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The Effect of the Environmental Protection Agency's Exhaust Emissions Standards on Diesel Tractor Fuel Efficiency

by

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The Effect of the Environmental Protection Agency's Exhaust Emissions Standards on Diesel Tractor Fuel Efficiency

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Since its inception the U.S. Environmental Protection Agency (EPA) has been tasked with the assessment, research, and education, of the nation's environment while also maintaining and enforcing national standards. A characteristic display of this agency's work is the Exhaust Emission Standards for Nonroad Compression-Ignition Engines that began in 1995. Since the introduction of exhaust emissions standards in 1995, no study has fully examined the subsequent impact on fuel efficiencies.

In this paper we analyze the resulting fuel efficiency caused by the EPA's exhaust emission standards. We identify the impact of the emissions standards on tractor fuel efficiency through a statistical analysis during various field operations across multiple tractor drivetrains, sizes, policy tiers, and horsepower while controlling for fuel efficiency advancements developed during the introduction of emission standards. To accomplish our objective, we use the University of Nebraska-Lincoln's Nebraska Tractor Test Lab database. Preliminary results suggest that overall emissions standards have negatively impacted fuel efficiency. However, the most recent emission standards, Tier 4 and Tier 4 Final have not impacted fuel efficiency as harshly as earlier emission standard tiers.

1. Introduction

Since its inception the U.S. Environmental Protection Agency (EPA) has been tasked with the assessment, research, and education, of the nation's environment while also maintaining and enforcing national standards. Today many public health and environmental organizations advocate that the EPA's actions move the nation forward, but critics of the agency argue government overreach to businesses and landowners. A characteristic display of this agency's work is the Exhaust Emission Standards for Nonroad Compression-Ignition Engines that began in 1995. Given the highly diverse group of equipment, ranging from small generators and hobbyist tractors to drastically larger mining equipment, construction equipment, locomotives, and agricultural equipment responsible for much of the nation's economic activity, interest groups from all sides come to join the conversation (EPA Final Rule 2004).

Discussion regarding the exhaust emission standards policy cost-effectiveness, alternatives, time for innovation development, application of requisite technology already available, and safety concerns were heavily debated. The largest concern coming from many manufactures was the difficulty of designing an engine to meet these standards without compromising the engines' power output and efficient fuel consumption (Lloyd and Cackette 2001; EPA Final Rule 2004). Since the introduction of exhaust emissions standards in 1995, no study has fully examined the subsequent impact on fuel efficiencies.

In this paper we analyze the resulting fuel efficiency caused by the Environmental Protection Agency's exhaust emission standards. Specifically, we investigate the impact of the exhaust emission standards on tractors' fuel efficiency through the use of agricultural tractors. We identify the impact of the emissions standards on tractor fuel efficiency through statistical and econometric analysis during various field operations across multiple tractor drivetrains, sizes, policy tiers, and horsepower while controlling for fuel efficiency advancements created during the introduction of the emission standards. To accomplish our objective, we use the University of Nebraska-Lincoln's Nebraska Tractor Test Lab (UNL-NTTL) database. The UNL-NTTL database contains tractor attributes of year, manufacturer, model, drivetrain, transmission, and EPA Tier along with corresponding metrics of engine size, compression ratio, and various emissions technologies that will be included in our analysis to detail the heterogenous impact to tractor fuel efficiency.

This paper is partitioned into seven distinct sections. The first is the introduction. The following section (section 2) provides a baseline background of the exhaust emissions standards. Section 3 presents a literature review of prior relevant research helpful to our study. Section 4 examines all data applied to our investigation and provides motivation for inclusion. The methods of this study are described in Section 5, presenting the statistical and econometric approaches. Section 6 includes the results of our models as well as interpretation and discussion of these results. Finally, section 7 concludes this paper by reiterating the key findings of our investigation, addressing the contribution this study has served, and the room for future research interests.

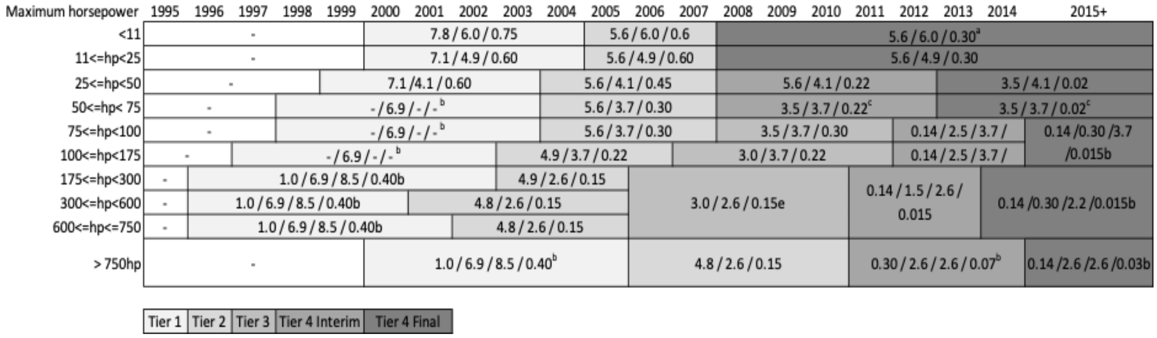
2. Background

The background is split into two subsections. The first is a policy description, providing an overview of the policy by detailing the regulatory design and framework. The second subsection describes the policy motivation and purpose leading to the regulatory action of exhaust emissions standards for nonroad diesel engines.

2.1 Policy Description

Following a similar framework as the 1970s and 1980s regulation of gaseous and particle emissions for highway use of diesel engines, the EPA enacted a regulatory action of exhaust emission standards designed as tiered system policy for nonroad diesel vehicles beginning in 1996 (EPA Final Rule 2004). Garnishing power from the 1990 Clean Air Act Amendments (CAAA), specific emissions: nitrogen oxides (NOx), carbon monoxide (CO), sulfur oxides (SOx), hydrocarbons (HC), non-methane hydrocarbons (NMHC) and particulate matter (PM), produced from all newly manufactured nonroad diesel vehicles were subject to maximum allowable concentration standards. These emissions standards were gradually phased-in depending on the engine size (measured by horsepower and abbreviated as "hp") and year of the equipment. Figure 1 shows the phase-in schedule and emission standard for each EPA Tier. It is important to note that the EPA ruled for the exhaust emissions standards to be met but did not dictate how manufactures achieve emission reductions. As a result, various emission reduction strategies were developed by manufacturers, differing with respect to engine calibration, power devices, emissions control devices, and engine configuration.

Figure 1. EPA emission tiers phase-in schedule



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

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

a) The PM standard for hand-start, air cooled, direct injection engines below 11hp 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 alternatively 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. (CARB 2017)

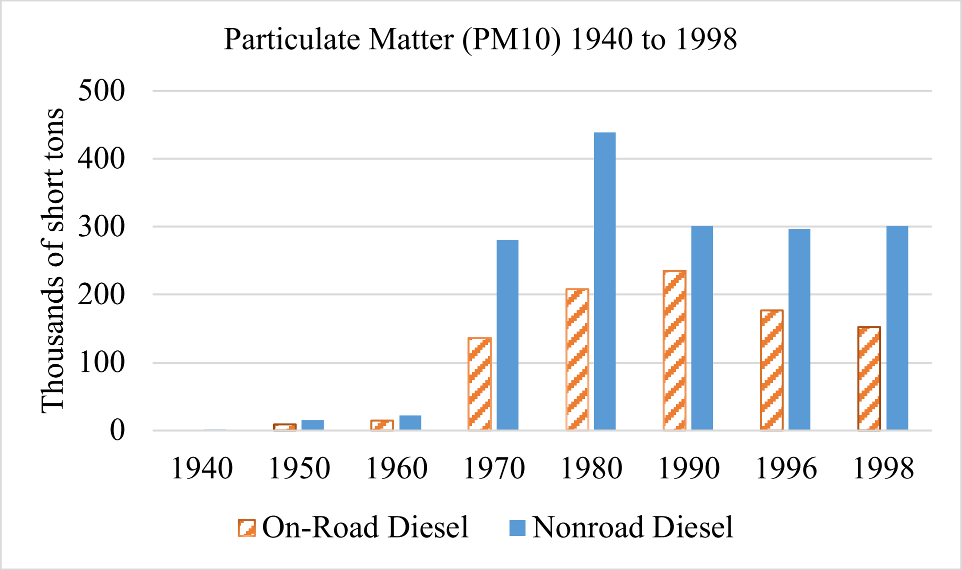
2.2. Policy Motivation

The basis for regulatory action was largely driven by health and environmental concerns. Citing the Regulatory Impact Analysis conducted, the EPA states “Such emissions lead to adverse health and welfare effects associated with ozone, PM, NOx, SOx, and volatile organic compounds, including toxic compounds” (EPA Final Rule 2004, p.6). Health problems related to these emissions include premature mortality, aggravation of respiratory and cardiovascular disease, aggravation of existing asthma, acute respiratory symptoms, chronic bronchitis, and decreased lung function (EPA Health Assessment 2002). There is also evidence that the exhaust is carcinogenic to humans via inhalation. Environmental welfare problems associated with these diesel emissions are regional haze leading to impaired visibility, while acid disposition and polycyclic organic matter

(POM) disposition have eutrophication and nitrification effects on fish, wildlife, and natural resources (Lloyd and Cackette 2001; EPA Final Rule 2004).

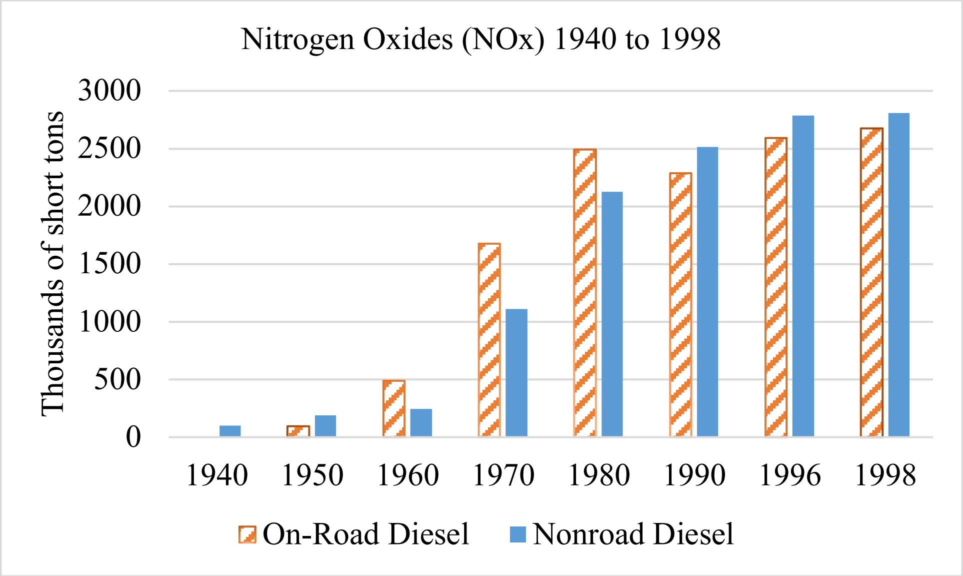
The EPA's integrated risk information system (IRIS) program conducted a technological, environmental, and health report by collecting data from gasoline and diesel vehicles including those used for both on-road and nonroad. Using this data, analysis of sulfur dioxide, carbon monoxide, volatile organic compounds (VOCs), nitrogen oxides, and particulate matter emissions exposed temporal evidence that nonroad diesel engines were lagging behind their on-road diesel and gasoline counterparts for emission improvements. Data from 1970 to 1998 presents improvements from total mobile sources (both gasoline and diesel, both on-road and nonroad) but the improvements were largely driven by gasoline and on-road diesel sources. For example, total PM_{10} (particulate matter 10 microns in size) from all mobile sources decreased from 12.2 million tons to just over 2.8 million tons between 1970 and 1998. Meanwhile, emissions from on-road and nonroad diesel engines increased from 320 thousand tons to more than 521 thousand tons during the same period. Such that, in 1970 diesel accounted for 3% of total PM_{10} emissions and increased to 18% of total PM_{10} emissions in 1998 (EPA Health Assessment 2002). Although, there were also large differences between the sources of on-road and nonroad diesel over this period which are illustrated in Figure 2. A shorter timeframe, 1980 to 1998, indicates on-road diesel sources were able to achieve a 27% reduction in PM_{10} from 208 thousand to 152 thousand tons while nonroad diesel PM_{10} emissions decreased about 31% from 439 thousand to 301 thousand tons (EPA Emission Trends 2000).

