier 4 Interim**	-0.546	0.83	-0.65	0.51	-2.18	1.09
New Holland	**Tier 4 Final**	-	-	-	-	-	-
Other	**Tier 1**	-	-	-	-	-	-
Other	**Tier 2**	0.885	0.43	2.05	0.04	0.04	1.73
Other	**Tier 3**	-0.159	0.56	-0.29	0.78	-1.25	0.93
Other	**Tier 4 Interim**	-0.509	0.48	-1.06	0.29	-1.45	0.43
Other	**Tier 4 Final**	0.168	0.39	0.43	0.67	-0.60	0.93

						[95% confidence interval]	
Chassis	**EPA Tier**	**Coefficient**	**Std error**	**t-stat**	**P-Value**	**Lower**	**Upper**
4WD	**Tier 1**	-	-	-	-	-	-
4WD	**Tier 2**	1.067	0.45	2.37	0.02	0.18	1.95
4WD	**Tier 3**	0.133	0.64	0.21	0.84	-1.13	1.39
4WD	**Tier 4 Interim**	-0.157	0.68	-0.23	0.82	-1.48	1.17
4WD	**Tier 4 Final**	2.489	0.69	3.63	0.00	1.14	3.83
Crawler	**Tier 1**	-	-	-	-	-	-
Crawler	**Tier 2**	0.410	0.44	0.93	0.35	-0.46	1.28
Crawler	**Tier 3**	-0.151	0.60	-0.25	0.80	-1.33	1.03
Crawler	**Tier 4 Interim**	0.071	0.64	0.11	0.91	-1.19	1.34
Crawler	**Tier 4 Final**	2.703	0.64	4.19	0.00	1.44	3.97
FWA	**Tier 1**	-	-	-	-	-	-
FWA	**Tier 2**	0.200	0.23	0.87	0.39	-0.25	0.65
FWA	**Tier 3**	0.686	0.47	1.46	0.15	-0.24	1.61
FWA	**Tier 4 Interim**	0.359	0.52	0.69	0.49	-0.67	1.38
FWA	**Tier 4 Final**	3.268	0.54	6.00	0.00	2.20	4.34
Other	**Tier 1**	-	-	-	-	-	-
Other	**Tier 2**	1.230	1.31	0.94	0.35	-1.34	3.80
Other	**Tier 3**	-2.336	1.46	-1.60	0.11	-5.20	0.53
Other	**Tier 4 Interim**	-1.845	1.38	-1.33	0.18	-4.56	0.87
Other	**Tier 4 Final**	1.465	1.29	1.13	0.26	-1.07	4.00

Model 3: All tested tractors with Max hp.hr/gal estimates for Tier 4 Final

Source	Sum of Squares	df	Mean Square
Model	301.95	14	21.57
Residual	168.29	299	0.56
Total	470.24	313	1.50

Number of observations	314
F(14,299)	38.32
Prob > F	0.00
R-squared	0.64
Adj. R-squared	0.63
Root MSE	0.75

		Coefficient	Std error	t-stat	P-Value	95% confidence interval Lower	Upper
Continuous	Constant	11.941	0.80	14.99	0.00	10.37	13.51
	PTOHP	0.011	0.00	19.30	0.00	0.01	0.01
	Time	0.141	0.03	5.27	0.00	0.09	0.19
Manufacturer	Case	0.028	0.54	0.05	0.96	-1.04	1.10
	CNH	0.688	0.13	5.48	0.00	0.44	0.94
	John Deere	0.091	0.12	0.74	0.46	-0.15	0.33
	Other	-0.487	0.20	-2.39	0.02	-0.89	-0.09
Chassis	Crawler	-1.658	0.27	-6.25	0.00	-2.18	-1.14
	4WD	-0.909	0.58	-1.56	0.12	-2.06	0.24
	Other	-0.720	0.26	-2.74	0.01	-1.24	-0.20

Manufacturer	Chassis	Coefficient	Std error	t-stat	P-Value	95% confidence interval Lower	Upper
Case	Other	-1.228	0.68	-1.81	0.07	-2.56	0.10
CNH	4WD	-1.323	0.60	-2.19	0.03	-2.51	-0.14
CNH	Other	-1.326	0.37	-3.61	0.00	-2.05	-0.60
John Deere	Crawler	1.014	0.36	2.85	0.01	0.31	1.71
John Deere	4WD	-0.104	0.65	-0.16	0.87	-1.38	1.18

