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# An Evaluation of Tractors Tested at The Nebraska Tractor Test Lab and the Effect of EPA Emission Standards Based Upon Average PTO Horsepower and Fuel Efficiency

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# An Evaluation of Tractors Tested at The Nebraska Tractor Test Lab and the Effect of EPA Emission Standards Based Upon Average PTO Horsepower and Fuel Efficiency

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## Abstract

Newly released tractor models are tested to ensure they meet advertising claims. This thesis utilizes tractor test data to analyze performance trends in tractors based upon their power take off (PTO) horsepower and fuel efficiency and it evaluates how the average fuel efficiency of tractors was affected by the introduction of emission standards by the United States Environmental Protection Agencies. In conclusion, tractors have shown continuous improvement and growth in both fuel efficiency and PTO horsepower, and emission standards have had a small, positive effect on tractors' average fuel efficiency.



**Key Words:** Agricultural Engineering, Agriculture, EPA Emission Standards, Fuel efficiency, Nebraska Tractor Test Lab, Power Take Off (PTO) Horsepower, Tractors

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# Introduction

Every year new tractors are designed and manufactured by leading agricultural companies around the world. These tractors deliver power in three different ways: power take-off (PTO), drawbar pull, and hydraulic flow. Before tractors are eligible for sale in Nebraska, testing must be conducted to ensure that the tractor's advertising claims are met. Many new tractor models are tested at the Nebraska Tractor Test Lab (NTTL) in Lincoln, Nebraska (USA). While at the NTTL, the tractor's performance is determined by performing three-point hitch, power take-off, drawbar pull, sound, hydraulic flow, and other requested tests. The NTTL tests the power at the tractor's output that will be directly available to the operator, which can then be transmitted to agricultural implements. The tractor's output power is more useful data than other indicators such as engine power, which is not directly available to the operator. The data from said tests are then compiled into an "NTTL Tractor Test Report " and made available to the public through NTTL's website. The NTTL data also becomes a source of information by websites such as "tractordata.com". All tractor test data in this thesis comes directly from the NTTL website: "tractortestlab.unl.edu".

Many variables can be used when determining the value of a tractor. These variables can also be different and unique to the needs of each operator. All tractors evaluated in this thesis are brand new tractors; therefore, the claim of value will not consider the age or condition of said tractors. The value of a new tractor can be determined by its ability to produce work. Grisso states:

> "The value of a tractor is measured by the amount of work accomplished relative to the cost incurred in getting the work done. Therefore, the ideal tractor converts all the energy from fuel into useful work" (Grisso et al. 2004)

Grisso’s statement represents the logic behind the focus of this thesis. The first goal of this thesis is to explore trends in PTO horsepower and tractor fuel efficiency over time. For perspective, as the agricultural sector consumes 5.4% of diesel in the US, fuel efficiency is a highly relevant item to study. (Hoy, 2014) The definition of fuel efficiency, when referring to tractors, represents the amount of fuel required by the tractor to produce horsepower, as opposed to determining miles per gallon as with most highway-driven vehicles.

Hoy and Kocher explain more about the NTTL tractor test reports, how they are created, and how to use them in ASABE distinguished lecture series *TRACTOR DESIGN No. 14* document “The Nebraska Tractor Test Laboratory: 100 Years of Service” (Hoy & Kocher, 2020)

When tractors first became popular, they were competing against draft animals and their ability to pull implements through a field. This phenomenon occurred throughout the 1890s and forward. As tractors became more common, there were no laws against faulty claims or standards for how the tractors performed. If a farmer was to spend most of his earnings on a tractor, attempting to improve the efficiency of his farm, and the tractor did not perform as advertised, the farmer faced hardship. The testing of tractors became mandatory in Nebraska in 1919 to protect farmers. Figure 1 shows the popularity of tractors as they began to outwork their draft animal competitors.

