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Diesel Tractor Fuel Efficiency and Exhaust Emissions Standards

Diesel engine performance and costs represent crucial factors for agricultural producers while pollutants from the exhaust are largely a social concern but also important to producers. Beginning in 1970, Congress authorized the Environmental Protection Agency to regulate emissions with amendments in subsequent years (U.S. EPA, 2023). In 1996 the EPA issued strict Exhaust Emission Standards for Nonroad Compression-Ignition Engines, causing a major paradigm shift in acceptable emission levels. A primary concern coming from many manufacturers 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). In this article, we examine the impact of fuel efficiencies as exhaust emission standards evolved in stringency from their beginning in 1996 to today's standard.

In part one of a two-part article series, we begin by describing health concerns, the EPA exhaust emission policy and the data from the Nebraska Tractor Test Lab (UNL-NTTL) database, we then discuss the introduction of technologies enhancing fuel efficiency, and we describe the approach we take to understand how tractor fuel efficiencies have evolved since the introduction of EPA tiers from our data. We end with a discussion between tiers and tractor fuel efficiency. In the second part of the series, we identify the impact of EPA tiers on fuel efficiency through an econometric analysis.

Health Concerns and Policy

The basis for regulatory action on diesel exhaust emissions was driven by health and environmental concerns. Citing the Regulatory Impact Analysis, the EPA states "Such emissions lead to adverse health and welfare effects associated with ozone, particulate matter (PM), nitrogen oxides (NOx), sulfur oxides (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). Environmental 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).

For total emissions, the EPA's integrated risk information system (IRIS) program conducted a technological, environmental, and health report by collecting data from diesel vehicles including those used for on-road and nonroad. In 1970 diesel accounted for 3% of total PM emissions while by 1998 PM emissions diesel increased to 18% (EPA Health Assessment 2002). However, there were also large differences between the sources of on-road and nonroad diesel over this period which are illustrated in Figure 1. From 1980 to 1998, nonroad diesel PM emissions decreased about 31% from 439 thousand to 301 thousand tons (EPA Emission Trends 2000).