Appendix 2. Farm Survey

Introduction

INFORMED CONSENT TO PARTICIPATE IN A RESEARCH PROJECT:
"Assessing the Cost and Fuel Consumption of Off-Road Agricultural Equipment"
This form asks for your agreement to participate in a research project on off-road agricultural equipment. Your participation involves brief taking a survey, and it is expected that it will take approximately 10 minutes. There are no risks anticipated with your participation, all responses will be aggregated into overall averages. All of California agriculture may benefit from your participation. If you are interested in participating, please review the following information:

The purpose of the study is to examine and compare the normal maintenance and repair costs and efficiency of agricultural tractors across EPA emissions tiers. Potential benefits associated with the study include a better understanding of the cost and fuel efficiency tradeoffs between older and newer pieces of agricultural equipment.

If you agree to participate, you will be asked to complete a brief (10 minute) survey, which will ask you questions about operating and maintenance rates for agricultural tractors. Please be aware that you are not required to participate in this research, refusal to participate will not involve any penalty or loss of benefits to which you are otherwise entitled, and you may discontinue your participation at any time. You may omit responses to any questions you choose not to answer. There are no risks anticipated with your participation in this study, as your survey responses will be collected anonymously.

This research is being conducted by Drs. Michael McCullough and Lynn Hamilton in the Agribusiness Department at Cal Poly, San Luis Obispo. If you have questions regarding this study or would like to be informed of the results when the study is completed, please contact Dr. McCullough at mpmccull@calpoly.edu or 805-756-5009.

If you have concerns regarding the manner in which the study is conducted, you may contact Dr. Michael Black, Chair of the Cal Poly Institutional Review Board, at (805) 756-2894, mblack@calpoly.edu, or Ms. Trish Brock, Director of Research Compliance, at (805) 756-1450, pbrock@calpoly.edu.

If you agree to voluntarily participate in this research project as described, please indicate your agreement by completing the survey. Please keep a copy of this form for your reference and thank you for your participation in this research.

US EPA Emission Tier Standards by Year

<table>
<tr><th>Maximum horsepower</th><th>1995</th><th>1996</th><th>1997</th><th>1998</th><th>1999</th><th>2000</th><th>2001</th><th>2002</th><th>2003</th><th>2004</th><th>2005</th><th>2006</th><th>2007</th><th>2008</th><th>2009</th><th>2010</th><th>2011</th><th>2012</th><th>2013</th><th>2014</th><th>2015+</th></tr>
<tr><td><11</td><td colspan="5">-</td><td colspan="5">7.8 / 6.0 / 0.75</td><td colspan="3">5.6 / 6.0 / 0.6</td><td colspan="8">5.6 / 6.0 / 0.30[a]</td></tr>
<tr><td>11<=hp<25</td><td colspan="5">-</td><td colspan="5">7.1 / 4.9 / 0.60</td><td colspan="3">5.6 / 4.9 / 0.60</td><td colspan="8">5.6 / 4.9 / 0.30</td></tr>
<tr><td>25<=hp<50</td><td colspan="4">-</td><td colspan="5">7.1 /4.1 / 0.60</td><td colspan="4">5.6 / 4.1 / 0.45</td><td colspan="5">5.6 / 4.1 / 0.22</td><td colspan="3">3.5 / 4.1 / 0.02</td></tr>
<tr><td>50<=hp< 75</td><td colspan="3">-</td><td colspan="6">- / 6.9 / - / - [b]</td><td colspan="4">5.6 / 3.7 / 0.30</td><td colspan="5">3.5 / 3.7 / 0.22[c]</td><td colspan="3">3.5 / 3.7 / 0.02[c]</td></tr>
<tr><td>75<=hp<100</td><td colspan="3">-</td><td colspan="6">- / 6.9 / - / - [b]</td><td colspan="4">5.6 / 3.7 / 0.30</td><td colspan="4">3.5 / 3.7 / 0.30</td><td colspan="3">0.14 / 2.5 / 3.7 /</td><td rowspan="2">0.14 /0.30 /3.7 /0.015b</td></tr>
<tr><td>100<=hp<175</td><td colspan="2">-</td><td colspan="6">- / 6.9 / - / - [b]</td><td colspan="4">4.9 / 3.7 / 0.22</td><td colspan="5">3.0 / 3.7 / 0.22</td><td colspan="3">0.14 / 2.5 / 3.7 /</td></tr>
<tr><td>175<=hp<300</td><td>-</td><td colspan="7">1.0 / 6.9 / 8.5 / 0.40b</td><td colspan="3">4.9 / 2.6 / 0.15</td><td colspan="5" rowspan="3">3.0 / 2.6 / 0.15e</td><td colspan="3" rowspan="3">0.14 / 1.5 / 2.6 / 0.015</td><td colspan="2" rowspan="3">0.14 /0.30 /2.2 /0.015b</td></tr>
<tr><td>300<=hp<600</td><td>-</td><td colspan="5">1.0 / 6.9 / 8.5 / 0.40b</td><td colspan="5">4.8 / 2.6 / 0.15</td></tr>
<tr><td>600<=hp<=750</td><td>-</td><td colspan="6">1.0 / 6.9 / 8.5 / 0.40b</td><td colspan="4">4.8 / 2.6 / 0.15</td></tr>
<tr><td>> 750hp</td><td colspan="5">-</td><td colspan="6">1.0 / 6.9 / 8.5 / 0.40[b]</td><td colspan="5">4.8 / 2.6 / 0.15</td><td colspan="4">0.30 / 2.6 / 2.6 / 0.07[b]</td><td>0.14 /2.6 /2.6 /0.03b</td></tr>
</table>