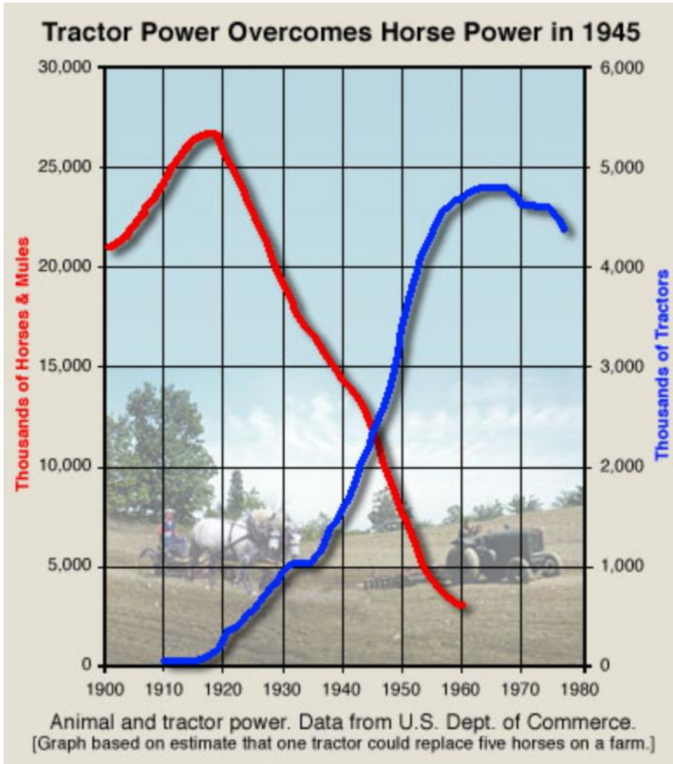


**Figure 1:** The Mechanical Advancement of Agriculture as Tractors Outworked Horses and Mules (Ganzel, 2018)

As the demand for tractors grew larger, so did the size, value, and efficiency of these tractors. Manufacturers understood the needs of the farmers as they began to farm more ground to support the growing economy and population. This growth continued until about 1980 when the economic recession began the demise of smaller farms. These small, family farms could not afford to continue farming as the equipment grew more expensive and their products became of less worth. The farmers that did not lose their farms to the bank, lost them to larger farmers. During the recession, the United States eliminated grain shipments to the Soviet Union due to the Soviet invasion of Afghanistan. Exporting less grain created a glut of grain and drove grain prices down extremely low, making farming unprofitable for many farmers.

The second goal of this thesis is to evaluate how the introduction of emission standards set by the United States Environmental Protection Agency affected the fuel efficiency of tractors.

The emission standards state there must be fewer emissions of toxic chemicals from burning diesel, so the diesel must burn more completely. With more of the fuel being burned, the fuel efficiency should increase, and emissions standards should have a positive impact on the fuel efficiency of tractors. Table 1 below shows the EPA emission tiers for nonroad compression-ignition engines.

| Rated Power (kW) | Tier | Model Year | NMHC (g/kW-hr) | NMHC + NOx (g/kW-hr | NOx (g/kW-hr | PM (g/kW-hr | CO (g/kW-hr) |
|---|---|---|---|---|---|---|---|
| 130 ≤ kW < 225 | 1 | 1996-2002 | 1.3 [j] | - | 9.2 | 0.54 | 11.4 |
| | 2 | 2003-2005 | - | 6.6 | - | 0.20 | 3.5 |
| | 3 | 2006-2010 | - | 4.0 | - | 0.20 | 3.5 |
| | 4 | 2011-2013 [h] | - | 4.0 | - | 0.02 | 3.5 |
| | | 2014+ [i] | 0.19 | - | 0.40 | 0.02 | 3.5 |

**Table 1:** Changes in EPA nonroad compression-ignition emissions standards. Retrieved from www.epa.gov
(United States Environmental Protection Agency, 2016)

The Tiers in Table 1 were phased into regulation upon their respective years. The superscript **i** upon the 2014+ standard indicates that only fifty percent of a manufacturer's engine production must meet the standard as it is phased in. The superscript **h** above this indicates that the standard is being phased out and no more than fifty percent of a manufacturer's engine production may meet the standard in that respective year. (United States Environmental Protection Agency, 2016) The headings of Table 1 represent the particles and chemicals an engine produces as it combusts diesel. NHMC represents the non-methane hydrocarbons, whereas $NO_x$ represents the production of nitrogen oxides. PM represents the particulate matter produced by the engine and CO represents the carbon monoxide. Sulfur oxides were eliminated from exhaust emissions with the introduction of ultra-low sulfur diesel and are not shown on Table 1.

Manufacturers were able to earn emission reduction credits if they reduced the emissions output by more than what was required by the EPA. Emission reduction credits could then be applied towards emission offsets that could compensate for the increase in emission production. Emission reduction credits acted as a commodity for the company and could also be bought and sold between companies. (Santa Barbara County Air Pollution Control District, 2022) Emissions reduction credits were not specific to tractors or agriculture companies. These credits could also be earned by other parts of the company.