Figure 2. Trends in PM_{10} emissions from on-road and nonroad diesel engines from 1940 to 1998 (EPA Emission Trends 2000)



Conversely, NOx emissions of nonroad diesel sources increased 33% from 2.1 million tons in 1980 to 2.8 million tons in 1998. Another illustration of emissions dynamics is described in Figure 3.

Figure 3. Trends in NOx emissions from on-road and nonroad diesel engines from 1940 to 1998 (EPA Emission Trends 2000)



As for SO2, in 1998 only 7% came from mobile sources, diesels were responsible for 74% of that total. Reduced SO2 emissions from on-road diesel engines have decreased 72% from 1980 to 1998 and this improvement is often contributed to the regulation of on-road diesel fuel sulfur content starting in 1993. Although nonroad diesels did not follow the same trend, by 1998 nonroad diesel engines emitted 785 thousand tons of SO2, accounting for 56% of mobile sourced SO2 emissions (EPA Health Assessment 2002).

The rising share of nonroad diesel engines on total emissions inventory concerned many, leading the EPA to design and implement the exhaust emission standards of nonroad diesel vehicles in 1995. With comprehensive engine and fuel standards taking effect by the 2008 model year though the phasing-in of rules over several years, the EPA derived estimates from similarly regulated on-road vehicles and the advanced exhaust emission control devices available to producers. Designing new test procedures, not-to-exceed requirements and certification standards, the agency estimated PM reductions of 95%, NOx reductions of 90%, and "virtual elimination" of sulfur oxides resulting in significant environmental and health benefits. "Total benefits of this rule will be approximately $80 billion annually by 2030.— Costs for both the engine and fuel requirements will be many times less, at approximately $2 billion annually" (EPA Final Rule 2004, p.2). Projections out to 2030 suggest a decrease in yearly emissions of NOx and PM by 738 thousand and 129 thousand tons, respectively (EPA Final Rule 2004).

3. Literature Review

While work similar to our interests have been done surrounding the CAFE standards that regulate on-road vehicles (Thorpe 1997; Crabb and Johnson 2010), little research has had a comprehensive empirical evaluation of the effect the exhaust emission standards have had on nonroad diesel vehicles' fuel efficiencies (McCullough, Hamilton, and Walters 2022). Instead, more specific research has investigated certain aspects of diesel engines that have changed over time. Ample work has been done from an engineering perspective by examining evolving engine calibration techniques, adopted or innovated emissions technologies, and developing predictive fuel consumption models (Grisso et al. 2010; De Rudder 2012; Stanton, Charlton, and Vajapeyazula 2013; Howard et al. 2013; Hoy et al. 2014). While other disciplines have reviewed environmental and health effects due to diesel emissions (McClellan 1987; Zhu et al. 2002; Delfino 2002). Furthermore, policy monitoring relating to mobile sources and diesel emissions regulations has had both overarching and acute research interests (Dowlatabadi, Lave, and Russell 1996; Lloyd and Cakette 2001; Hubbel et al. 2009). Expanding on evolving engine calibration techniques and adopted or innovated technologies, previous work has recognized and measured changes in tractor power and fuel efficiencies, but no studies have analyzed the effect the EPA's exhaust emissions standards has had on tractors' fuel efficiencies.

Work by Hoy et al. (2014) from the Nebraska Tractor Test Lab (NTTL) has examined changes in diesel consumption and the tractor technologies available to manufactures and producers today. The NTTL describes many of the technologies that manufacturers, or producers choose to use and what the benefit of those technologies may be. Hoy et al. (2014) concluded that primary fuel use technologies implemented by manufacturers, like transmission type, waste heat recovery systems, exact compression ratios and combustion temperatures have shown efficiency gains at testing conditions while uncertain gains from field conditions. Reporting specific fuel consumption (measured as horsepower hour per gallon, Hp.hr/gal) of "tractors tested at NTTL from 1958 to 2012 improved by 19.7% for Power Take-Off (PTO) power and 23.4% for drawbar power when comparing data averaged over the last 5 years of this period versus the first 5 years of this period" (Hoy et al. 2014, p.4).

On behalf of the California Air Resources Board, Lloyd and Cackette (2001), "summarized and evaluated published information on diesel emissions, their effects on the environment and human health, and ways to minimize emissions and effects" (Lloyd and Cackette 2001, p.2). Highlighting the growing role diesel engines have in the public and private sectors, the authors examine several technological advancements that could drastically reduce emissions and result in a Decade of Clean Diesel while also recognizing the difficulty in doing so. Acknowledging that "Some fuel combustion efficiency has been traded for lower emissions to attain standards" (Lloyd and Cackette 2001, p.20).

Another report for the California Air Resource Board reviewed various effects caused by the EPA tiered regulation (McCullough, Hamilton, and Walters 2022). McCullough, Hamilton, and Walters (2022) describe the variability of fuel efficiency throughout the EPA tiered regulation. Using Nebraska Tractor Test Laboratory measures of tractors from 1988 to 2021, the authors found that early EPA Emission Tiers resulted in initial negative impacts on fuel efficiency, although on average tractors meeting Tier 4 Final standards are statistically more fuel efficient than earlier tiers (McCullough, Hamilton, and Walters 2022). The report concludes with logical next steps for future research. Reiterating how the EPA rule required manufactures to meet the emission standards but did not dictate how standards are met resulted in various independent paths between manufacturers, the authors state that an analysis including specific emission technologies is needed to understand the different individual effects on fuel efficiency. This paper builds on McCullough, Hamilton, and Walters (2022). Important characteristics like drawbar power, advanced emission reduction devices, and engine performance technologies that are missing from this past CARB report are incorporated in this study. By including these variables, we can control for unobservable effects in previous analysis, providing a better perspective for understanding the effect on manufactured tractors' fuel efficiencies throughout the exhaust emissions standards.

Grisso (2010) compared common and innovative models to estimate tractor fuel consumption. This study used reported tractor metrics of Power-take-off horsepower (PTO_{Hp}), Drawbar horsepower (DB_{Hp}), Engine Speed (measured as revolutions per minute (RPM)), and fuel efficiency (Hp.hr/gal) at varying load profiles to derive a "specific" fuel consumption model that has the capacity to predict fuel consumption at full or partial loads, as well as when engine speeds are reduced from full throttle. Applying data from 1980 to 2020, fuel savings of 10% to 15% were reported by using average and maximum specific fuel consumption (Grisso 2010). Our analysis applies Grisso's "specific" model, that best represents measured fuel consumption, to predict fuel consumption measures during various field operations. By normalizing these fuel consumption measures by tractor power we calculate the fuel efficiency based on typical load profiles during common field operations. These resulting fuel efficiencies are then used in our analysis to determine the heterogenous effects of tractor fuel efficiencies throughout the exhaust emission standards.

4. Data

To study the changes and effects on tractor fuel efficiency throughout the EPA's exhaust emission standards for nonroad compression-ignition engines we must utilize data that is relevant to the investigation. This section examines the origin and motivates the purpose for the data included in our analysis.

Our analysis calls upon compiled data from the Nebraska Tractor Test Laboratory (NTTL) test reports. With over 3500 tests total and approximately twenty-five annually, the NTTL tests tractors at various operating conditions. Measurements of power, speed, and fluid consumption are recorded and published to be publicly available on the NTTL website (NTTL, 2023). Given our interests of the modern industrial agricultural sector, our market level analysis includes tractors with a PTO horsepower greater than one hundred, as smaller tractors are rarely operational on modern farms and ranches in the United States. Leaving us with 1046 applicable observations.

The NTTL is one of only a handful of Organization for Economic Co-operation and Development (OECD) certified agricultural tractor test centers, and the lone location for the United States (OECD 2022). Certified OECD test centers are responsible for unbiased third-party testing and since 1973, OECD member countries and notable non-member countries of China, India, and the Russian Federation, all adhere to the tractor test codes. The results of the OECD tractors test are commonly used as certification of performance. Most tractors sold in the United States have an official OECD test report, while the few untested tractors are not intended for on-farm use (McCullough, Hamilton, and Walters 2022).

4.1 Tractor Attributes and Metrics

Tractor fuel efficiency is often measured differently than other modern technology. Instead of using kilometer per liter (km/L) or miles per gallon (mpg) to understand how far a vehicle can travel from a specific volume of fuel, a tractor's fuel efficiency is measured by how much "work" can be done in a specific amount of time. Tractor's fuel efficiency is measured this way because the Power Take-off (PTO) units, hydraulics, and drawbar capabilities required by the tractor depend on the specific application. For example, a tractor used in alfalfa operations would likely need to use all three capabilities. Images in Figure 4 demonstrate three different tractor uses in the production of alfalfa. The PTO of a tractor is often used with implements (attachments) to utilize rotational forces. This could be the use of powering blades of a mower, or to power the auger feeding and bale tensioning mechanisms of a round baler. The drawbar capacity of a tractor refers to the machine's ability to pull (tow). Alfalfa applications of drawbar power are of concern to pulling a planter, rake, baler, or trailer. Finally, hydraulic functions typically consider the lifting capability. Again, in alfalfa production this could be the use of hydraulics to alter the height of the conditioner, or it could be using a bale spear to lift, move, and handle a bale after production.

Figure 4. Various tasks involved with Alfalfa production

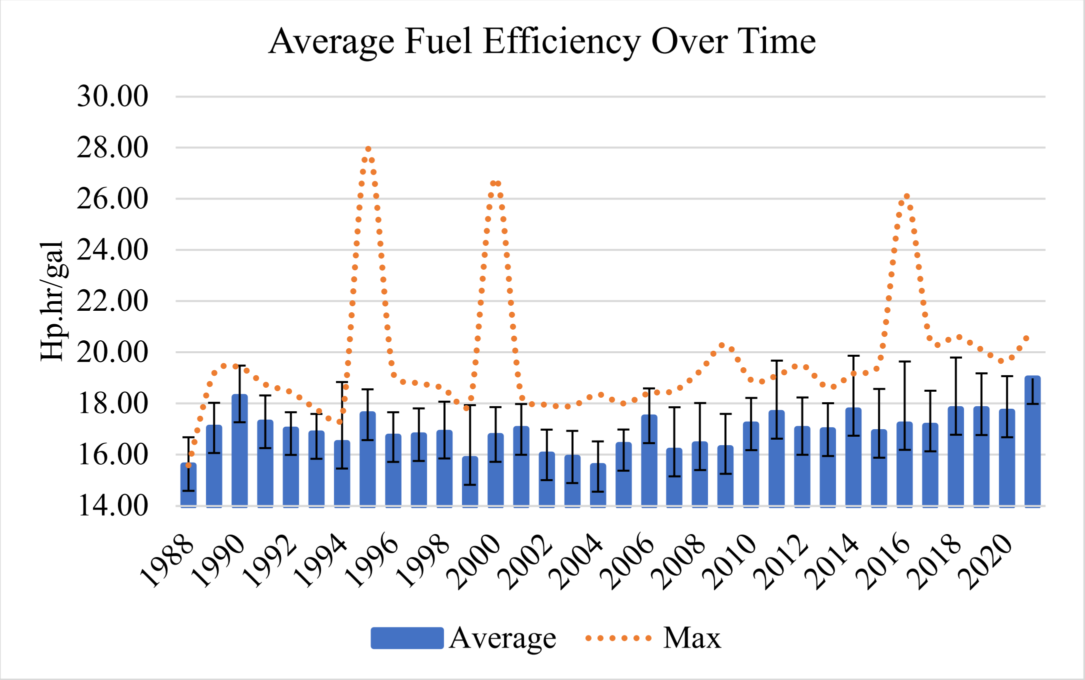
a) PTO (Conditioner) b) Drawbar (Baling) c) Hydraulic (Lifting)

Another example in which a tractor would be needed in various scenarios is in the production of corn. During corn production, a tractor's PTO may be used to provide power to a planter or a fertilizer spreader. Commonly the drawbar ability of a tractor during corn production would be involved in tilling, planting, and assisting harvest operations with pull-behind implements. Hydraulic power is often used in corn production to run an air drill planter, and for lifting or folding equipment like tillage implements.

Given the diverse responsibilities and versatility of a tractor, the measure of fuel consumption must account for more than only the fuel spent over a given distance. Instead, the rate of work, or the rate of expending energy is considered power, and reported as horsepower (Hp). Horsepower-hour (Hp-hr) is therefore a unit of work, or energy, as it is power multiplied by time. So, horsepower-hour per gallon (Hp-hr/gal) is a measure of efficiency as it is useful work done by the tractor divided by the fuel (energy) expended.

Summary statistics presented in Figure 5 illustrate that average fuel efficiency has increased over time. Although, variability across tested tractors indicate there could be other confounding factors affecting this trend. The following section describes each attribute included in our analysis individually.

