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UNIVERSITY TRANSPORTATION RESEARCH CENTER

Final Report

Air Quality and Energy Impacts of NYSDOT Highway ROW Management

NYSDOT Research Project C-07-13

Prepared for NYS DOT by
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<tr><td colspan="5">16. Abstract: Mowing the highway right-of-way is important for the safety of roadway users and maintaining the highway infrastructure. However, little quantitative data are available on the energy use and air quality impacts of highway mowing activities. In this report, fuel usage and exhaust emission rates are reported from a study that monitored tractors operating in real-world conditions by the New York State Department of Transportation. The emissions and fuel consumption from the mowing practices of twelve tractors were compared based on miles-mowed per hour and acres-mowed per hour. The distance-based comparison revealed that there was substantial variability in emissions and fuel rates due to the technology of each tractor. Due to the high fuel rates of the relatively newer (2004) and larger tractors, the absolute emissions levels from these tractors were comparable to the older 1980's era tractors. In the area-based comparison, the operating conditions and mower type were the dominant variables determining the emission and energy rates. The sickle bar, flail and rotary equipped mowers had comparable fuel consumption and emission rates. Mowing over the guiderails, which use a large tractor and a small cutting head, had fuel consumption and emission rates 2 to 4 times higher than the other mowing activities. Highway mowing activities are an important source of air-borne pollutants and this study showed that mowing the median or highway roadside can be equivalent to 20-60 passes of a 1990's era heavy-duty diesel truck for CO_2 and NOx emissions, and 50-60 passes for PM emissions.</td></tr>
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1.0 Background and Literature Review

The New York State Department of Transportation (NYSDOT) funded research to evaluate the energy use and emissions impact from right-of-way (ROW) vegetation management. The New York State Department of Transportation (NYSDOT) is the state's largest public work's agency (Nelson et al. 2002), and manages approximately 1 million roadside acres throughout the state (NYSDOT, 2009). As such, the vegetation management of ROW areas has a significant impact on the statewide emissions and energy usage. These environmental concerns are of particular concern to the NYSDOT, which through the RFP states:

> *The New York State Department of Transportation owns about 1% of the land in New York State, much of which is associated with highway right-of-way (ROW). In order to properly manage the ROW, a variety of oftentimes competing risks must be identified, evaluated and prioritized. Safety of the traveling public requires that highways be properly drained during wet weather. Proper drainage of highways also extends the functional life span of roads and bridges. Trees need to be kept out of the clear zone. The guide rail needs to be kept free from vegetation so that it will function as designed. Worker and public safety requires control of poisonous and toxic plants in the ROW. Although other approaches are being evaluated, mechanical equipment and herbicides are the two primary methods currently used to control vegetation. The energy expenditure required for, and the pollution produced by, each of these practices is not known.*

The New York State Department of Transportation (NYSDOT) formed an Environmental Initiative to incorporate environmental objectives into its maintenance and operation practices (Nelson et al. 2007). As part of the Environmental Initiative, the NYSDOT developed an Environmental Handbook for Transportation Operations, with the most recent version updated in February, 2009 (NYSDOT, 2009). The Handbook outlines environmental concerns regarding ROW management. The first two methods listed in the handbook or vegetation management include: "Mechanical (mowing, weeding/string trimming/tree and brush cutting) and Selective use of herbicides and growth regulators" (NYSDOT, 2009).

Through the Conservation Alternative Mowing Plans (CAMP) program the NYSDOT "encourages changes in mowing practices that may conserve funds for staff hours and <u>fuel usage, improve air quality through reduced fuel emissions</u>, reduce required equipment maintenance, and reduce habitat fragmentation without impacting the safety or functionality of the roadside" (NYSDOT, 2009). However, no quantitative information is known on the fuel and air quality impacts of mowing practices.

While the Environmental Handbook states that herbicide application is generally used in areas "that cannot be mowed, such as around guiderail and sign posts." In many areas, either mowing or herbicide application can be used for vegetation management purposes. Both methods have tradeoffs according to safety, expense, and other tradeoffs (NYSDOT, 2009). However, environmental risks including energy and air quality emissions need to be also considered when selecting mowing or herbicide application.