## Literature Review

Many different models are available for predicting tractor fuel consumption and PTO horsepower based upon criteria such as maximum PTO horsepower and average fuel consumption. These models have been developed and analyzed by different parties for many years. Recent technology, such as Computer Area Network Systems, has allowed for very accurate and live, in-field data to be collected. This data has also allowed for a better understanding of the fuel use and horsepower requirements of tractors while performing specific agricultural tasks. (Pitla, 2016)

In 2004 Grisso et. al. analyzed the increase in fuel efficiency since 1984 and statistically developed new equations to predict tractor fuel efficiency. These equations are useful for estimating tractor fuel usage at varying loads and speeds. Grisso graphically compared actual fuel consumption from tractor test reports to the calculated fuel consumption based upon equations from ASAE Standards that had previously been developed. The standard way tractor fuel efficiency is measured is specific volumetric fuel consumption (SVFC). However, it is more common to see the reciprocal of this value in reports due to ease of computation. The reciprocal is presented as specific volumetric fuel efficiency (SVFE) with units of hph/gal (kWh/L). Averages of the SVFC were estimated by dividing the fuel consumption by the power at the estimated load percentage to allow the equations to account for the varying of fuel consumption with loads. Grisso (2004) concluded a 4.80% decrease in average annual specific volumetric fuel consumption over the previous twenty years.

In 2017 five fuel consumption models were statistically analyzed and proven against actual data collected at the NTTL by Kocher (2017). These analytical models came from standards, such as ASABE Standard EP496.3 (2015), as well as previous academic articles, such as work done by Howard (2010). These previous articles utilized multiple models that were dependent upon test speeds and drawbar loads which limits the usefulness of these equations. Kocher's goal was to find an accurate fuel consumption model to represent fuel consumption at varying drawbar loads and gear/speed selections. With this model, Kocher (2017) could then evaluate the benefits of continuously variable transmissions as well as running tractors across multiple gears with different loads. This allowed Kocher (2017) to evaluate the efficiency of methods such as "gear up throttle back". Evaluating these models was done based upon the coefficients for the fuel consumption models and the regression statistics, linear or multiple linear regression, for each tractor tested. While it would be preferred to have one model that is accurate amongst various drawbar loads, the findings showed the most accurate models to be specific to the drawbar loads the tractor was under and travel speed.

## Methods

The data evaluated in this thesis was obtained from the Nebraska Tractor Test Lab's website ( https://tractortestlab.unl.edu/). The Nebraska Tractor Test Lab's website is a public website that contains Nebraska tractor test results as portable document format (pdf) documents. From these documents, the principal information from the power take-off performance section of the tests was gathered into a spreadsheet. Specifically, the year of the test, PTO horsepower, and fuel efficiency at rated engine speed and 100% load was used. With this spreadsheet, data was filtered and analyzed to draw useful conclusions. The data was divided into three columns and evaluated with pivot tables using Microsoft Excel. The pivot tables calculated the average PTO horsepower and fuel efficiency of each year. Although metric units are preferred in technical publication, the NTTL primarily utilizes English units for recording data, so this thesis will follow said convention to ensure accuracy and consistency.

Many methods were considered when determining how to analyze the tractor data. The general nature of this data has several points for each year and is randomly scattered. When manufacturers design and test new tractors, they typically do it in series (groups based upon size). Some years the NTTL may test all large tractors or all small tractors, depending on the manufacturers' needs and what the companies send the NTTL to be tested. For example, John Deere might only send their smallest tractors to be tested one year, then their largest series of tractors the next. This method correlates with how the tractor designs are being updated and the new tractors are being released.

A box and whisker plot with the minimum, maximum, and average of each year shown was one of the first methods considered. Figures 2 and 3 exemplify the wide range of tractors being tested each year using box and whisker plots. While box and whisker plots are useful, they were not able to efficiently represent the trends that this thesis analyzes.