Figure 5. Fuel efficiency descriptive statistics at max power



4.2 Manufacturer

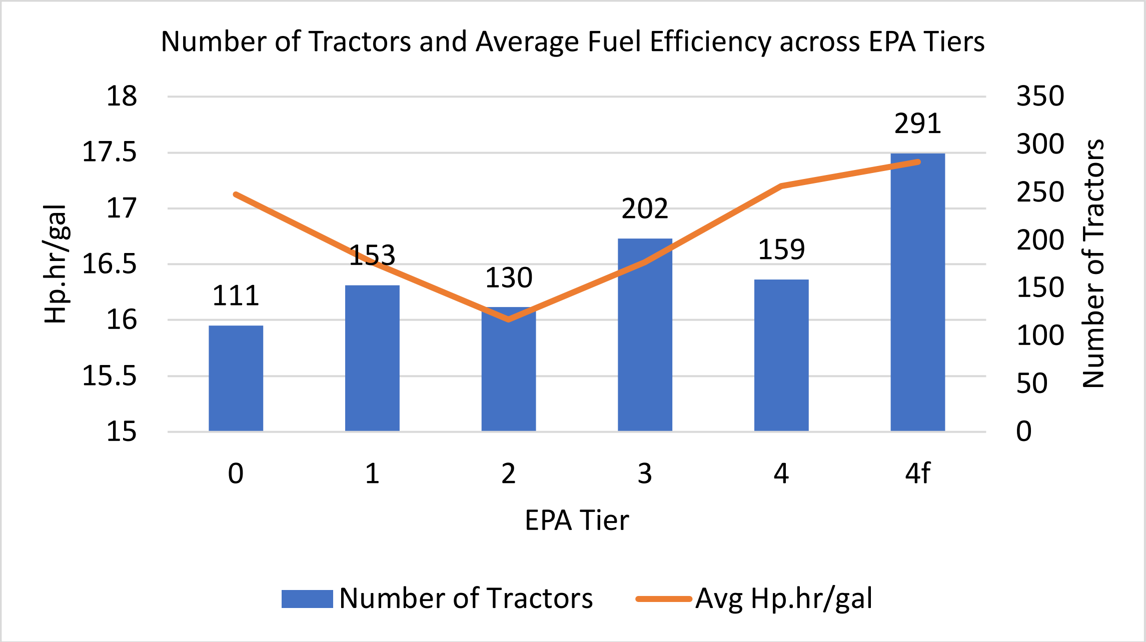
Within our dataset of 1046 tractors there are 40 different manufacturers recorded, although three parent companies produced the majority of tested tractors; AGCO/Massey (AGCO), Case New Holland (CNH), and John Deere (JD), with 400, 332, and 260 tractors tested since 1988, respectively. The 54 other tractors that were not produced by these three manufacturers are grouped together and labeled as ‘Other.’

4.3 EPA Tier

The design of the EPA’s regulation provides a framework specifying the maximum allowable emission concentrations for tractors, dependent on respective horsepower and manufactured year. These categorizing bins of tractors are considered Tiers and beginning with Tier 1 in the 1996 model year, policy rules mandate that tractor manufacturers gradually phase in lower emitting diesel tractors. It is also important to note that within each tier the EPA allowed for emission credits to be collected for engines that emit less than what is required. These emission credits can then be used to offset engines that do not comply after a new emission tier goes into effect.

As mentioned before, the EPA ruled for the emission standards to be met but did not stipulate how the manufactures achieve emission reductions. This type of ruling allowed manufacturers to take different approaches with respect to engine calibration, power devices, emissions control devices, and engine configuration. Our dataset includes 111 tractors prior to emissions regulation, 153 tractors adhering to the first regulation installment, 130 Tier 2 tractors, 202 Tier 3, 159 Tier 4 interim, and 291 Tier 4 final tractors. Figure 6 provides the number of tractors within each tier and the average fuel efficiency across these tiers. Again, across all tiers tractors vary in the methods used by manufacturers to meet emission standards.

Figure 6. Tested tractors and hp.hr/gal at max power by Emissions Tier



4.4 Drivetrain

An important tractor attribute to account for the impact on tractor fuel efficiency is the drivetrain. The drivetrain of a tractor refers to the components that deliver mechanical power from the engine to the driven components that propel the tractor. Our data contains seven different drivetrain configurations. Figure 7 includes images representing five different drivetrains. Within our dataset, Front Wheel Assist (FWA) comprises the majority at 754 of our observations. Four Wheel Drive (4WD), Crawlers, and Two Wheel Drive (2WD) are the following most common configurations, with 109, 127, and 56 observations, respectively. Less commonly implemented are Quadtracs (4TD, John Deere's FTA) and half tracs for which there are 29 and 6 observations, respectively. FWA tractors are essentially rear wheel driven tractors that have a limited ability to engage the front wheels, as opposed to 4WD in which all four wheels are allocated power constantly. Crawlers have two permanent tracks in place of tires and wheels, while Quadtracs implement four individual tracks and half-tracks use a combination of wheels in the front and tracks in the rear. Due to the similarities between Crawlers, half-tracks, and quad-tracks, within our analysis we grouped the three drivetrains together and considered them all 'crawlers.'

Figure 7. Images correspond to different tractor drivetrain configurations.

a) Front Wheel Assist (FWA)

b) Four Wheel Drive (4WD)

c) Crawler

d) Quad-track (4TD, FTA)

e) Half-Track

Source: NTTL 2023

4.5 Transmission

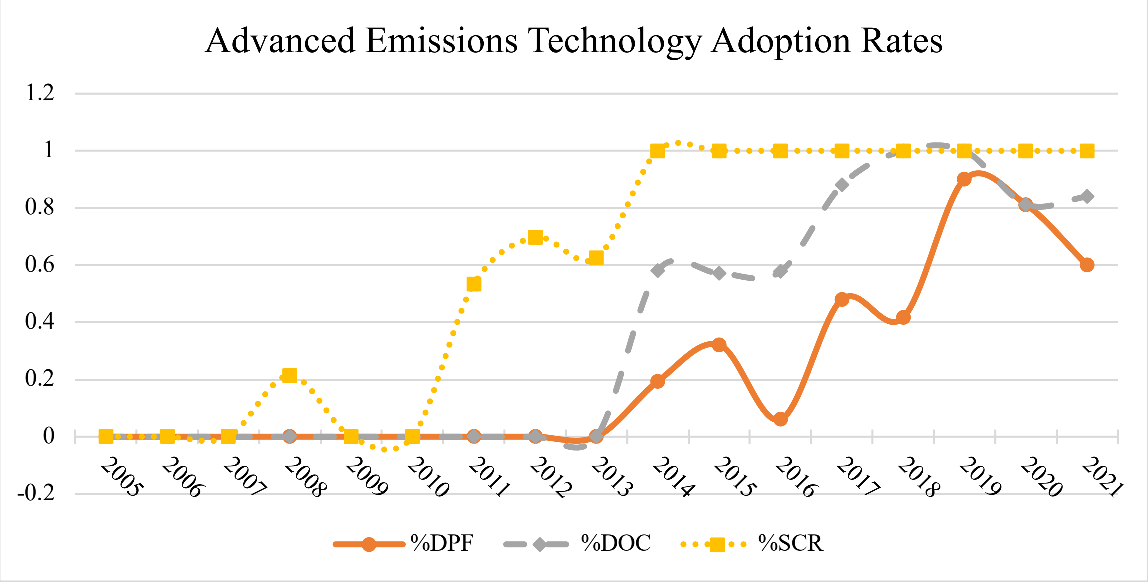
Critical to the function of a tractor, a device called a transmission uses gears to alter the speed or direction of the rotational forces produced by the engine and spun though a driveshaft. A transmission can safely and efficiently harness engine power by using multiple gear ratios to match the range of input speeds (RPM) to the output speed (MPH or KPH) for a given situation. The transmission technologies applied to tractors have evolved over time, resulting in innovative devices designed to more efficiently apply engine power to output power. Our dataset includes 13 technologies, although many of these applications are similar to each other in mechanical design. For example, Powershift Transmissions (PSH) may differ regarding how many gears it has or how many clutches are in use. Given these similarities, within our analysis we group all transmissions as either a PSH, a CVT, or a manual transmission (MAN). Much of our dataset is comprised of tractors equipped with Powershift transmissions, 830 observations. While less frequently, Continuously Variable Transmissions and Manual transmissions are implemented, with 223 and 34 observations, respectively.

4.6 Emissions Control Devices

Given the framework of the EPA's Exhaust Emission Standards to gradually phase-in and tighten maximum allowable concentrations of specific emissions over time, many manufacturers were first able to produce tractors to meet Tier 1 and Tier 2 standards without advanced emissions technologies. Instead, Tier 1 and Tier 2 Emissions Standards were often satisfied by calibrating engine settings like fuel injection rates, adjusting engine size, and by implementing forced induction devices like turbochargers and/or intercoolers. Later emissions standards, Tier 3, Tier 4, and Tier 4 final saw tractor manufacturers more frequently adopt a single advanced emission technology (I.e., Diesel Particulate Filter (DPF), Diesel Exhaust Catalyst (DOC), or Selective Catalyst Reduction (SCR)) while continuing reliance on intercoolers and turbochargers. Figure 8 serves to illustrate the frequency in which tractors employ advanced emission technologies. By the advent of Tier 4 Final Standards, available emissions control technologies advanced in efficacy and reliability leading manufacturers to depend on a combination of advanced emissions control devices to meet EPA standards.

The practice of employing multiple emissions devices is likely a result of the difficult challenge to effectively reduce both NOx and PM emissions, as these emissions are formed under opposite conditions. Particulate matter emissions are produced from a lower temperature (less efficient) combustion process, while NOx emissions are produced by a high temperature (more efficient) combustion process. Within our dataset, Tier 4 Final tractors' emissions system configurations often included a Diesel Oxidation Catalyst (DOC), a Diesel Particulate Filter (DPF), and a Selective Catalytic Reduction catalyst (SCR) to control for both particulate matter and NOx emissions. The following section introduces the various Emission Control Devices employed by tractor manufacturers then addresses the concerns regarding each device.

Figure 8. Adoption rates of advanced emission technologies over time.



One approach by some manufactures to reduce NOx emissions is by recirculating exhaust gas into the combustion chamber to achieve a lower oxygen concentration, leading to a lower combustion temperature and subsequently decreasing the formation of NOx. This process is called Exhaust Gas Recirculation (EGR) and by reducing oxygen concentration (unless compensated by higher boost pressure) engine-out exhaust produces less NOx, although it resulted in higher particulate matter emissions. Also, to take full advantage of using EGR, tractors are often equipped with an EGR cooler to lower the temperature of recirculated gases. This addition to the cooling package can be considered a “parasitic load,” which decreases overall fuel efficiency (Hoy et al. 2014). Another consideration with EGR, is given the application of recirculating exhaust gas to lower combustion temperatures result in a less efficient power stroke and subsequently worse fuel consumption (De Rudder 2012).

The application of Diesel Particulate Filters (DPF) to agricultural tractors in our dataset began around 2014 as manufactures implemented the technology to reduce the emission of particulate matter. A DPF is able to trap and remove particulate matter by running the exhaust gas through a screen, commonly made of cordierite (a ceramic material), effectively catching and clogging the pores of a filter element. With routine use, the passage of exhaust gas through the pores will progressively block flow through the filter element increasing exhaust backpressure. This backpressure harms fuel efficiency by reducing the effectiveness of the overall exhaust system. Consequently, a DPF is used in combination with an exhaust backpressure monitoring system. This system relays information for the tractor when backpressure has reached a manufacturer specified limit and initiates a regeneration phase to raise exhaust temperatures, burning off the accumulated particulate matter on the filter element, clearing the pores, and relieving exhaust backpressure. There are typically two regeneration phases the engine can rely on. “Passive” regeneration occurs when the exhaust gas temperatures are high enough to combust the collected particulate matter within the DPF without added fuel, heat, or operator action. The second regeneration option, aptly named “Active regeneration,” may require operator action and/or additional fuel to raise the DPF temperature for particulate matter combustion. This second option for regeneration can occur either in a controlled event while the tractor is stationary, or during normal operation. Although, regardless of how often regeneration phases occur, DPFs may eventually require cleaning to remove noncombustible materials and ash from the filter element. But with proper engine and DPF maintenance the EPA claims the DPF technology can achieve greater than 85% reductions in PM emissions as well as, 70% to 90% reductions in carbon monoxide and hydrocarbon emissions (EPA 2010).