Tier 1	Tier 2	Tier 3	Tier 4 Interim	Tier 4 Final

Q1 Please indicate each bin of horsepower/EPA tier tractor you own, lease, or rent.
(Choose all that apply)

	Less than 25hp	Between 25hp and 50hp	Between 50hp and 75hp	Between 75hp and 100hp	Between 100hp and 175hp	Between 175hp and 300hp	Between 300hp and 600hp	Between 600hp and 750hp	Above 750hp
Tier 0									
Tier 1									
Tier 2									
Tier 3									
Tier 4 Interim									
Tier 4 Final									

Q2 Please indicate the brand of tractor(s) you own, lease, or rent. (Choose all that apply)

- o Case IH
- o Challenger
- o CLAAS
- o Fendt
- o John Deere
- o Kubota
- o Massey Ferguson
- o New Holland
- o Versatile
- o Other ____

Q3 Where is maintenance and/or repair work on the tractors you operate performed? (Choose all that apply)

- o Onsite by farm employee
- o Onsite by mobile mechanic
- o Offsite by service provider/dealer

Q3a What is your average farm employee mechanic labor rate? ($/hr)

____

Q3b What is your average mobile mechanic labor rate? ($/hr)

____

Q3c What is your average offsite service provider labor rate? ($/hr)

____

Q4 Do any of your tractor's purchase/lease/rental agreements include a maintenance and/or repair plan(warranty)?

- ○ Yes
- ○ No

Q4a Please describe the terms of your maintenance and/or repair(warranty) plan(s).

____

The following two questions refer to annual normal operational ***maintenance*** time spent on tractors you own or lease.

Q5 On average, how many hours per year do you have maintenance performed on a single tractor? (Please enter average hours into the boxes for those tractor hp/EPA tier combinations you own, lease, or rent)

	Less than 25hp	Between 25hp and 50hp	Between 50hp and 75hp	Between 75hp and 100hp	Between 100hp and 175hp	Between 175hp and 300hp	Between 300hp and 600hp	Between 600hp and 750hp	Above 750hp
Tier 0									
Tier 1									
Tier 2									
Tier 3									
Tier 4 Interim									
Tier 4 Final									

Q6 Does average maintenance hours/year change for hours of use per year?

- ○ Yes
- ○ No

Q7 On average, by how many hours do maintenance hours/year change for every 100 hours of use per year?

0 5 10 15 20

Hours

The following two questions refer to annual average ***repair*** time spent on tractors you own or lease.

Q8 On average, how many hours per year do you have repairs performed on a single tractor?
(Please enter average hours into the boxes for those tractor hp/EPA tier combinations you own, lease, or rent)

	Less than 25hp	Between 25hp and 50hp	Between 50hp and 75hp	Between 75hp and 100hp	Between 100hp and 175hp	Between 175hp and 300hp	Between 300hp and 600hp	Between 600hp and 750hp	Above 750hp
Tier 0									
Tier 1									
Tier 2									
Tier 3									
Tier 4 Interim									
Tier 4 Final									

Q9 Does average repair hours/year change for hours of use per year?

- ○ Yes
- ○ No

Q10 On average, by how many hours do repairs hours/year change for every 100 hours of use per year?

	0	5	10	15	20
Hours