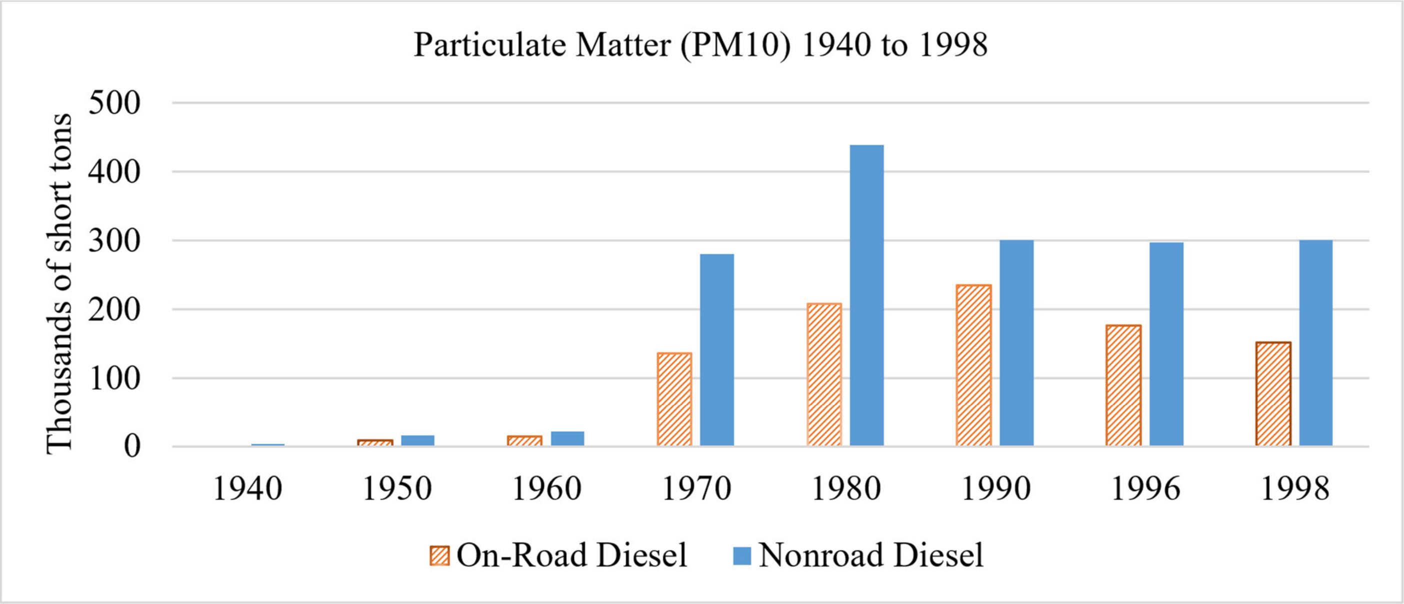


Figure 1. Trends in PM emissions from on-road and nonroad diesel engines from 1940 to 1998 (EPA Emission Trends 2000)

For NOx emissions and nonroad diesel sources, emissions increased 33% from 2.1 million tons in 1980 to 2.8 million tons in 1998, Figure 2.

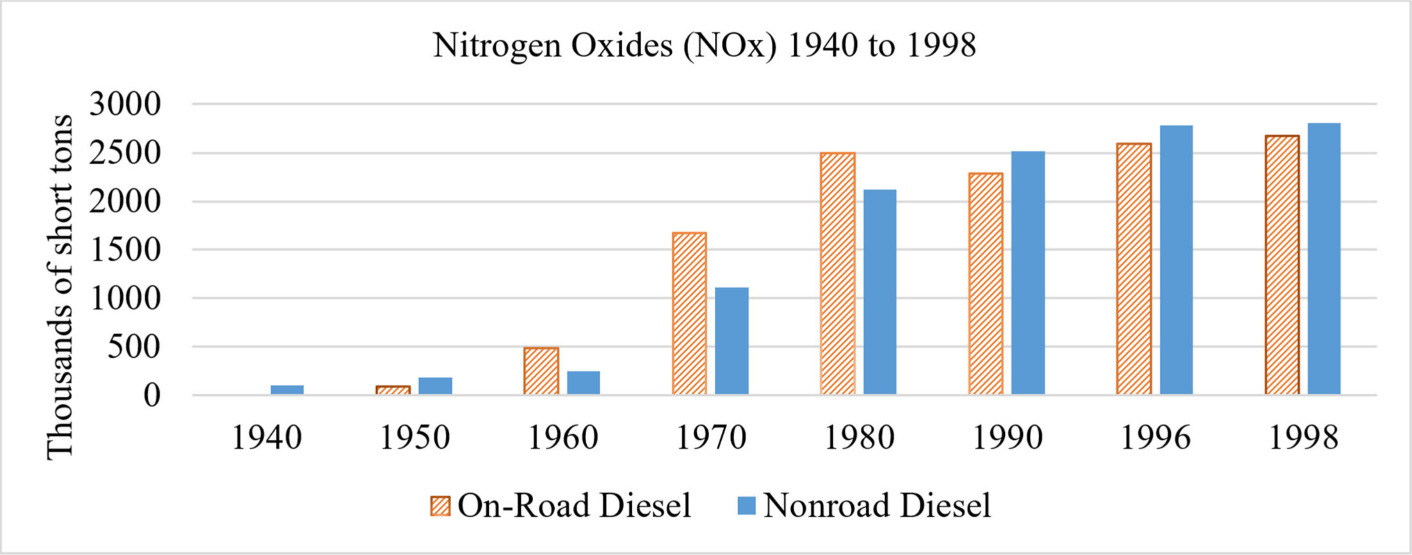
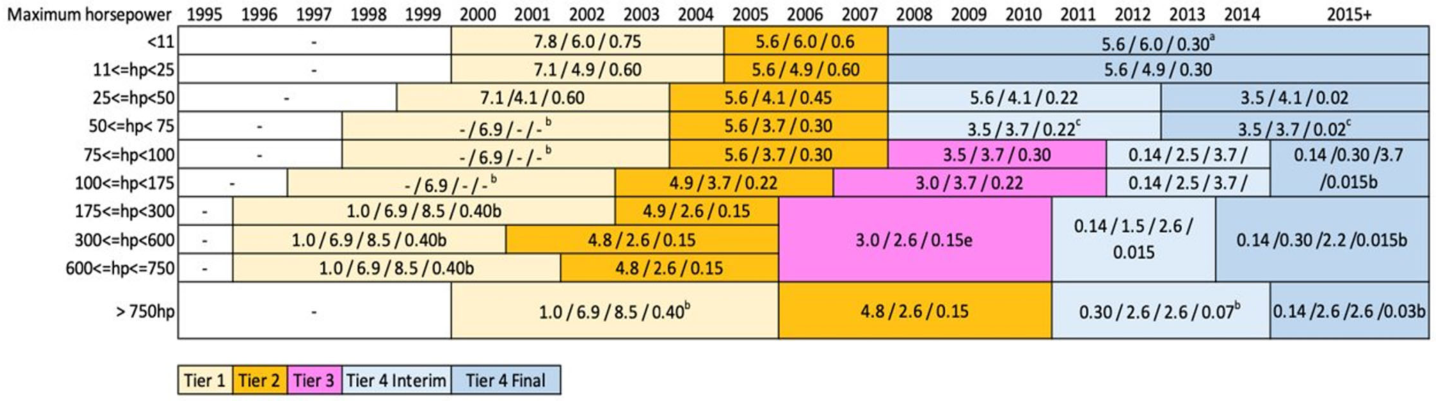