Another exhaust aftertreatment device some manufacturers adopted to reduce emissions is the Diesel Oxidation Catalyst (DOC). DOCs are commonly composed of a precious metal coated flow-through honeycomb structure wrapped in a stainless-steel housing. The method by which the exhaust treatment device works is by passing the diesel exhaust through the honeycomb structure. By doing this, the precious metal, often palladium, reacts with the exhaust to break down pollutants into less harmful components. The EPA and CARB suggest that DOC technology is typically effective at reducing PM by 20% to 40%, reducing hydrocarbons by 40% to 74%, and carbon monoxides by 10% to 60% (EPA 2010).

To curb the emission of nitrous oxides (NOx) some manufactures began constructing tractors with a Selective Catalytic Reduction system (SCR). This catalyst would work in conjunction with Diesel Exhaust Fluid (DEF), by spraying an aqueous solution of urea, which partially decomposes to ammonia (NH3), into the exhaust system to react over a SCR catalyst with NOx, forming harmless H2O and N2. The SCR system can be used to achieve 50% to 85% reduction in NOx emissions (De Rudder 2012).

While each of these advanced emission technologies are effective at reducing harmful emissions, tractor manufacturers, equipment owners, and operators all face serious concerns to costs and equipment availability when the emission systems are applied. In the following paragraphs are descriptions of issues and concerns related to diesel particulate filters, diesel oxidation catalysts and selective catalytic reduction systems applied to nonroad diesel engines.

Given the role of a diesel particulate filter is to catch particulate matter, carbon monoxide, and hydrocarbons from the exhaust then burn the emissions off the filter element during a regeneration cycle, the exhaust system must be able to sustain extreme temperatures for at least 30% of the time the vehicle operates for passive regeneration or

10% of the time the vehicle operates for active regeneration (EPA 2014). These high temperatures can create hazardous scenarios in various agricultural environments. Thus, manufacturers often configure exhaust systems between other vehicle components to insulate the high temperatures from the environment. This configuration further complicates the ability to perform the routine maintenance of removing, cleaning, and reassembling the DPF with the exhaust system. Often in agricultural jobs, timeframes in which a farm operation can occur are small due to weather and seasonal environmental changes (I.e., planting, harvesting); If equipment is unable to be used because it requires maintenance or cleaning, the producer risks not completing the farm operation. The EPA recommends if equipment down time during cleaning is a concern, “consider buying extra filters to have in stock at the time of cleaning” (EPA 2010, p.2). Although, in another EPA technical bulletin from the same year, the agency describes the cost of DPF systems to range between $5,000 to $15,000 depending on engine size, filter technology and installation requirements (EPA 2010). Furthermore, the EPA estimate the longevity of DPFs when properly installed and maintained to “remain effective for the life of the vehicle, generally five to ten years or 10,000 or more hours of operation” (EPA 2010, p.2). Other concerns related to DPFs are regarding the effects from other engine components. For example, issues to a bad fuel injector or increase in fluid consumption may be masked by a DPF and result in difficulty diagnosing the issue. Or if a DPF is experiencing inadequate regeneration it may be due to an engine emitting excessive particulate matter from a failed EGR valve or turbocharger causing the DPF to be removed and cleaned more frequently. The EPA addresses that when the DPF is removed for cleaning, it may be helpful to check the opacity of the engine to determine if an issue exists (EPA 2010; EPA 2010).

Diesel oxidation catalysts (DOCs) concerns are regarding increases to the nitrogen dioxide (NO2) fraction total of NOx emissions and the release of ultrafine particles. Typically, NO2 produced by a DOC is dependent on the catalyst formulation. The EPA and CARB address the increase of NO2 by establishing a limit on NOx emissions and provide a list of DOCs that comply to this limit used for diesel engine retrofits. As for the concern of ultrafine particles, the EPA associates these emissions with the use of diesel fuel containing greater than 15 parts per million of sulfur. Fuel below the 15ppm concentration had already been required for on-road vehicles and began to be phased in for the nonroad sector starting in 2010 (EPA 2010). Although, while the EPA did not require ultralow sulfur fuel until later for nonroad vehicles, the availability for fuel with greater than 15 parts per million of sulfur after 2007 was slim.

Selective catalyst reduction (SCR) systems are extremely effective at reducing NOx emissions and even allow manufacturers the ability to meet emission standards without employing EGR although they do have many disadvantages: costs, high heat rejection, size, and temperature considerations. First, because SCR systems work in tandem with diesel exhaust fluid to reduce NOx emissions, the total fluid consumption of the engine increases, resulting in greater costs to operate the tractor. Second, given the SCR's ability to control for NOx without reliance on EGR, raw engine out exhaust has high temperatures providing similar concerns to fire hazard conditions similar to a DPF. Third, the addition of an SCR system claims a large space and depending on the manufacturers design, it may reduce operators' visibility while increasing the overall size and weight of the tractor. The SCR systems are able to control for NOx emissions best by employing geometric bends and mixing elements in the exhaust system, these deviations from a straight pipe, promote air to swirl and allow for greater “residence time” in which the DEF can react with the exhaust. Although, these bends and mixing elements used in the exhaust system do increase the area the SCR system claims along with engine backpressure. Fourth and final concern of selective catalyst reduction system is the issue of cool environmental temperatures influencing the byproducts of the DEF/urea to ammonia reaction. Causing the byproducts to crystalize and form deposits that can build up and plug exhaust systems in a matter of hours. These deposits partially decompose at warmer temperatures, but the remaining fraction can change chemical composition and are difficult to remove (De Rudder 2012).

4.7 Engine Enhancement Techniques and Technology

Prior to the exhaust emission standards, manufacturers still had incentive to innovate and improve their fuel efficiencies. This incentive can be seen by the inclusion of new technologies like intercoolers, aftercoolers, and turbochargers, but manufactures were also able to calibrate the engines to perform best by adjusting injection settings, compression ratios, engine sizes, etc. Hoy et al. (2014) described how improvements in engine and powertrain efficiency, fuel systems, and manufacturing could be achieved by tighter tolerances and advanced materials. The following seven paragraphs describe other tractor attributes and mechanisms included in our analysis that relate to tractor size and/or efficiency.

There are two common measures of the size of engine size: number of cylinders and displacement. The cylinders of an engine are the area in which the internal combustion process occurs. Providing housing for the pistons, fuel, glow plugs, and valves, the number of cylinders report an estimate of the size of an engine. Our dataset includes tractors with engines composed of four, six, seven, and twelve cylinders. However, a more precise measure of engine size is displacement. Displacement describes the total volumetric space within the cylinder in which the piston head moves between top-dead-center and bottom-dead-center. This measure is recorded as cubic inches (in^3) and is correlated with the number of cylinders. The displacement within our data ranges from 207 in^3 to 1105 in^3 with an average of 496 in^3.

The compression ratio of an engine describes the ratio of the volume in which compression occurs and the piston head area. This ratio is determined when the piston is at the top (top-dead-center) and bottom (bottom-dead-center) of its travel. The compression ratio is designed by the manufacturers to most effectively compress the intake air. Typically, higher compression ratios produce higher combustion temperatures and therefore greater fuel efficiency. Although, as stated before, higher combustion temperatures are associated with greater concentrations of NOx in exhaust gas. Meanwhile, lower combustion temperatures are associated with greater concentrations of particulate matter.

Forced induction is a term that describes the practice of increasing the density of intake air to produce more power for a given displacement. Turbochargers are devices implemented by manufacturers that use the flow of exhaust gases to compress intake air (increasing the gas's density) to achieve forced induction. Most tractors in our dataset are equipped with turbochargers, although there is differentiation in the number and configuration of these devices.

First, and most common, is a single turbocharger. Here, manufacturers design engines to use a lone turbocharger to increase intake gas density, providing the engine with more air and greater efficiency in the combustion process. The magnitude in which the density of the air is increased is often called “boost.”

Two or four turbochargers can be used to improve the combustion process and fuel efficiency. Often when more than one turbocharger is applied, they are configured in parallel, commonly called twin turbochargers. A parallel configuration is designed to split the responsibilities of forced induction between identical sized turbochargers, providing the same amount of boost from each turbocharger to the intake manifold.

A rare and unique format when applying multiple turbochargers is called compound turbocharging. The exercise of compound turbocharging applies different sized turbochargers, with the larger considered the high-pressure turbocharger, while the smaller called a low-pressure turbocharger in series. In the compound configuration the low-pressure turbocharger is responsible for using exhaust gas to compress intake air then pass the compressed intake air to the larger turbocharger, which then again uses exhaust gas to further compress intake air, essentially providing compounding effects for greater boost and improving fuel efficiency.

An unintended result of forced induction is the warming of intake air as it is compressed. This inadvertent effect prompted manufacturers to further control intake air temperatures to mitigate damages to sensitive components by applying intercoolers and aftercoolers. Commonly considered interchangeable, both devices are able to remove heat generated by forced induction, therefore permitting greater supply of air to the engine, which in turn, boosts overall efficiency and power output. The cooling process operates on the principles of heat exchange between two mediums, typically air to air or water to air.

5. Methods

This research uses data compiled cooperatively with UNL-NTTL. Using UNL-NTTL publicly available reports, a dataset of 3824 tractors of model years 1920 to 2021 was compiled with corresponding measurements of power, speed, and fluid consumption of Power Take-Off (PTO) and Drawbar performance during various operating conditions. During UNL-NTTL standardized tests, PTO and drawbar performance is recorded by output power (HP), engine speed (RPM), fuel consumption (Hp.hr/gal), vehicle speed (km/h), and drawbar pull (ls) at manufacturer specified ratings, and at test conditions of maximum power (100%), 75% of pull at max power, 50% of pull at max power, 75% of pull at reduced power, and 50% of pull at reduced power. Included in Appendix A is an example NTTL report.

These measurements at varying operating conditions provide detailed information of how a tractor performs at specific testing conditions but are unable to fully represent how a tractor is operating in field conditions. This is because a tractor's use in an agricultural operation involves a spectrum of environmental and operational conditions and often fluctuates between and past the standardized conditions recorded in the NTTL reports. To represent tractor measurements more accurately during field operations the "specific" fuel consumption model derived by Grisso (2010) has the capacity to predict fuel consumption at full or partial loads, as well as, when engine speeds are reduced from full throttle. The equation for a specific tractor is:

$$Q = (aX + b) \cdot [1 - (N - 1) \cdot (cX - d)] \cdot P_{PTO} \tag{1}$$

where,

$$a = \frac{(Q_{75F} - Q_{50F})}{[P_{PTO}(X_{75F} - X_{50})]}$$

$$b = \left(\frac{Q_{75F}}{P_{PTO}}\right) - aX_{75F}$$

$$c = \frac{\left(\frac{f}{h} - \frac{e}{g}\right)}{(X_{75F} - X_{50F})}$$

$$d = cX_{50F} + \frac{f}{h}$$

$$e = 1 - [\frac{X_{75F} \cdot Q_{75R}}{X_{75R} \cdot Q_{75F}}]$$

$$f = 1 - [\frac{X_{50F} \cdot Q_{50R}}{X_{50R} \cdot Q_{50F}}]$$

$$g = (RPM_{75F} - RPM_{75R})/RPM_{75F}$$

$$h = (RPM_{50F} - RPM_{50R})/RPM_{50F}$$

$Q =$ Diesel fuel consumption (gal/h),

$X =$ Ratio of equivalent PTO power to rated PTO power (decimal),

$N =$ Ratio of reduced- and full-throttle engine speeds at operating load (decimal),

P_{PTO} =Rated PTO power (hp).

It should be noted that the X ratio used in the formula is better described as “the estimated ratio of rated power that is being used during field operation.” (Grisso 2010)

$X = \frac{(RPM_{HI} - RPM_{FES})}{(RPM_{HI} - RPM_{RATED})}$.

where,

RPM_{HI} =High-idle engine speed (RPM)

RPM_{FES} =Field engine speed during field operations at full throttle (RPM)

RPM_{RATED} =Rated engine speed for the tractor being considered (RPM)

Grisso also provides X ratio estimates derived from ASABE Standards representing common field operations.