As such, knowledge about energy expenditure and emissions from ROW management practices, identification of factors that affect such energy consumption and emissions, and scientifically-based recommendations of practical guidelines in these operations are desirable for the NYSDOT to implement successful fuel saving and emission control strategies. Evaluating each of the practices presents important economic and environmental challenges, and mitigation opportunities as well.

1.1 Air Quality

Under the Clean Air Act (CAA), the US Environmental Protection Agency (US EPA) regulates six criteria pollutants important for human health, which include carbon monoxide (CO), ground-level ozone (O_3), nitrogen oxides (NOx), lead (Pb), sulfur dioxide (SO_2), and particulate matter (PM). The primary precursor pollutants of ozone are NOx and hydrocarbon (HC) emissions, so hydrocarbons are also regulated as criteria pollutant. As of 2006 more than 100 million US citizens lived in areas with ozone or $PM_{2.5}$ concentrations that exceed the national air quality standards (EPA, 2008). Diesel vehicles are major sources for NOx and PM emissions. The US fleet is dominated by light-duty gasoline vehicles; however, heavy-duty diesel vehicles contribute over 27% of mobile-source NOx and 60% of mobile-source PM (Yanowitz et al., 2000). Carbon monoxide (CO) is another important criteria pollutant produced from combustion sources. Near-exposure of combustion source pollutants is a serious concern. Research has shown that individuals living near major roadways have a greater risk for asthma and premature death (Brunekreef and Holgate, 2002, Lin et al. 2002).

Besides the criteria pollutants, there are a host of other important emissions from offroad diesel and gasoline engines that can impact human health. These include air toxics such as benzene and formaldehyde (U.S. EPA latest findings, 2008, Baldau et al. 2006) and ultrafine particles (particles with diameter < 100 nm). Formaldehyde emission rates are now regulated on new heavy-duty diesel vehicles (US EPA, 2001 CRC) but not from offroad diesel vehicles (US EPA 2005 Crankcase). Multiple pollutants should be addressed in emission studies to evaluate environmental risks with a balanced perspective.

Recently, the US EPA made a momentous decision by including carbon dioxide (CO_2) as a regulated vehicle emission under the Clean Air Act (EPA, 2009). Lowering greenhouse gas emissions will be another important co-objective in reducing emissions from maintenance activities at the State DOT level.

1.2 Environmental Risks of Roadside Vegetation Management

Very few studies have examined the energy and criteria pollutant emissions associated with herbicide roadside maintenance applications. Most studies are concerned environmental contamination of herbicide application (Guidice et al. 2007, Chèvre et al. 2006). Guidance is focused primarily on the safety of individuals applying the herbicides, treatment of noxious species, and protecting wetlands and watersheds. No guidance is given with regard to emissions and energy use of herbicide application for roadside application. This report will be one of the first of its kind to address the emissions and energy impacts of herbicide application for ROW management.

1.3 Off-road engine emissions

One of the major environmental risks of both mowing practices are the associated emissions from the off-road tractors, commercial mowers, and small engines used for weed and brush control.

The diesel mowing tractors used for vegetation management emit harmful emissions to both operators and nearby residents and users of the freeway. Off-road diesel engines are major contributors to air pollution in the United States, with an estimated 650,000 pieces of off-road equipment sold annually, and over 6 million currently in use (EPA, 2004c). Nonroad diesel contribute 47% of the mobile source diesel PM and 25% of the mobile-source NOx. (EPA 2004c). Historically, off-road diesel engines have not been as regulated as highway vehicles. In fact, many off-road diesel engines had no emission standards until the mid-1990's (EPA, 2004b). Due to the long lifespan of diesel engines, these unregulated engines can have significant emission rates for years to come. The US Environmental Protection Agency regulates off-road diesel engines with nonroad emission standards. Rather than classified according to application, the EPA categorizes nonroad diesel engines according to horsepower sizes: 0-25, 25-75, 75-175, 175-750, and >750. Most of agricultural and mowing tractors are in the 25 to 75 hp category. (EPA, 2004d).