Figure 2. Trends in NOx emissions from on-road and nonroad diesel engines from 1940 to 1998 (EPA Emission Trends 2000)

EPA Policy and Emission Devises

To lower emissions, the EPA enacted a regulatory action of exhaust emission standards designed as a tiered policy system for nonroad diesel vehicles beginning in 1996 (EPA Final Rule 2004). Emissions standards were gradually phased in depending on engine size (measured by horsepower and abbreviated as "hp") and year of the equipment, Figure 3. The tiered phase-in policy began with Tier 1 and ended with Tier 4 final. The EPA required exhaust emissions standards to be met but did not direct how manufacturers were to achieve these emission standards. Various emission reduction strategies were developed by manufacturers, differing with respect to engine calibration, power devices, emissions control devices, and engine configuration.



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 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.

Figure 3. EPA emission tiers phase-in schedule

Many manufacturers were able to produce tractors to meet Tier 1 and Tier 2 standards without advanced emissions technologies as emission 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, such as Tier 3, Tier 4 Interim, and Tier 4 Final resulted in tractor manufacturers to more frequently adopt a single advanced emission technology (i.e., Diesel Particulate Filter (DPF), Diesel Exhaust Catalyst (DOC), or Selective Catalyst Reduction (SCR)). Figure 4 shows the adoption of emission technology over time. For Tier 4 Final standards, multiple emissions control technologies were required to meet EPA standards.