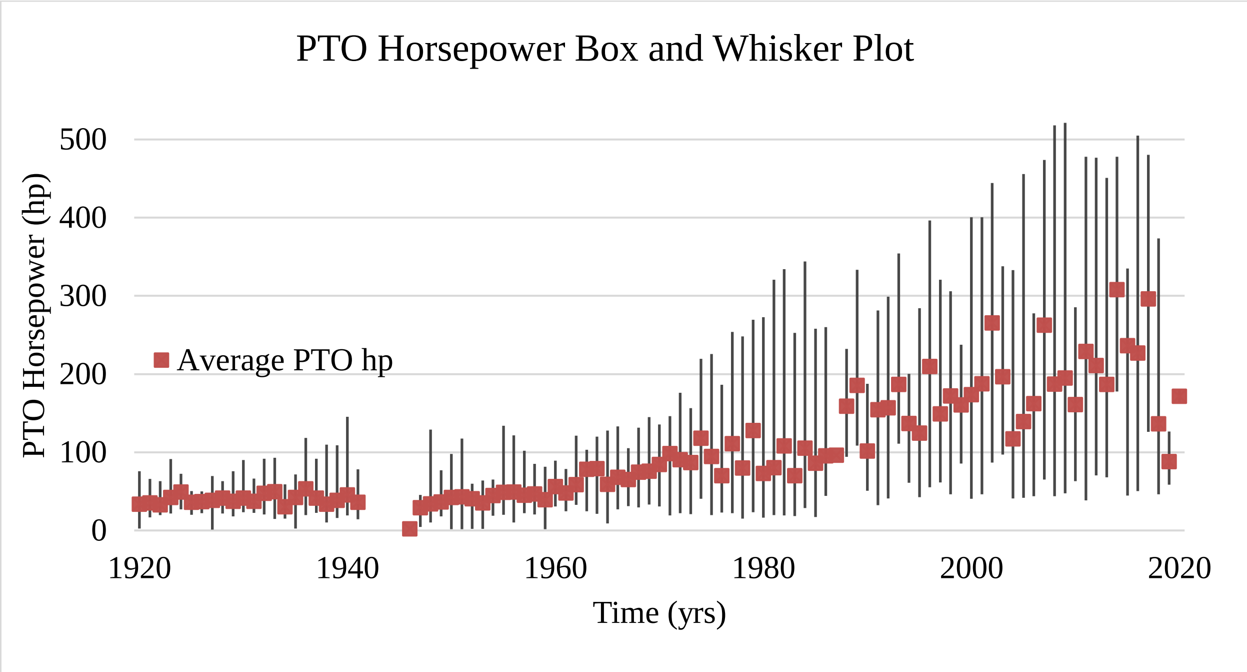


**Figure 2:** Box and whisker plot representing the power take off horsepower of tractors tested at the NTTL

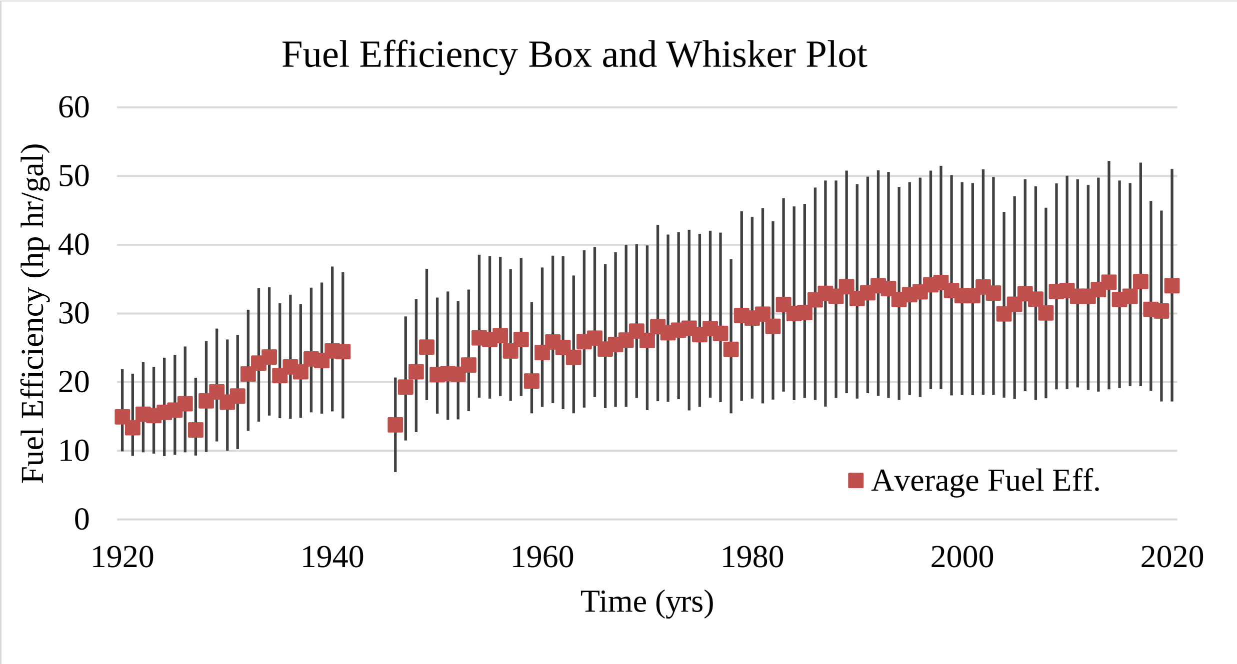


**Figure 3:** Box and whisker plot representing the fuel efficiency of tractors tested at the NTTL

Another consideration was to quantify the enhancements of all tractors based upon the improvement of a single series of tractors. This was attempted using John Deere's second-largest production all-wheel-drive tractor. This method did not have a large enough sample size to accurately display the data or draw conclusions. While this is a popular series of tractors, its advancements did not effectively represent the evolution of tractors. A third method considered was to simply graph the averages of each year from the pivot table. This method did not work due to the large variation of tractors being tested each year, which made the graph sporadic and difficult to draw conclusions. Figure 4 shows the yearly averages of PTO horsepower and fuel efficiency of the tractors tested at NTTL.