Table 3. Grisso provided X ratios

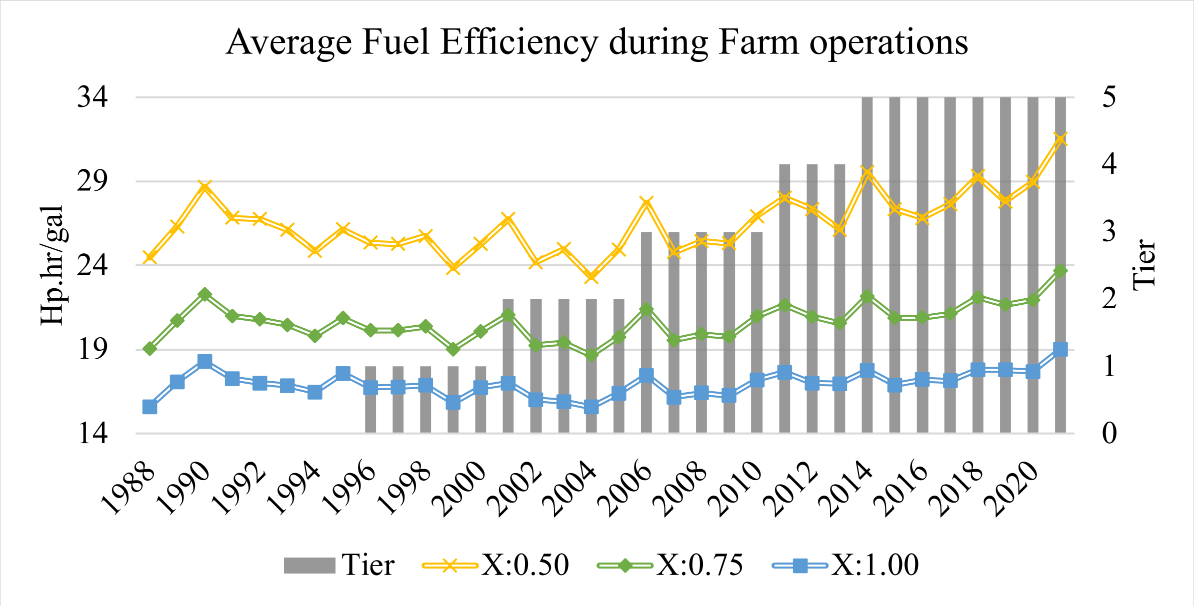
Field Operation	X ratio
15-ft no-till drill (cover crop)	0.75
30-ft Sprayer (2-X)	0.35
15-ft, 6-row planter	0.6
12-ft mower/conditioner	0.5
12-ft tedder	0.2
12-ft side-delivery rake	0.2
Round baler	0.4

For more information regarding the specific formula please reference Grisso's 2010 Virginia Tech extension paper as well as, Grisso, Kocher, and Vaughan's 2004 Biological Systems Engineering paper.

We employ Grisso (2010) "specific" fuel consumption model across our dataset of 1046 tractors to calculate fuel consumption measures during various field operations. These measures are reported by the "specific" model as gal/h. To normalize fuel consumption amongst varying sizes of tractors we relate the fuel consumption measurement yielded from the "specific" formula (gal/h) by tractor corresponding Rated Power Take-off Horsepower (PTO_{RATED}). This relationship allows for fuel efficiency to then be measured as Hp.hr/gal. The resulting fuel efficiency measures are analyzed via multivariate pooled regression.

To gather fuel efficiency measures across a spectrum of representative farm operations we choose to employ two X ratios provided by Grisso (2010), as well as another X ratio representing a hypothetical operation that uses 100% of rated engine speed. Tractor fuel efficiency measures are considered at each of these operation's X ratios; 1.0, 0.75, and 0.50. These ratios' corresponding farm operations are the hypothetical operation using 100% of rated power, No-till Drill Planting using 75% of rated power, and a Conditioner using 50% of rated power. Figure 9 illustrates the temporal changes of average fuel efficiency for each year at various load profiles.

Figure 9. Average fuel efficiencies at load profiles representing a hypothetical operation, No-till Drill Planting, and Conditioner.



5.1 Estimation

Applying ordinary least squares using the robust option in Stata version SE 15. A multivariate regression model is fit to each of the three models that represent farm operations with the corresponding fuel efficiency measurements as the dependent variable. Included categorical explanatory variables are EPA Tier ($Tier_i$), tractor manufacturer ($Manu_i$), tractor drivetrain (DTR_i), tractor transmission ($Trans_i$), and tractor technology ($Tech_i$). Continuous explanatory variables included are tractor rated PTO horsepower (Hp), and engine displacement ($Dspl$). Equation (1) serves as an example regression model.

$$LnEff_{x,i} = \alpha_0 + \sum_{h=0}^{5} \delta_h \, Tier_{h,i} + \sum_{j=0}^{3}\sum_{k=0}^{3}\sum_{l=0}^{2}\sum_{m=0}^{2} B_{j,k,l.m}\left[Manu_{j,i} \times DTR_{k,i} \times Trans_{l,i} \times Tech_{m,i}\right] + \alpha_1 Hp_i + \ \alpha_2 Dspl_i + \mu_i \tag{1}$$

Where the dependent variable, $LnEff_{x,i}$, is the log of tractor efficiency measures resulting from a specific farm operation. Given that our models are mostly composed of categorical variables, this logarithmic transformation of allows for more intuitive interpretation of results as percent changes.

- $Tier_h$, represents the corresponding EPA Tier with h equal to 0 for tractors prior to regulation, the first tier h equal to 1 for tractors in the first tier of regulation, …, and for the latest tier 4 final tractors h equal to 5.
- $Manu_j$ is the tractor manufacturer. Where j equal to 0 represents AGCO, 1 represents Case New Holland, 2 represents John Deere, and 3 represents all other manufacturers.
- DTR_k refers to the specific category of drivetrain employed. Where k equal to 0 represents a two-wheel drive tractor, 1 represents a front wheel assist tractor, 2 represents a four wheel drive tractor, and 3 represents any configuration with tracks. 3 includes Crawlers, Quad-tracs, and Front-tracks.

- $Trans_l$ represents the transmission technology used. Where l equal to 0 represents a tractor with a manual transmission, 1 represents a powershift transmission, 2 represents any variation of continuously variable transmissions.
- $Tech_m$ describes the efficiency technology employed. Where m equal to 0 represents tractors equipped with a single turbocharger, 1 represents tractors equipped with a single turbocharger and either an intercooler or aftercooler, 2 represents any tractor configured with multiple turbochargers and an intercooler or aftercooler.
- Hp and $dspl$ are used as control variables to represent technology changes over time. Horsepower has changed over time and this change can be seen across engines of all sizes indicating that manufacturers are able to get lesser or greater power out of similar sized engines. Displacement serves as another control variable demonstrating how the sizes of engines have changed over time.

It is important to note that the comparison tractor (the tractor considered in the constant) is a Tier 0, AGCO, two-wheel drive tractor, equipped with a manual transmission and a single turbocharger.

Given that our primary objective is to analyze the effect of the EPA's emissions standards on tractor efficiency, we interact all categorical variables other than $Tier$. Thus, all explanatory variables (other than $Tier$) serve as controls to best isolate the effect of the EPA's emission standards (tiers) on tractor efficiency.

Below are three multivariate regression models, representative of a tractor performing a farm operation at 100% of rated power (4), no-till drill planting (3), and using a conditioner (2).

$$LnEff_{0.50,i} = \alpha_0 + \sum_{h=0}^{5} \delta_h \, Tier_{h,i} + \sum_{j=0}^{3}\sum_{k=0}^{3}\sum_{l=0}^{2}\sum_{m=0}^{2} B_{j,k,l.m}\left[Manu_{j,i} \times DTR_{k,i} \times Trans_{l,i} \times Tech_{m,i}\right] + \alpha_1 Hp_i + \alpha_2 Dspl_i + \mu_i \tag{2}$$

$$LnEff_{0.75,i} = \alpha_0 + \sum_{h=0}^{5} \delta_h \, Tier_{h,i} + \sum_{j=0}^{3}\sum_{k=0}^{3}\sum_{l=0}^{2}\sum_{m=0}^{2} B_{j,k,l.m}\left[Manu_{j,i} \times DTR_{k,i} \times Trans_{l,i} \times Tech_{m,i}\right] + \alpha_1 Hp_i + \alpha_2 Dspl_i + \mu_i \tag{3}$$

$$LnEff_{1.00,i} = \alpha_0 + \sum_{h=0}^{5} \delta_h \, Tier_{h,i} + \sum_{j=0}^{3}\sum_{k=0}^{3}\sum_{l=0}^{2}\sum_{m=0}^{2} B_{j,k,l.m}\left[Manu_{j,i} \times DTR_{k,i} \times Trans_{l,i} \times Tech_{m,i}\right] + \alpha_1 Hp_i + \alpha_2 Dspl_i + \mu_i \tag{4}$$

6. Results

Findings from this analysis are presented in the following ways. First, regression results of the three models are presented. Second, a short discussion of the control variables and the interactions between these control variables. Third, interpretation and discussion of the effect the EPA's exhaust emissions standards on tractor fuel efficiency. Fourth and finally, we quantify economic effects by relating the emissions standards influence on efficiencies to costs.

6.1 Regression Results

The regression results, Table 4, report the effect of each tier, along with all statistically significant interactions among explanatory variables. For brevity and ease of interpretation, non-statistically significant interactions, and missing parameter estimates are omitted. Given the rarity of certain tractor configurations, some parameter estimates were unable to be calculated due to less common configurations. Full regression results are provided in Appendix 2.

Again, it is important to note that the comparison tractor (the tractor considered in the constant) is a Tier 0, AGCO, two-wheel drive tractor, equipped with a manual transmission and a single turbocharger.

Table 4. Regression results from models representing various tractor operations.

	Model 1 X:0.50 (Conditioner)	Model 2 X:0.75 (No-Till Drill)	Model 3 X:1.00 (Hypothetical)
Tier 1	-0.0427***	-0.0344***	-0.0294***
	(0.00946)	(0.00760)	(0.00751)
Tier 2	-0.0684***	-0.0616***	-0.0610***
	(0.0117)	(0.0105)	(0.0101)
Tier 3	-0.0625***	-0.0513***	-0.0444***
	(0.0118)	(0.0101)	(0.00991)
Tier 4	-0.00916	-0.0110	-0.0130
	(0.0125)	(0.0111)	(0.0110)
Tier 4 Final	-0.0254**	-0.0236**	-0.0228*
	(0.0123)	(0.0114)	(0.0118)
AGCO, Manual, TurboInt, 4WD	0.0248	0.0442**	0.0555***
	(0.0278)	(0.0201)	(0.0181)
AGCO, PSH, TurboInt, FWA	0.0496***	0.0416**	0.0328*
	(0.0181)	(0.0181)	(0.0197)
AGCO, PSH, TurboInt, 4WD	-0.111***	-0.0973***	-0.0854**
	(0.0288)	(0.0276)	(0.0380)
AGCO, PSH, TurboInt, Crawler	-0.0627***	-0.0224	0.00412
	(0.0200)	(0.0189)	(0.0202)
AGCO, PSH, MTurbos, Crawler	-0.0936***	-0.0793***	-0.0701**
	(0.0174)	(0.0222)	(0.0321)
AGCO, CVT, TurboInt, FWA	0.0510***	0.0288*	0.0114
	(0.0153)	(0.0171)	(0.0193)
AGCO, CVT, TurboInt, Crawler	0.0673***	0.0904***	0.106***
	(0.0259)	(0.0211)	(0.0193)
AGCO, CVT, MTurbos, FWA	-0.0359*	-0.0502***	-0.0628***
	(0.0192)	(0.0155)	(0.0172)

AGCO, CVT, MTurbos, Crawler	0.0631***	0.0171	-0.00998
	(0.0223)	(0.0187)	(0.0343)
CNH, Manual, Turbo, 4WD	0.319***	0.238***	0.185***
	(0.0167)	(0.0168)	(0.0185)
CNH, Manual, TurboInt, FWA	-0.118***	-0.0967***	-0.0859***
	(0.0271)	(0.0270)	(0.0327)
CNH, PSH, TurboInt, 4WD	-0.0356**	-0.0116	-0.00663
	(0.0149)	(0.0176)	(0.0171)
CNH, PSH, TurboInt, Crawler	-0.0559***	-0.0249	-0.00701
	(0.0168)	(0.0177)	(0.0193)
CNH, PSH, MTurbos, 4WD	-0.195***	-0.168***	-0.152***
	(0.0202)	(0.0216)	(0.0232)
CNH, PSH, MTurbos, Crawler	-0.248***	-0.189***	-0.153***
	(0.0194)	(0.0264)	(0.0331)
CNH, CVT, TurboInt, Crawler	-0.0461***	-0.0203	-0.00814
	(0.0104)	(0.0133)	(0.0156)
JD, Manual, Turbo, FWA	0.109***	0.112***	0.109***
	(0.0282)	(0.0232)	(0.0223)
JD, PSH, Turbo, 2WD	0.0784***	0.0616***	0.0464**
	(0.0229)	(0.0205)	(0.0210)
JD, PSH, Turbo, FWA	0.0759***	0.0728***	0.0666***
	(0.0203)	(0.0197)	(0.0210)
JD, PSH, TurboInt, 2WD	0.126***	0.119***	0.109***
	(0.0177)	(0.0182)	(0.0198)
JD, PSH, TurboInt, FWA	0.0440***	0.0403**	0.0345*
	(0.0169)	(0.0174)	(0.0190)
JD, PSH, MTurbos, 4WD	-0.186***	-0.171***	-0.163***
	(0.0396)	(0.0420)	(0.0439)
JD, PSH, MTurbos, Crawler	-0.130***	-0.113***	-0.104***
	(0.0344)	(0.0334)	(0.0333)
JD, CVT, Turbo, FWA	0.358***	0.162***	0.0454**
	(0.0181)	(0.0182)	(0.0197)
JD, CVT, TurboInt, FWA	0.0517**	0.0466**	0.0401*
	(0.0212)	(0.0196)	(0.0210)
Other, PSH, Turbo, FWA	-0.104***	-0.0806***	-0.0696***
	(0.0283)	(0.0242)	(0.0239)
Other, PSH, TurboInt, 2WD	0.142***	0.105***	0.0805***
	(0.0209)	(0.0206)	(0.0230)
Other, PSH, TurboInt, 4WD	-0.175***	-0.117***	-0.0797**
	(0.0180)	(0.0225)	(0.0370)
Other, CVT, TurboInt, FWA	0.0993***	0.0574***	0.0272
	(0.0158)	(0.0165)	(0.0195)
Displacement	0.00079***	0.000650***	0.000574***
	(5.78e-05)	(6.00e-05)	(6.34e-05)