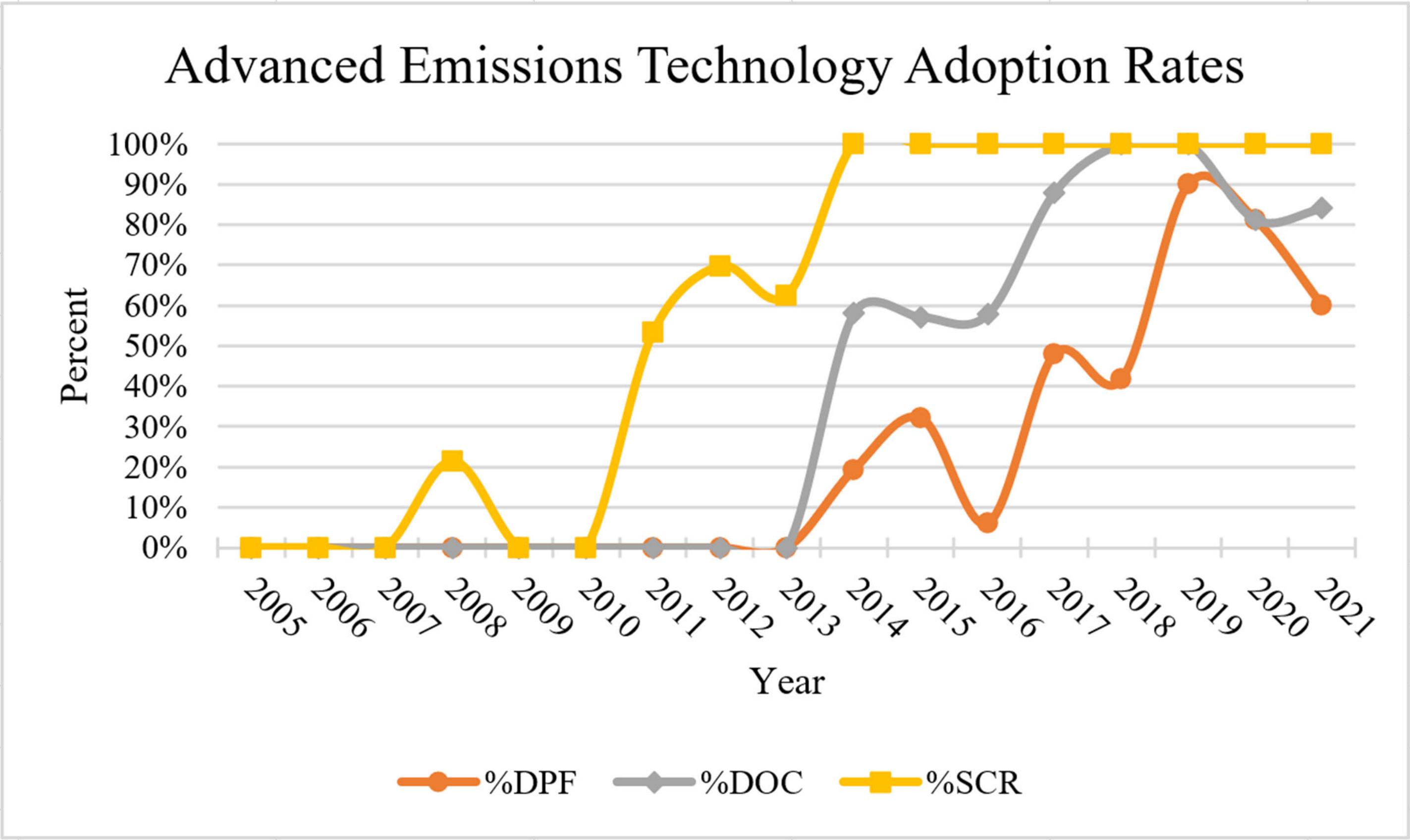


Figure 4. Adoption rates of advanced emission technologies over time.

The application of Diesel Particulate Filters (DPF) to agricultural tractors began around 2014 as manufacturers implemented the technology to reduce the emission of particulate matter. A DPF can 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. 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).

Diesel Oxidation Catalyst (DOC) represents another exhaust aftertreatment device used by some manufacturers. 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 suggests that DOC technology is typically effective at reducing PM by 20% to 40%, reducing hydrocarbons by 40% to 74%, and carbon monoxide by 10% to 60% (EPA 2010).

To curb the emission of NOx some manufacturers 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).