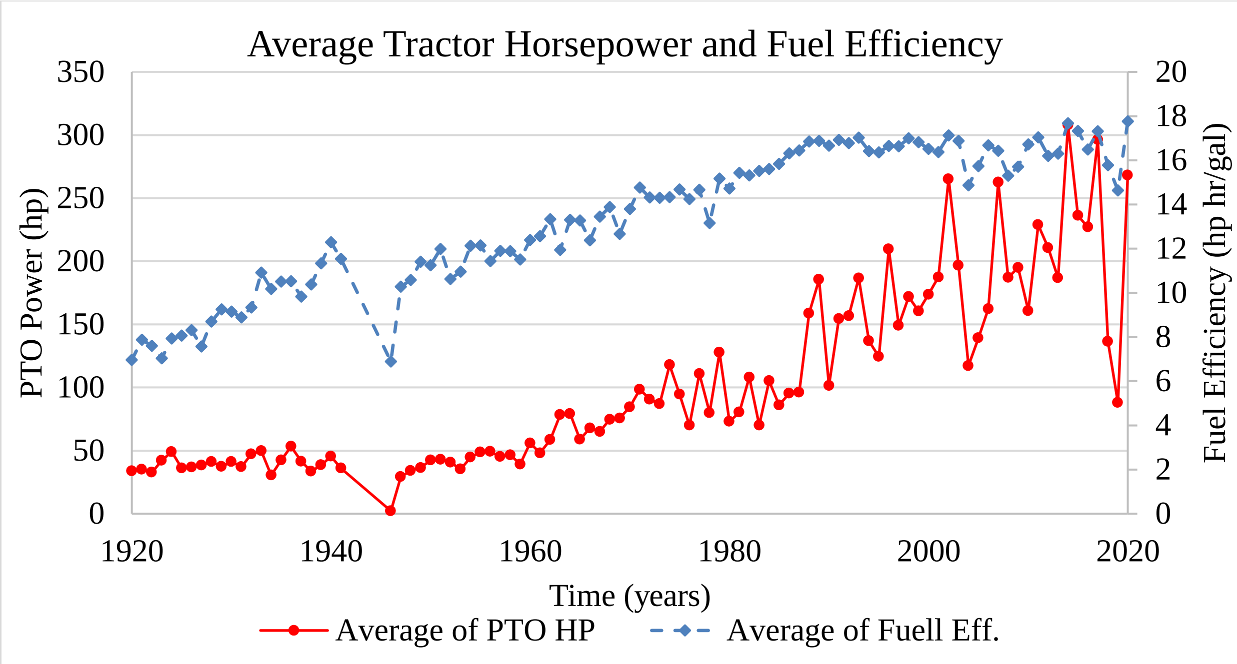


**Figure 4:** The yearly averages of PTO Horsepower and Fuel Efficiency of the tractors tested at NTTL

The fourth method considered, and the one applied to evaluate this data and show solid trends, was to take rolling five-year averages of the data. Each data point shown is an average of the two previous years' data, the current years' data, and the two upcoming years' data. A five-year average was chosen because it is readily apparent that the tractors tested at the NTTL in a single year do not accurately represent the average new tractor for the year. It should also be noted that the year a tractor model is released to the public is not always the year that model was tested at NTTL. This thesis uses the lab test date, not the release date of the tractors.

This method of analyzing the data also allowed for better conclusions to be drawn from tractors' fuel consumption and its relation to the changing of EPA emission standards. Depending on how well a manufacturer's current production model complies with the emission standards, the model can be carried over past the date range (using their emissions reduction credits). An emission standard may go into effect in 2005, but the new tractor design may not be tested and released until 2006 or 2007. Averaging the 5 years of data smoothed out the aberrations of these effects. One limitation of using rolling five-year averages is the inability to analyze data past 2016. The last year of appropriately sized data in the dataset analyzed was 2018. Therefore, a five-year average ending in 2018 corresponds to a data point in 2016.