PTOhp	0.00195***	0.00151***	0.00122***
	(9.22e-05)	(8.69e-05)	(8.96e-05)
Constant	3.275***	3.049***	2.873***
	(0.0298)	(0.0304)	(0.0320)
Observations	1,046	1,046	1,046
R-squared	0.599	0.530	0.431

Notes: Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

6.2 Control Variables

Across load profiles (represented by Models/ X ratios) and interactions, we find statistically significant parameter estimates indicating both positive and negative effects corresponding to changes in fuel efficiency. Interpretation of these control variables are all in comparison to the tractor considered in the constant: an AGCO equipped with a manual transmission and a lone turbocharger, on a two-wheel drive drivetrain (AGCO, manual, turbo, 2WD).

The regression results considering the control variables and their interactions provide interesting statistical evidence highlighting the varying average effects to fuel efficiency dependent upon tractor manufacturer and configuration. Of the statistically significant regression results we find that heterogeneous effects experienced by tractor configuration vary with parameter estimates from negative 0.248 to positive 0.358.

Although the results of these variables are not of primary concern to this study it is still important that these variables and their interactions are accounted for as we investigate the effect of the exhaust emission standards on tractor fuel efficiencies. These control variables serve a purpose to remove many other factors influencing tractor fuel efficiencies and help to provide a greater perspective for understanding the effect of the EPA’s exhaust emission standards (Tiers) on tractor fuel efficiencies.

6.3 Tiers

Tier parameter estimates are reported in the regression results and as percentages for Tiers across all three models are reported in Table 6. The results indicate negative effects on tractor fuel efficiencies from the regulation on diesel exhaust emissions.

Table 6. Regression Model results across Emission standards (Tiers)

	Model 1 X:0.50	Model 2 X:0.75	Model 3 X:1.00	Average
Constant (Tier 0)	3.2750	3.0490	2.8730	3.0657
Tier 1	-0.0427	-0.0344	-0.0294	-0.0355
	-4.1801%	-3.3815%	-2.8972%	-3.4863%
Tier 2	-0.0684	-0.0616	-0.0610	-0.0637
	-6.6113%	-5.9741%	-5.9177%	-6.1677%
Tier 3	-0.0625	-0.0513	-0.0444	-0.0527
	-6.0587%	-5.0006%	-4.3429%	-5.1341%
Tier 4	-0.0092	-0.0110	-0.0130	-0.0111
	-0.9118%	-1.0940%	-1.2916%	-1.0991%
Tier 4 Final	-0.0254	-0.0236	-0.0228	-0.0239
	-2.5080%	-2.3324%	-2.2542%	-2.3649%

Notes: Parameter estimates are presented first, the following percentages are results a log-linear transformation, allowing for parameter estimates to be represented as percentages.

The results shown in Table 6 describe the heterogenous impact experienced by tractors within a specific tier dependent upon tractor use. Given that tractor use is represented at varying load profiles through the three models, we find evidence suggesting that tractor efficiencies across most tiers experience a smaller reduction in fuel efficiency at greater load profiles. For example, the average tractor adhering to Tier 3 exhaust emissions standards experienced a 6.0587% reduction in fuel efficiency when operating at the lowest load profile considered and modeled (Model 1). Model 2 represents a greater load profile and found a smaller reduction in fuel efficiency for the average Tier 3 tractor with a reduction of 5.0006%. Similarly, when considering operating at the highest load profile modelled as Model 3, results show an even smaller reduction in fuel efficiency at 4.3429% for Tier 3 tractors. This trend is found throughout all tiers except Tier 4. Within Tier 4, the results indicate an increase to the loss of fuel efficiency when the tractors are operating at higher load profiles.

Also illustrated by the result in Table 6, we find the average effect experienced across load profiles (represented by Model/ X Ratio/ Farm operation) for Tier 1 is -3.49%, Tier 2 is -6.17%, Tier 3 is -5.13%, Tier 4 is -1.10% and Tier 4 Final is -2.36%. These results can be interpreted the average effect of tractors adhering to Tier 2 of the EPA's exhaust emissions standards had a 6.17% reduction in fuel efficiency across considered farm operations when compared to Tier 0 tractors. Alternatively, tractors adhering to Tier 4 had on average a 1.10% reduction in fuel efficiency across considered farm operations when compared to Tier 0 tractors. The results indicate that there has been an overall negative effect to tractor fuel efficiencies in response to the EPA exhaust emission standards. Although, the more recently produced tractors, Tier 4 and Tier 4 Final, experience a smaller effect on fuel efficiency than tractors produced during Tiers 1, 2 and 3.

The degree to which fuel efficiencies changed in response to certain tiers is likely influenced by the specific changes to emission concentrations allowed by each tier. For instance, prior to Tier 1, nonroad diesel engines had no limitations as to the hydrocarbon (HC), nitrogen oxides (NOx), carbon monoxide (CO), and particulate matter (PM) concentrations emitted from the exhaust. Although, with the onset of Tier 1 all tractors sold in the U.S were subject to maximum NOx concentrations and many Tier 1 tractors were subject to maximum concentrations for other emissions. The negative impact to fuel efficiencies experienced to Tier 1 tractors could demonstrate the challenge to manufacturers to develop engines that could meet the emission standards. Similarly, our results show that the following standard, Tier 2, was associated with the largest reduction in fuel efficiency. Many of the standards applied to Tier 2 tractors allowed greater concentrations of hydrocarbon emissions but lowered the allowable NOx and CO concentrations. For the majority of tractors within our dataset allowable NOx concentrations from Tier 1 to Tier 2 fell 6.9g/bhp-hr to 3.7g/bhp-hr or 46.4% for tractors sized 100hp to 175hp and 6.9g/bhp-hr to 2.6g/bhp-hr or 62.3% for tractors sized 176hp to 300hp. It is possible that manufacturers felt this steep reduction in allowable NOx concentrations difficult to meet without sacrificing fuel efficiency as many of the early techniques employed to control NOx like EGR result in less oxygen during combustion and cooler combustion cycle, thus resulting in a less efficient engine. Meanwhile, NOx control techniques employed in later Tiers like SCR systems do not rely on influencing intake oxygen concentrations. Therefore, SCR systems, are likely able to control NOx emissions without compromising engine performance to the same degree as EGR.

Another consideration that may influence the degree to which an emission standard (Tier) influenced fuel efficiency may be in relation to the time in which manufacturers had to reach specified emission concentrations. During the initial rollout of emission standards, it is possible that manufacturers either did not know or expect standards would be placed on them. With each following standard there could have been greater understanding between regulators and manufacturers through more clear expectations and communication as to what emissions and concentrations would be considered.

6.4 Economic Analysis

We quantify the economic effects of the emissions standards by relating the change in fuel efficiency experienced by the onset of the emissions standards to the price of fuel. To do this we adjust each tractor’s fuel efficiency measure to reflect the influence of the appropriate emission standard. After, we remove the rated PTO hp from the respective tractor’s adjusted fuel efficiency measure (hp.hr/gal) resulting in a consumption value (gal/hr). Next, we calculate the difference in fuel consumption between each tractor’s adjusted fuel consumption and original fuel consumption. This difference is the increase in fuel consumption to the tractor due the efficiency losses brought on by the emissions standards. Using the difference in consumption we relate the price of fuel to gather the change in cost associated with running the tractor for an hour.

The economic calculation described above was performed to all three models resulting in a measure that estimates the change in cost per hour associated with the three load profiles representing various farm operations. The average change in costs due to reduction of fuel efficiencies brought on by Tier 4 Final are presented in Table 7. We considered 2 different fuel prices. The first is the average price of fuel over the week of 05/29/2023 in the Midwest ($3.781), while the second is the average price of fuel over the same week in California ($4.81). These prices were taken from the U.S. Energy Information Administration (EIA) website on July 6th, 2023. (EIA, 2023)

Table 7. The average change in costs per hour for each model

	Model 1 X:0.50	Model 2 X:0.75	Model 3 X:1.00	Price

Costs ($/hr)	0.80	0.98	1.17	Midwest: $3.781
	1.02	1.25	1.49	California: $4.81

Notes: These calculations are using the average price of diesel as reported by the EPA for the week of 05/29/2023 in respective regions. Only considering the increase in diesel fuel consumption. DEF, hydraulic, oil fluid or any other increase in costs are not considered.

We find that the average cost incurred due to increased fuel consumption as a result of lower fuel efficiency to differ between $0.80/hr - $1.17/hr for the Midwest and $1.02/hr - $1.49/hr for California depending on the use of the tractor. For example, if the price of diesel was $4.81/gal (California price) the average Tier 4 Final tractor that is used for 10,000 hours of operations at a low load profile (Model 1, Conditioner) would face an increase to fuel costs of approximately $10,200 ($\$1.02 \times 10{,}000$hrs). While the same Tier 4 Final tractor operated the same number of hours at a high load profile (Model 3, Hypothetical), would incur increase fuel costs of approximately $14,900 ($\$1.49 \times 10{,}000$hrs).

7. Conclusion

In this study we examined the changes in tractor fuel efficiencies throughout the Environmental Protection Agency's exhaust emission standards. We identified the impact of the emissions standards on tractor fuel efficiency through a statistical and econometric analysis during various field operations across multiple tractor manufacturers, transmissions, drivetrains, efficiency technology, policy tiers, horsepower, and engine size while controlling for fuel efficiency advancements created during the introduction of the emission standards. Using the University of Nebraska-Lincoln's Nebraska Tractor Test Lab (UNL- NTTL) database, our analysis found statistical evidence suggesting varying degree of impacts to tractor fuel efficiencies dependent upon the tractor manufacturer and configuration. Fuel costs to manufactures, equipment owners, and equipment operators are calculated to understand the change in costs to operate tractors adhering to the EPA's exhaust emission standards. Finding that if the price of diesel is $4.81/gal (California price), then an increase in fuel costs for average Tier 4 Final tractors operating 10,000 hours is between approximately $10,200 and $14,900 dependent upon the farm operation (load profile/Model/X Ratio) considered.

The primary interest of our analysis was to understand the overall effects experienced to tractor fuel efficiency throughout EPA exhaust emission standards. The results we found indicate overarching negative effects to tractor fuel efficiencies throughout the regulation with an average tier effect to be negative 3.65%. Although, the degree to which a tier impacted tractor fuel efficiency varied greatly. With a range of average effect experienced from negative 6.17% for Tier 2 to negative 1.1% for Tier 4. We expect this variability to be indicative of the difficultly manufacturers experienced while developing tractors adhering to phased-in exhaust emission standards. Overall, our results suggest that more recently produced tractors (Tier 4 and Tier 4 Final) experience a smaller effect on fuel efficiency than tractors produced during Tiers 1, 2, and 3.

Continuations of this study may be interested in removing some of the limitations to our study by expanding upon our dataset to include variables we had not considered. Inclusion of improvements and changes in technology like electronic fuel injectors, variable valve timing, cylinder deactivation, active alternators, and the hybridization/electrification of tractors may allow for greater insight to the changes in efficiencies and emissions. There is also room for improved predictive fuel consumption models, considering more load profiles at testing conditions, real field data, and new tractor power technology such as power bulges to assess and predict the rate at which specific tractors will consume fuel accurately. Such a model would serve to move away from aged ASABE standards and create models more representative of farm equipment used today. Further economic analysis may provide comprehensive operational costs by including the cost and rate of consumption of diesel exhaust fluid. Interesting welfare analysis could relate the loss in fuel efficiency to health benefits brought forward by emission standards. Finally, policy analysis may be interested in understanding appropriate regulatory rates in which environmental standards can be implemented and enforced successfully.