Nebraska Tractor Test Laboratory Data

The Nebraska Tractor Test Laboratory (NTTL) tests tractors at various operating conditions while measuring and recording parameters such as power, speed, and fluid consumption. 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 in the United States (OECD 2022). NTTL has tested over 3800 tractors since opening in 1920. Our analysis focuses on tractors with a PTO horsepower greater than one hundred as the remaining larger tractors do the bulk of work on Midwest farms between 1988 and 2021. For our analysis, we have a sample of 1,046 observations, with 111 tractors prior to any emissions regulation, 153 tractors in Tier 1, 130 in Tier 2, 202 in Tier 3, 159 in Tier 4 interim, and 291 in Tier 4 final.

Introduction of Technologies Enhancing Fuel Efficiency

Prior to the exhaust emission standards and throughout the introduction of emission standards, manufacturers continued to innovate, thereby improving fuel efficiencies. Manufacturers adopted technologies such as intercoolers and aftercoolers, while also improving engine performance by adjusting injection settings, compression ratios, engine sizes, turbos, etc.

The compression ratio of an engine describes the ratio of the volume in which compression occurs in 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. 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. A single turbocharger is most common. 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 rare and unique format when applying multiple turbochargers is called compound turbocharging and applies to different-sized turbochargers.

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 can remove heat generated by forced induction, therefore permitting a greater supply of air to the engine, which in turn, boosts overall efficiency and power output.

Approach

Given the versatility of a tractor, the measure of fuel consumption must account for more than only the fuel spent over a given distance. We focus on horsepower hour per gallon (Hp-hr/gal) to measure efficiency by measuring work done by the tractor divided by the fuel (energy) expended. The higher the hp-hr/gal, the more efficient the tractor.

These measurements of efficiency 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. A tractor's use in an agricultural operation involves a spectrum of environmental and operational. To represent tractor measurements more accurately during field operations the specific fuel consumption model derived by Grisso (2010) can predict fuel consumption at full or partial loads, as well as when engine speeds are reduced from full throttle. For more information regarding the specific formula see Grisso (2010).

We apply the model of fuel consumption developed by Grisso (2010) across our dataset of 1046 tractors to calculate fuel consumption measures during various field operations. These measures are reported by the specific model as gallons per hour (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 use the measure of tractor fuel efficiency defined by Grisso (2010) as the operation's X ratios. We chose a hypothetical operation using 100% of rated power (X ratio = 1.0), No-till Drill Planting using 75% of rated power (X ratio = 0.75), and a Conditioner using 50% of rated power (X ratio = 0.50).

Evolution of Fuel Efficiency under EPA Tiers

Figure 5 provides the number of tractors within each tier and the average fuel efficiency across tiers. Results indicate a reduction in fuel efficiency from Tier 0 to Tier 2 and an increase in fuel efficiency from Tier 2 to Tier 4 Final (4f). At the tractor market level, fuel efficiency initially dropped and then increased. Overall average efficiency is higher in Tier 4f than Tier 0.