The data analyzed in this thesis was recorded during the power take-off portion of the tractor's testing. Specifically, when the tractor was at rated engine speed and one-hundred percent load. Per OECD Code 2, rated engine speed is declared by the manufacturer of the tractor. (OECD, 2022) The reported torque at rated engine speed is determined by the average of at least six measurements taken over a one-hour period after the tractor is fully warmed up. The dynamometer measures PTO torque and speed. The torque and speed can then be used to determine horsepower based upon the equation below. One hundred percent load can be defined as the maximum load power the tractor's engine can deliver to the PTO at the rated engine speed and is measured with the engine operating at full throttle.

$$H = \frac{Tn}{63025}$$

Where:
H = Power (SAE HP)
T = Torque (lbf-in)
n = Shaft speed (RPM)

(Budynas & Nisbett, 2020)

The use of fuel is also documented during the one-hour period and measured in pound mass of fuel per hour. The specific gravity of the fuel is determined when fuel is purchased by the NTTL. The specific gravity of the fuel allows the documented fuel rate to be converted into units of gallons per hour. The reciprocal of the units gallons per hour multiplied by the amount of horsepower being produced at that moment can be seen in the Tractor Test Reports with units of hph/gal (kWh/L). Horsepower hour per gallon are the units of fuel efficiency evaluated in this thesis which represents how efficiently a tractor can convert fuel energy into mechanical energy. PTO performance was evaluated in this thesis because it reflects full engine power and the testing conditions used produced less variation than other tractor performance tests. While drawbar data is also useful when comparing the value of tractors, it can be difficult to draw conclusions from due to its wide variability of testing.

**Results**

Below, Figure 5 shows the five-year averages of PTO horsepower and fuel efficiency of tractors from 1922 to 2016. There was a 126.1% increase in average fuel efficiency over this time frame and a 524.5% increase in average PTO horsepower.

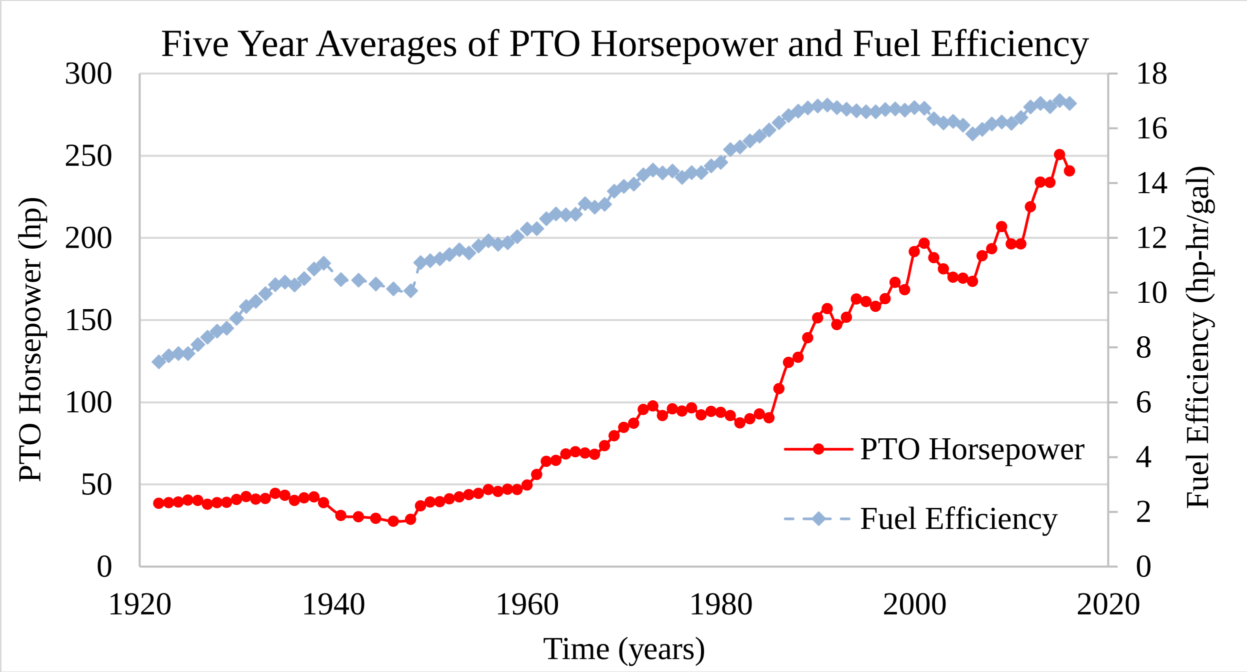


**Figure 5:** The average PTO horsepower and fuel efficiency of all tractors tested at NTTL from 1920-2018

The curves in Figure 5 not only represent changing fuel efficiency and PTO horsepower throughout time, but also represent trends in the agriculture sector of the United States economy. The two largest stagnant periods in tractor improvement are seen in the nineteen-forties and eighties. The large decline in the nineteen-forties represents World War II and how it affected the economy and the lack of ability to improve tractors. With most of the skilled labor going to the war effort, tractors were not being produced or tested. Because new tractors were not being produced, the NTTL was closed from 1942 to1946. During the war, farmhands were being drafted or enlisted to the war effort; then, after serving in WWII, many farmhands did not want to return to work the farms. This sparked a time known as “the green revolution” which resulted in larger tractors being manufactured to lessen the workforce needed on the farm. Thus, in the nineteen-forties, most remaining horses and draft animals were replaced by tractors.