The EPA has implemented emission standards in several tiers over the last several decades, spanning between Tier 1 to Tier 4. Tier 1, 2 and 3 standards were phased in for nonroad engines diesel between 1994 and 2003. The standards set limits on carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx) and particulate matter (PM) (EPA, 1998a). The Tier 4 emission standards come into effect for nonroad diesel vehicles between 2008 and 2015. The rule set emission standards similar to the highway diesel standards that began with 2007 vehicles. The standards for 25 to 75 hp engines are 0.02 PM g/hp-hr and 3.5 g/hp-hr for combined NOx and non-methane hydrocarbons. The standard begins for 2013 year vehicles (EPA, 2004e). The new emission standard will decrease emissions from these engines by more than 90 percent (EPA, 2004e). For the rate power ranges typical of agricultural tractors (25-75 hp), the rule comes into effect with new 2013 tractors. For nonroad diesel engines smaller than 50 hp, Tier 1 regulations did not take affect until 1999/2000 (EPA, 2004a). Thus, many of the currently used diesel tractors for mowing practices in the NYSDOT have unregulated engine emissions. Thus, the environmental impact of mowing practices is anticipated to depend greatly on the emission standards (or tier level) of the tractors used by NYSDOT.

Small gasoline engines used in vegetation control can also contribute significant emissions, and are major sources particularly for HC and CO emission in the United States (EPA, 2008a). Baldauf et al. (2006) has found that personal exposure rates of operators of small lawn gasoline engines can exceed the National Ambient Air Quality Standards (NAAQS) for $PM_{2.5}$ and CO emissions. However, the emission exposure levels are highly dependent on the mode of operation and ambient weather conditions, and "refined activity data will be needed to determine the frequency of events leading to potentially high exposures"(Baldauf et al. 2006). This project will help identify such events by collecting high-frequency measurements of exhaust from mowing and herbicide activities.

1.4 Modeling Energy and Emissions Impacts from Maintenance Operations

Estimating the emissions and energy impact of on-road vehicles and nonroad equipment operation is conducted by multiplying activity by emission factors:

$$Emission\ impact = Emission\ \ factor \times Activity$$

The emission factors and activities can be defined using several approaches. Current off-road emission standards are given in terms of g/hp-hr, which is the measure of the energy produced by the engine. The US EPA has developed an emission model entitled, NONROAD, used to estimate off-road emission factors for critical air pollutants and estimates rates in grams/hp-hr. The total hp-hr of operation can be input into the model to estimate total emission impacts. However, the compression-ignition (diesel) emission rates are tested under stationary steady-state conditions, and approximate adjustment factors are given for real-world transient driving conditions. In many instances no emissions data is available where emission standards are used in place of data (EPA, 2004b). The emission rates are useful to provide estimates for emissions over broad areas where no other data is available. However, NONROAD is insufficient to provide accurate assessment of ROW maintenance operations because the diesel emission factors in the NONROAD model are insensitive to type of vegetation, operator type, mowing equipment, and different loads. The emission rates in NONRROAD are differentiated according to ranges of horsepower of off-road vehicles, but no distinction is given for factors such as turbo-charge or cylinder size (EPA, 2004b). The emission model emission rates are insufficient to support decisions at the level of detail needed for the ROW project.

On-road emission rates are commonly reported in gram/mile, such as in EPA's MOBILE6 model and California's EMFAC emission model. The vehicle miles traveled can then be used to compute total emissions. Currently, EPA's new on-road emission model, MOVES, reports emission rates in gram/second of operation. The MOVES model has emission rates resolved to operating modes, which can facilitate estimates of resolved vehicle activity.
However, off-road emission rates have not yet been incorporated in the MOVES model.
This study may assist the development of emission and energy factors for future applications, such as EPA's MOVES, by providing emissions data from herbicide and mowing operations.