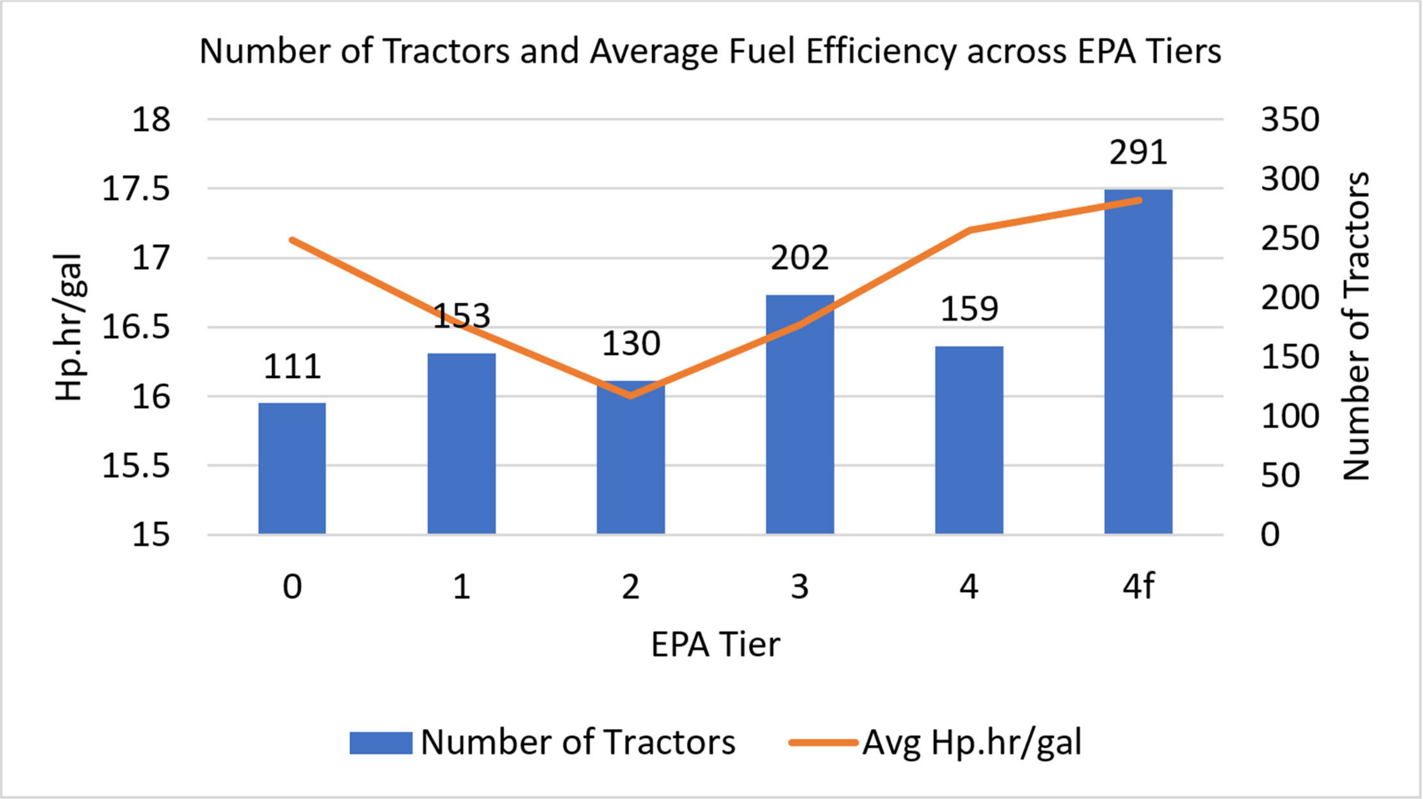


Figure 5. Tested tractors and hp.hr/gal at max power by Emissions Tier

Figure 6 shows the average fuel efficiency by application: hypothetical operation using 100% of rated power (X ratio = 1.0), No-till Drill Planting using 75% of rated power (X ratio = 0.75), and a Conditioner using 50% of rated power (X ratio = 0.50). Running the tractor at a higher rated power (X ratio), i.e., more throttle, resulted in lower fuel efficiency, as expected. Overall and across all three applications, fuel efficiency initially declined from 1990 to around 2005 and increased afterward. Fuel efficiencies across all three applications (X ratios) are also higher than they were in the late 80’s and early 90’s. Results indicate fuel efficiency has improved during the introduction of emission standards.