Next, the recession of the nineteen-eighties can be seen clearly in the PTO Horsepower curve. The recession of the early nineteen-eighties affected farmers in particular due to the volume of agricultural exports diminishing, which led to crop prices falling, and interest rates growing substantially. With many farmers losing their farms to the banks or larger farmers, the demand for new tractors was low. After the collapse of the Soviet Union in 1991, the growth trends in average PTO horsepower resumed. It can also be noted that in 2012 there was a change in the laws for testing tractors. Prior to the law change, every tractor above 40 PTO horsepower was required to be tested. This was changed to state that only tractors over 100 PTO horsepower were required to be tested in Nebraska. This change in the law could have had a marginal effect on the average power curve due to testing fewer small tractors.

The first compression-ignition engine was invented by Dr. Rudolf Christian Karl Diesel in 1892. (Pripps, 2020) Years later, improved technology in the manufacturing and fabrication of diesel engines caused growth trends in PTO horsepower. This improved technology led to compression-ignition engines that were more efficient in converting fuel energy to mechanical energy. Although diesel engines were introduced into tractors in the 1930s, non-diesel tractors were tested at NTTL until 1978. By transitioning away from alternative fuel types to primarily diesel, more efficient power was available for tractor use. The thermal efficiency of diesel is greater than that of gasoline: thus, there is more heat value in diesel than gasoline. Burning diesel allowed for significant torque rise as more load is placed on the engine. High torque rise is desirable in tractors as it allows for fewer gear shifts required as load is added. Another advantage of diesel is its ability to be used as a compression-ignition fuel. Spark-ignition engines are forced to run rich (high fuel consumption per piston stroke) for cooling purposes. (Pripps, 2020) Diesel also burns more completely than gas, which increases the efficiency of the engine as there is less waste in the exhaust.

There are correlations between average tractor fuel efficiency and PTO horsepower that correspond with the changing of the United States Environmental Protection Agencies (US EPA) emission standard regulations. These relationships come from tractor manufacturers having to change their engine designs and exhaust systems to meet the standards. EPA emission standards were introduced with the goal of reducing the pollutants produced from nonroad compression-ignition engines. Some of the design changes included increasing the number of valves on the engine cylinders, computer-controlled fuel injection, and exhaust recirculation. In recent years there has also been the addition of diesel exhaust fluid (DEF), which mixes with the engine’s exhaust stream to clean the exhaust of $NO_x$ emissions. Another emissions exhaust technology is the use of regenerative diesel particulate filters (DPFs). These filters catch the particulate matter within the exhaust stream and allows it to be burned off instead of projected into the atmosphere.