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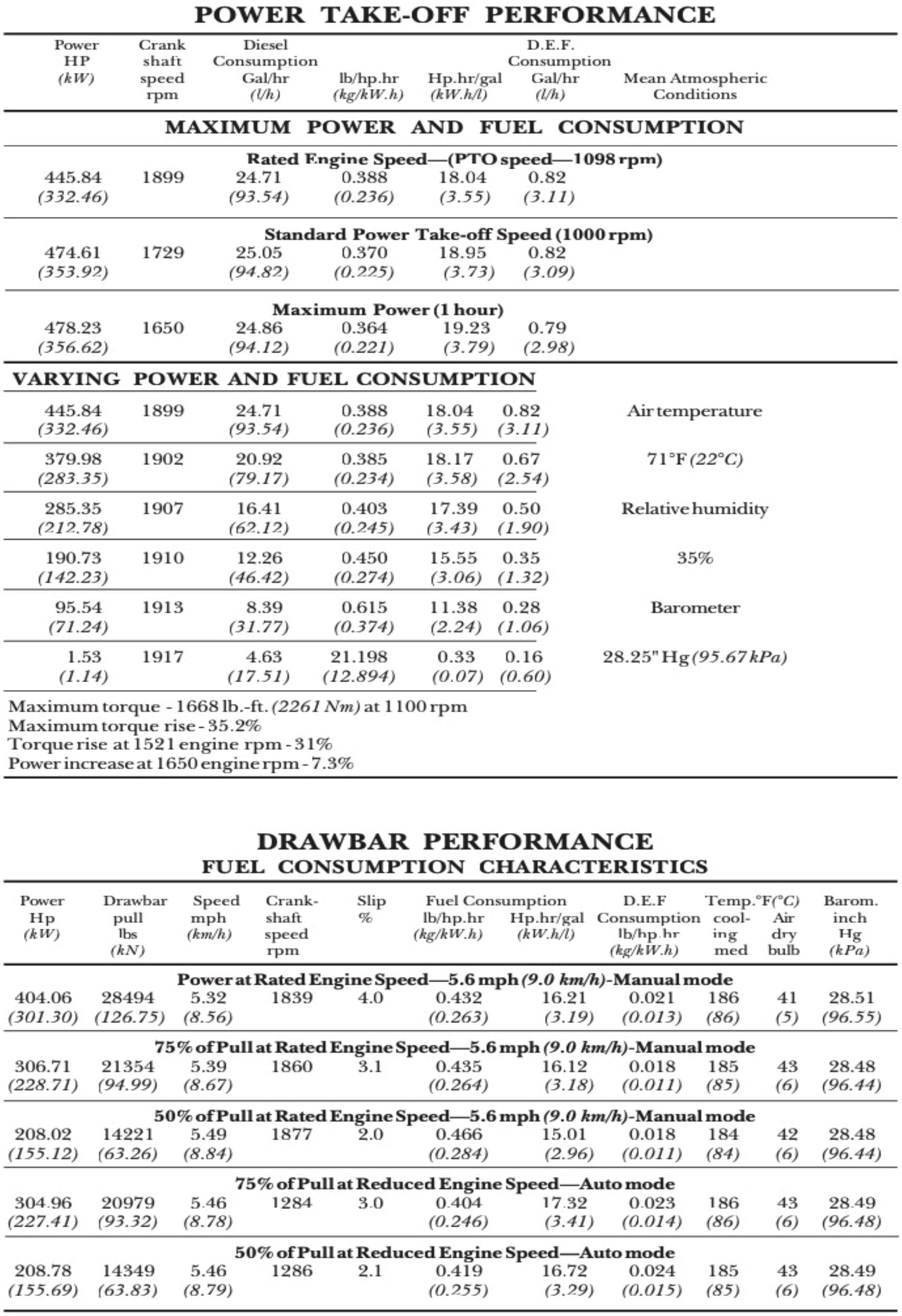
9. Appendix

9.1 Appendix 1. Example NTTL Tractor Test Report



POWER TAKE-OFF PERFORMANCE

Power HP *(kW)*	Crank shaft speed rpm	Diesel Consumption Gal/hr *(l/h)*	lb/hp.hr *(kg/kW.h)*	Hp.hr/gal *(kW.h/l)*	D.E.F. Consumption Gal/hr *(l/h)*	Mean Atmospheric Conditions
MAXIMUM POWER AND FUEL CONSUMPTION						
Rated Engine Speed—(PTO speed—1098 rpm)						
445.84 *(332.46)*	1899	24.71 *(93.54)*	0.388 *(0.236)*	18.04 *(3.55)*	0.82 *(3.11)*	
Standard Power Take-off Speed (1000 rpm)						
474.61 *(353.92)*	1729	25.05 *(94.82)*	0.370 *(0.225)*	18.95 *(3.73)*	0.82 *(3.09)*	
Maximum Power (1 hour)						
478.23 *(356.62)*	1650	24.86 *(94.12)*	0.364 *(0.221)*	19.23 *(3.79)*	0.79 *(2.98)*	
VARYING POWER AND FUEL CONSUMPTION						
445.84 *(332.46)*	1899	24.71 *(93.54)*	0.388 *(0.236)*	18.04 *(3.55)*	0.82 *(3.11)*	Air temperature
379.98 *(283.35)*	1902	20.92 *(79.17)*	0.385 *(0.234)*	18.17 *(3.58)*	0.67 *(2.54)*	71°F *(22°C)*
285.35 *(212.78)*	1907	16.41 *(62.12)*	0.403 *(0.245)*	17.39 *(3.43)*	0.50 *(1.90)*	Relative humidity
190.73 *(142.23)*	1910	12.26 *(46.42)*	0.450 *(0.274)*	15.55 *(3.06)*	0.35 *(1.32)*	35%
95.54 *(71.24)*	1913	8.39 *(31.77)*	0.615 *(0.374)*	11.38 *(2.24)*	0.28 *(1.06)*	Barometer
1.53 *(1.14)*	1917	4.63 *(17.51)*	21.198 *(12.894)*	0.33 *(0.07)*	0.16 *(0.60)*	28.25" Hg *(95.67 kPa)*

Maximum torque - 1668 lb.-ft. *(2261 Nm)* at 1100 rpm
Maximum torque rise - 35.2%
Torque rise at 1521 engine rpm - 31%
Power increase at 1650 engine rpm - 7.3%

DRAWBAR PERFORMANCE

FUEL CONSUMPTION CHARACTERISTICS

Power Hp *(kW)*	Drawbar pull lbs *(kN)*	Speed mph *(km/h)*	Crank-shaft speed rpm	Slip %	Fuel Consumption lb/hp.hr *(kg/kW.h)*	Fuel Consumption Hp.hr/gal *(kW.h/l)*	D.E.F Consumption lb/hp.hr *(kg/kW.h)*	Temp.°F*(°C)* cool-ing med	Temp.°F*(°C)* Air dry bulb	Barom. inch Hg *(kPa)*
Power at Rated Engine Speed—5.6 mph *(9.0 km/h)*-Manual mode										
404.06 *(301.30)*	28494 *(126.75)*	5.32 *(8.56)*	1839	4.0	0.432 *(0.263)*	16.21 *(3.19)*	0.021 *(0.013)*	186 *(86)*	41 *(5)*	28.51 *(96.55)*
75% of Pull at Rated Engine Speed—5.6 mph *(9.0 km/h)*-Manual mode										
306.71 *(228.71)*	21354 *(94.99)*	5.39 *(8.67)*	1860	3.1	0.435 *(0.264)*	16.12 *(3.18)*	0.018 *(0.011)*	185 *(85)*	43 *(6)*	28.48 *(96.44)*
50% of Pull at Rated Engine Speed—5.6 mph *(9.0 km/h)*-Manual mode										
208.02 *(155.12)*	14221 *(63.26)*	5.49 *(8.84)*	1877	2.0	0.466 *(0.284)*	15.01 *(2.96)*	0.018 *(0.011)*	184 *(84)*	42 *(6)*	28.48 *(96.44)*
75% of Pull at Reduced Engine Speed—Auto mode										
304.96 *(227.41)*	20979 *(93.32)*	5.46 *(8.78)*	1284	3.0	0.404 *(0.246)*	17.32 *(3.41)*	0.023 *(0.014)*	186 *(86)*	43 *(6)*	28.49 *(96.48)*
50% of Pull at Reduced Engine Speed—Auto mode										
208.78 *(155.69)*	14349 *(63.83)*	5.46 *(8.79)*	1286	2.1	0.419 *(0.255)*	16.72 *(3.29)*	0.024 *(0.015)*	185 *(85)*	43 *(6)*	28.49 *(96.48)*

9.2 Appendix 2. Regression Results

VARIABLES	(1) 50%	(2) 70%	(3) 100%
Tier 1	-0.0427***	-0.0344***	-0.0294***
	(0.00946)	(0.00760)	(0.00751)
Tier 2	-0.0684***	-0.0616***	-0.0610***
	(0.0117)	(0.0105)	(0.0101)
Tier 3	-0.0625***	-0.0513***	-0.0444***
	(0.0118)	(0.0101)	(0.00991)
Tier 4	-0.00916	-0.0110	-0.0130
	(0.0125)	(0.0111)	(0.0110)
Tier 4 Final	-0.0254**	-0.0236**	-0.0228*
	(0.0123)	(0.0114)	(0.0118)
AGCO, Manual, Turbo, 2WD	0	0	0
	(0)	(0)	(0)
AGCO, Manual, Turbo, FWA	-0.00459	0.0190	0.0306
	(0.0205)	(0.0205)	(0.0219)
AGCO, Manual, Turbo, 4WD	0	0	0
	(0)	(0)	(0)
AGCO, Manual, Turbo, Crawler	0	0	0
	(0)	(0)	(0)
AGCO, Manual, TurboInt, 2WD	0	0	0
	(0)	(0)	(0)
AGCO, Manual, TurboInt, FWA	0	0	0
	(0)	(0)	(0)
AGCO, Manual, TurboInt, 4WD	0.0248	0.0442**	0.0555***
	(0.0278)	(0.0201)	(0.0181)
AGCO, Manual, TurboInt, Crawler	0	0	0
	(0)	(0)	(0)
AGCO, Manual, MTurbos, 2WD	0	0	0
	(0)	(0)	(0)
AGCO, Manual, MTurbos, FWA	0	0	0
	(0)	(0)	(0)
AGCO, Manual, MTurbos, 4WD	0	0	0
	(0)	(0)	(0)
AGCO, Manual, MTurbos, Crawler	0	0	0
	(0)	(0)	(0)
AGCO, PSH, Turbo, 2WD	0.0249	0.0309	0.0309
	(0.0299)	(0.0246)	(0.0260)
AGCO, PSH, Turbo, FWA	0.0167	0.0196	0.0166
	(0.0212)	(0.0202)	(0.0217)
AGCO, PSH, Turbo, 4WD	0	0	0
	(0)	(0)	(0)

AGCO, PSH, Turbo, Crawler	0	0	0
	(0)	(0)	(0)
AGCO, PSH, TurboInt, 2WD	-0.0306	-0.0180	-0.0117
	(0.0313)	(0.0266)	(0.0257)
AGCO, PSH, TurboInt, FWA	0.0496***	0.0416**	0.0328*
	(0.0181)	(0.0181)	(0.0197)
AGCO, PSH, TurboInt, 4WD	-0.111***	-0.0973***	-0.0854**
	(0.0288)	(0.0276)	(0.0380)
AGCO, PSH, TurboInt, Crawler	-0.0627***	-0.0224	0.00412
	(0.0200)	(0.0189)	(0.0202)
AGCO, PSH, MTurbos, 2WD	0	0	0
	(0)	(0)	(0)
AGCO, PSH, MTurbos, FWA	0	0	0
	(0)	(0)	(0)
AGCO, PSH, MTurbos, 4WD	0	0	0
	(0)	(0)	(0)
AGCO, PSH, MTurbos, Crawler	-0.0936***	-0.0793***	-0.0701**
	(0.0174)	(0.0222)	(0.0321)
AGCO, CVT, Turbo, 2WD	0	0	0
	(0)	(0)	(0)
AGCO, CVT, Turbo, FWA	0	0	0
	(0)	(0)	(0)
AGCO, CVT, Turbo, 4WD	0	0	0
	(0)	(0)	(0)
AGCO, CVT, Turbo, Crawler	0	0	0
	(0)	(0)	(0)
AGCO, CVT, TurboInt, 2WD	0	0	0
	(0)	(0)	(0)
AGCO, CVT, TurboInt, FWA	0.0510***	0.0288*	0.0114
	(0.0153)	(0.0171)	(0.0193)
AGCO, CVT, TurboInt, 4WD	0	0	0
	(0)	(0)	(0)
AGCO, CVT, TurboInt, Crawler	0.0673***	0.0904***	0.106***
	(0.0259)	(0.0211)	(0.0193)
AGCO, CVT, MTurbos, 2WD	0	0	0
	(0)	(0)	(0)
AGCO, CVT, MTurbos, FWA	-0.0359*	-0.0502***	-0.0628***
	(0.0192)	(0.0155)	(0.0172)
AGCO, CVT, MTurbos, 4WD	0	0	0
	(0)	(0)	(0)
AGCO, CVT, MTurbos, Crawler	0.0631***	0.0171	-0.00998
	(0.0223)	(0.0187)	(0.0343)
CNH, Manual, Turbo, 2WD	0	0	0
	(0)	(0)	(0)
CNH, Manual, Turbo, FWA	0	0	0
	(0)	(0)	(0)