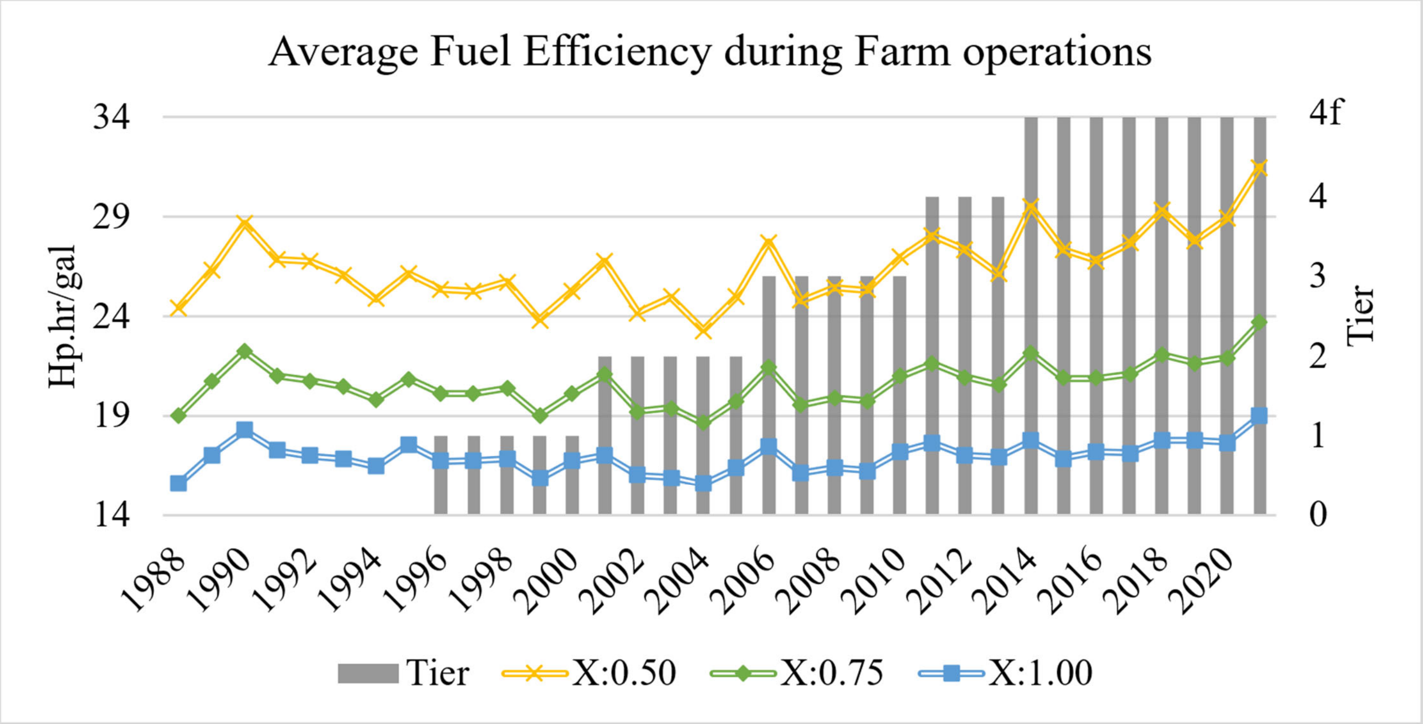


Figure 6. Average fuel efficiencies at load profiles representing a hypothetical operation, No-till Drill Planting, and Conditioner.

Discussion

Implementing emission standards on diesel motors shook the agricultural community with uncertainty and opened the door for the potential of unintended consequences. In this article we reviewed exhaust emission standards and inspected average fuel efficiencies as tiers were introduced.

Results suggest tiered emission standards impacted fuel efficiency with an initial negative impact, followed by a positive impact. We also found that fuel efficiency to be better under Tier 4 final than before the implementation of exhaust emission standards. A result suggesting two outcomes. First, manufacturers improved fuel efficiency over time with the development and introduction of better technology. Second, manufacturers learned about how to implement advanced emission technologies over time, thereby leading to better fuel efficiencies observed today.

In our next article, we will disentangle the influence of emission control (Tiers) from other innovations that took place during the same time on emissions.

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