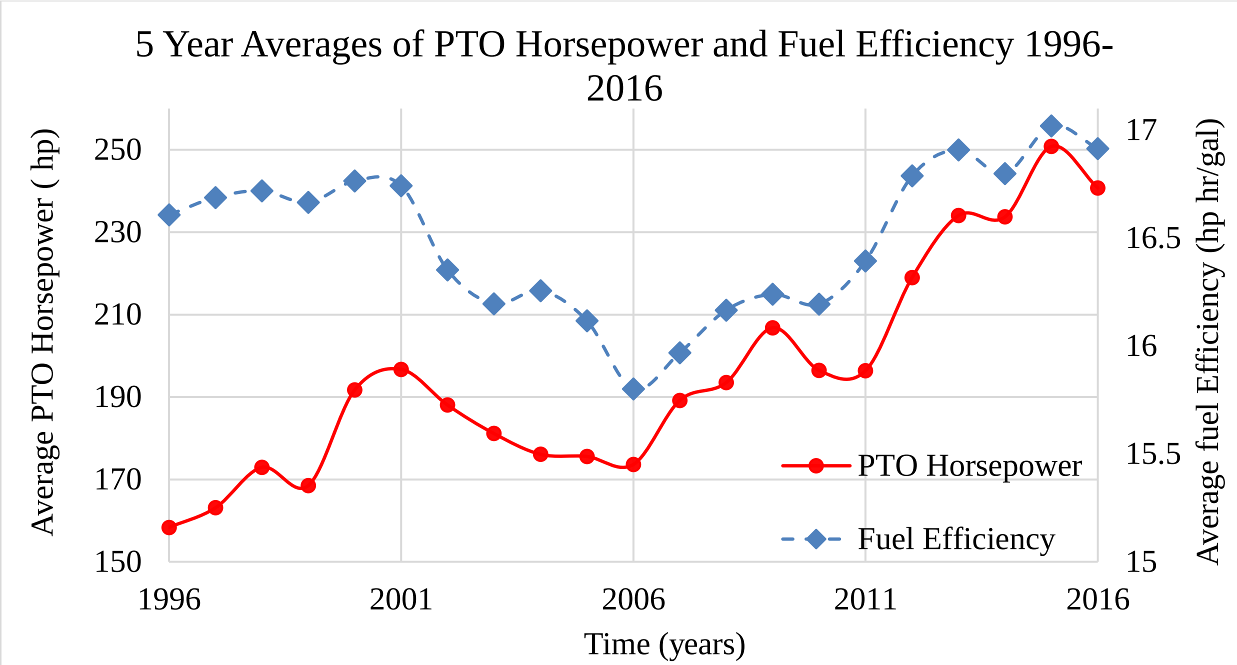


**Figure 6:** The five-year averages of PTO horsepower and fuel efficiency of tractors tested at the NTTL from 1996 to 2016.

Figure 6 shows the average fuel efficiency and PTO horsepower of tractors tested at the NTTL from 1996 to 2016, which encompasses the period of the introduction of EPA emission standards. Tier 1 (1996-2002) emission standards had a minimal effect on the fuel efficiency of tractors. Tier 2 (2003-2005) emissions standard had a largely negative effect upon average fuel efficiency of tractors, with a decrease of roughly 3.36%. Tiers 3 and 4A (2006-2013) had positive effects on the trends in average fuel of tractors. Overall, Tier 3 (2006-2010) had the largest increase in average fuel efficiency of 3.60%. After the introduction of Tier 3 AGCO started implementing the use of DEF in their tractors to decrease the amount of $NO_x$ emissions. The introduction of DEF also made the tractors seem as if they had significantly enhanced fuel efficiency because the use of DEF did not get measured during testing until 2011. Tier 3 was also largely recognized by the introduction of a four-valve unit injection systems to the engines of many tractors. The unit injection system permitted better control of fuel injection and increased the pressure at which the fuel could be injected into the engine, allowing for better ignition within the cylinders. Tier 4A (2011-2013) had an increase of 2.50% in average fuel efficiency, which is attributable to the addition of DEF systems throughout the industry to reduce $NO_x$ emissions. The effects of Tier 4B are inconclusive within this thesis due to the limited data from the most recent years.

While Figure 6 appears to have smooth trends, this is the result of the method of data analysis used. As with Figure 5, the data points are all rolling five-year averages of the true data. Rolling five-year averages limit the abrupt changes based upon the wide range of data from the Nebraska Tractor Test Lab each year. The five-year averages also filter the ambiguities that come with emissions reduction credits and help eliminate the misrepresentations of data based upon the unique technological enhancements that manufacturers were implementing to meet emission standards. Averaging five years of data into a single data point allows for this limitation to be minimized, but not avoided.

Although fuel efficiency increased by 126.1% from 1922 to 2016, Figure 5 demonstrates a plateau in the curve from 1989 to 1996 where fuel efficiency stabilized with a 0.85% decrease in average fuel efficiency. The steps in the average fuel efficiency curve from 1996 to 2016 correspond with the changes in emission standards. Ideally, as tractor's engines become more environmentally friendly, they burn more of the fuel particles and become more fuel-efficient. Over the twenty years from 1996 to 2016, there was a 1.84% increase in average fuel efficiency. This 1.84% represents a firm correlation between increased average fuel efficiency of tractors tested at NTTL and the introduction of EPA emission standards.

## Conclusions

The goals of this thesis were to evaluate the overall trends within mean tractor PTO horsepower and fuel efficiency as tractors have become more environmentally friendly machines and to determine the effect that US EPA emission standards had upon the average fuel efficiency of tractors.

Tractors have significantly increased in their ability to produce power efficiently since 1922. This is apparent from the large increase of average PTO horsepower and fuel efficiency of tractors tested at NTTL over time. From 1922 to 2016 there was a 524.5% increase in the average PTO horsepower and a 126.1% increase in fuel efficiency of tractors tested at the NTTL. As tractors have become larger, more efficient, and more powerful machines, their usefulness has also grown as more emerging technologies have been applied each year.

The fuel efficiency of tractors has changed significantly since tractor testing started in 1920. The increase in fuel efficiency of tractors occurred for many different reasons, such as the introduction of EPA emissions standards. The changes in average fuel efficiency throughout the seven-year period before emissions standards were introduced, were negligible with a 0.85% decrease from 1989 to 1996. The increase in average fuel efficiency of the tractors tested at NTTL from 1996 to 2016 was 1.84%.

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