CNH, Manual, Turbo, 4WD	0.319***	0.238***	0.185***
	(0.0167)	(0.0168)	(0.0185)
CNH, Manual, Turbo, Crawler	0	0	0
	(0)	(0)	(0)
CNH, Manual, TurboInt, 2WD	0	0	0
	(0)	(0)	(0)
CNH, Manual, TurboInt, FWA	-0.118***	-0.0967***	-0.0859***
	(0.0271)	(0.0270)	(0.0327)
CNH, Manual, TurboInt, 4WD	0.0253	0.0326	0.0364
	(0.0451)	(0.0374)	(0.0366)
CNH, Manual, TurboInt, Crawler	0	0	0
	(0)	(0)	(0)
CNH, Manual, MTurbos, 2WD	0	0	0
	(0)	(0)	(0)
CNH, Manual, MTurbos, FWA	0	0	0
	(0)	(0)	(0)
CNH, Manual, MTurbos, 4WD	0	0	0
	(0)	(0)	(0)
CNH, Manual, MTurbos, Crawler	0	0	0
	(0)	(0)	(0)
CNH, PSH, Turbo, 2WD	0.0325	0.0159	0.00125
	(0.0247)	(0.0225)	(0.0239)
CNH, PSH, Turbo, FWA	0.0280	0.0301	0.0282
	(0.0225)	(0.0211)	(0.0231)
CNH, PSH, Turbo, 4WD	0	0	0
	(0)	(0)	(0)
CNH, PSH, Turbo, Crawler	0	0	0
	(0)	(0)	(0)
CNH, PSH, TurboInt, 2WD	0.0140	0.0194	0.0244
	(0.0212)	(0.0205)	(0.0247)
CNH, PSH, TurboInt, FWA	0.0223	0.0212	0.0173
	(0.0180)	(0.0179)	(0.0192)
CNH, PSH, TurboInt, 4WD	-0.0356**	-0.0116	-0.00663
	(0.0149)	(0.0176)	(0.0171)
CNH, PSH, TurboInt, Crawler	-0.0559***	-0.0249	-0.00701
	(0.0168)	(0.0177)	(0.0193)
CNH, PSH, MTurbos, 2WD	0	0	0
	(0)	(0)	(0)
CNH, PSH, MTurbos, FWA	0	0	0
	(0)	(0)	(0)
CNH, PSH, MTurbos, 4WD	-0.195***	-0.168***	-0.152***
	(0.0202)	(0.0216)	(0.0232)
CNH, PSH, MTurbos, Crawler	-0.248***	-0.189***	-0.153***
	(0.0194)	(0.0264)	(0.0331)
CNH, CVT, Turbo, 2WD	0	0	0
	(0)	(0)	(0)

CNH, CVT, Turbo, FWA	0	0	0
	(0)	(0)	(0)
CNH, CVT, Turbo, 4WD	0	0	0
	(0)	(0)	(0)
CNH, CVT, Turbo, Crawler	0	0	0
	(0)	(0)	(0)
CNH, CVT, TurboInt, 2WD	0	0	0
	(0)	(0)	(0)
CNH, CVT, TurboInt, FWA	-0.00845	0.00591	0.0123
	(0.0207)	(0.0193)	(0.0215)
CNH, CVT, TurboInt, 4WD	0	0	0
	(0)	(0)	(0)
CNH, CVT, TurboInt, Crawler	-0.0461***	-0.0203	-0.00814
	(0.0104)	(0.0133)	(0.0156)
CNH, CVT, MTurbos, 2WD	0	0	0
	(0)	(0)	(0)
CNH, CVT, MTurbos, FWA	0	0	0
	(0)	(0)	(0)
CNH, CVT, MTurbos, 4WD	0	0	0
	(0)	(0)	(0)
CNH, CVT, MTurbos, Crawler	0	0	0
	(0)	(0)	(0)
JD, Manual, Turbo, 2WD	0	0	0
	(0)	(0)	(0)
JD, Manual, Turbo, FWA	0.109***	0.112***	0.109***
	(0.0282)	(0.0232)	(0.0223)
JD, Manual, Turbo, 4WD	0	0	0
	(0)	(0)	(0)
JD, Manual, Turbo, Crawler	0	0	0
	(0)	(0)	(0)
JD, Manual, TurboInt, 2WD	0	0	0
	(0)	(0)	(0)
JD, Manual, TurboInt, FWA	0.0247	0.0138	0.00123
	(0.0225)	(0.0229)	(0.0250)
JD, Manual, TurboInt, 4WD	0	0	0
	(0)	(0)	(0)
JD, Manual, TurboInt, Crawler	0	0	0
	(0)	(0)	(0)
JD, Manual, MTurbos, 2WD	0	0	0
	(0)	(0)	(0)
JD, Manual, MTurbos, FWA	0	0	0
	(0)	(0)	(0)
JD, Manual, MTurbos, 4WD	0	0	0
	(0)	(0)	(0)
JD, Manual, MTurbos, Crawler	0	0	0
	(0)	(0)	(0)

JD, PSH, Turbo, 2WD	0.0784***	0.0616***	0.0464**
	(0.0229)	(0.0205)	(0.0210)
JD, PSH, Turbo, FWA	0.0759***	0.0728***	0.0666***
	(0.0203)	(0.0197)	(0.0210)
JD, PSH, Turbo, 4WD	0	0	0
	(0)	(0)	(0)
JD, PSH, Turbo, Crawler	0	0	0
	(0)	(0)	(0)
JD, PSH, TurboInt, 2WD	0.126***	0.119***	0.109***
	(0.0177)	(0.0182)	(0.0198)
JD, PSH, TurboInt, FWA	0.0440***	0.0403**	0.0345*
	(0.0169)	(0.0174)	(0.0190)
JD, PSH, TurboInt, 4WD	0.000385	-0.0180	-0.0312
	(0.0230)	(0.0254)	(0.0278)
JD, PSH, TurboInt, Crawler	-0.0180	-0.0158	-0.0167
	(0.0235)	(0.0272)	(0.0301)
JD, PSH, MTurbos, 2WD	0	0	0
	(0)	(0)	(0)
JD, PSH, MTurbos, FWA	0.0253	0.0166	0.00747
	(0.0175)	(0.0178)	(0.0193)
JD, PSH, MTurbos, 4WD	-0.186***	-0.171***	-0.163***
	(0.0396)	(0.0420)	(0.0439)
JD, PSH, MTurbos, Crawler	-0.130***	-0.113***	-0.104***
	(0.0344)	(0.0334)	(0.0333)
JD, CVT, Turbo, 2WD	0	0	0
	(0)	(0)	(0)
JD, CVT, Turbo, FWA	0.358***	0.162***	0.0454**
	(0.0181)	(0.0182)	(0.0197)
JD, CVT, Turbo, 4WD	0	0	0
	(0)	(0)	(0)
JD, CVT, Turbo, Crawler	0	0	0
	(0)	(0)	(0)
JD, CVT, TurboInt, 2WD	0	0	0
	(0)	(0)	(0)
JD, CVT, TurboInt, FWA	0.0517**	0.0466**	0.0401*
	(0.0212)	(0.0196)	(0.0210)
JD, CVT, TurboInt, 4WD	0	0	0
	(0)	(0)	(0)
JD, CVT, TurboInt, Crawler	0.00641	0.00969	0.00777
	(0.0138)	(0.0158)	(0.0179)
JD, CVT, MTurbos, 2WD	0	0	0
	(0)	(0)	(0)
JD, CVT, MTurbos, FWA	0.0143	0.00945	0.00277
	(0.0194)	(0.0172)	(0.0178)
JD, CVT, MTurbos, 4WD	0	0	0
	(0)	(0)	(0)

JD, CVT, MTurbos, Crawler	-0.0346	-0.0213	-0.0163
	(0.0244)	(0.0212)	(0.0204)
Other, Manual, Turbo, 2WD	0	0	0
	(0)	(0)	(0)
Other, Manual, Turbo, FWA	0	0	0
	(0)	(0)	(0)
Other, Manual, Turbo, 4WD	0	0	0
	(0)	(0)	(0)
Other, Manual, Turbo, Crawler	0	0	0
	(0)	(0)	(0)
Other, Manual, TurboInt, 2WD	0	0	0
	(0)	(0)	(0)
Other, Manual, TurboInt, FWA	0	0	0
	(0)	(0)	(0)
Other, Manual, TurboInt, 4WD	0	0	0
	(0)	(0)	(0)
Other, Manual, TurboInt, Crawler	0	0	0
	(0)	(0)	(0)
Other, Manual, MTurbos, 2WD	0	0	0
	(0)	(0)	(0)
Other, Manual, MTurbos, FWA	0	0	0
	(0)	(0)	(0)
Other, Manual, MTurbos, 4WD	0	0	0
	(0)	(0)	(0)
Other, Manual, MTurbos, Crawler	0	0	0
	(0)	(0)	(0)
Other, PSH, Turbo, 2WD	0	0	0
	(0)	(0)	(0)
Other, PSH, Turbo, FWA	-0.104***	-0.0806***	-0.0696***
	(0.0283)	(0.0242)	(0.0239)
Other, PSH, Turbo, 4WD	0	0	0
	(0)	(0)	(0)
Other, PSH, Turbo, Crawler	0	0	0
	(0)	(0)	(0)
Other, PSH, TurboInt, 2WD	0.142***	0.105***	0.0805***
	(0.0209)	(0.0206)	(0.0230)
Other, PSH, TurboInt, FWA	-0.00877	0.0131	0.0248
	(0.0314)	(0.0253)	(0.0245)
Other, PSH, TurboInt, 4WD	-0.175***	-0.117***	-0.0797**
	(0.0180)	(0.0225)	(0.0370)
Other, PSH, TurboInt, Crawler	-0.0280	-0.00846	0.000647
	(0.0227)	(0.0234)	(0.0251)
Other, PSH, MTurbos, 2WD	0	0	0
	(0)	(0)	(0)
Other, PSH, MTurbos, FWA	0	0	0
	(0)	(0)	(0)

Other, PSH, MTurbos, 4WD	0	0	0
	(0)	(0)	(0)
Other, PSH, MTurbos, Crawler	0	0	0
	(0)	(0)	(0)
Other, CVT, Turbo, 2WD	0	0	0
	(0)	(0)	(0)
Other, CVT, Turbo, FWA	0	0	0
	(0)	(0)	(0)
Other, CVT, Turbo, 4WD	0	0	0
	(0)	(0)	(0)
Other, CVT, Turbo, Crawler	0	0	0
	(0)	(0)	(0)
Other, CVT, TurboInt, 2WD	0	0	0
	(0)	(0)	(0)
Other, CVT, TurboInt, FWA	0.0993***	0.0574***	0.0272
	(0.0158)	(0.0165)	(0.0195)
Other, CVT, TurboInt, 4WD	0	0	0
	(0)	(0)	(0)
Other, CVT, TurboInt, Crawler	0	0	0
	(0)	(0)	(0)
Other, CVT, MTurbos, 2WD	0	0	0
	(0)	(0)	(0)
Other, CVT, MTurbos, FWA	0	0	0
	(0)	(0)	(0)
Other, CVT, MTurbos, 4WD	0	0	0
	(0)	(0)	(0)
Other, CVT, MTurbos, Crawler	0	0	0
	(0)	(0)	(0)
Displacement	-0.000787***	-0.000650***	-0.000574***
	(5.78e-05)	(6.00e-05)	(6.34e-05)
PTOhp	0.00195***	0.00151***	0.00122***
	(9.22e-05)	(8.69e-05)	(8.96e-05)
Constant	3.275***	3.049***	2.873***
	(0.0298)	(0.0304)	(0.0320)
Observations	1,046	1,046	1,046
R-squared	0.599	0.530	0.431