There are large difficulties in measuring emissions from off-road sources. One of the major issues is the scarcity of accurate activity rates of off-road equipment. For example, Kean et al. (2000) found that the EPA's national off-road emissions were 2.3 times larger than a comparable emission inventory derived from fuel-usage estimates. Similar emission rates were used in each study, so the differences were attributed to differences in estimating off-road activity. The difficulty of obtaining accurate activity estimates, coupled with limited emissions data is one of the reasons real-world measurements need to be made in the current study.

Fuel-based standards can also be used to quantify off-road emissions. Fuel-based and time-based standards have been used to quantify NOx, CO, and HC emissions from construction graders (Frey et al. 2008b) and from construction equipment (Frey et al. 2010). The emission rates were differentiated by manifold absolute pressure (MAP) for the grader equipment in order to differentiate emission rates according to specific duty cycles, as well as to compare emissions according to common duty cycles that were not replicated in field-testing.

2.0 Sampling Methodology: Portable Emissions Measurement System

This study chose to make measurements taken on-board engines in real-operating conditions. Portable emission measurement systems (PEMS) facilitate individual measurements that can be used to quantify operational, fuel, location, and other impacts on energy and emissions. Additionally, the measurements are made in the real-world which cannot be accomplished using dynamometer studies. For example, emission rates for the EPA MOVES model are based primarily using laboratory tests where engines or vehicles are tested with simulated loads and driving conditions on dynamometers (EPA 2009). However, dynamometer tests cannot fully replicate real-world driving conditions (Kittelson et al. 2006a), and engine dynamometer test need to be extrapolated to real-world operation using approximate models or assumptions (Kear, and Niemeier 2006).

The Axion system, a portable 5-emission measurement system, was used to collect the emissions and fuel rate data. The Axion system is an updated version of the Montana System produced by Clean Air Technology International, and used by Frey et al. (2006a, 2006b, 2008a, 2008b, 2010) in a number of on-board, real-world emission measurement studies. The Axion system provides measurement rates of four gaseous emissions: hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NOx), carbon dioxide (CO_2), and a measure of particulate matter (PM). The Axion system also measures the fuel rate, as well as engine speed, intake air temperature, and boost-pressure (for turbocharged CI engines) (Clean Air Technologies, 2008). HC, CO, and CO_2 are measured using a nondispersive IR (NDIR) sensor, and HC and CO yields measurements within 10% accuracy compared to laboratory settings (Frey et al. 2006b). The fuel rates from the Montana System are shown to be very consistent with actual fuel rates (Frey et al. 2006b). The PM emissions are measured through light-scattering methods that can be used to make relative comparisons with vehicles within a single study, but can only be used semi-qualitatively when comparing absolute PM levels with other studies (Frey et al. 2008b). The Montana System has been used to successfully test emissions from many vehicles types including light-duty passenger cars (Frey et al., 2006a), and heavy-duty trucks (Frey et al. 2006b), and off-road graders (Frey et al. 2008b) and off-road construction equipment (Frey et al. 2010).

3.0 Mowing Equipment Overview

3.1 Diesel Tractors

Tractor mowing is the major means for maintaining highway management in Region 9. To evaluate the energy and emission impacts from NYSDOT mowing activities, a sample of eighteen tractors used in highway mowing activities were tested. The tractors were chosen to provide a representation of different ages of tractors, tractor types, and mower configurations. The equipment ID, description, tractor specifications, mower type, and test number for each tractor is given in Table 1.

Table 1. Tractor Descriptions for the Conducted Tests

Equipment ID	Make	Model	Year	Cyl.	Engine hp	Displ [L]	Mower Type	Stationary Test	Mobile Test
83-7091	Ford	5610	1983	4	72	4.2	Batwing	S1	M1
83-7110	Ford	5610	1983	4	72	4.2	OTR	S5	M15*
84-7118	Ford	2910	1984	3	40	2.9	Sickle Bar	S2	M13
84-7107	Ford	2910	1984	3	40	2.9	Sickle Bar	S4	M4
84-7152	John Deere	401B	1984	4	62	3.6	Batwing	S12	M2*
84-7153	John Deere	401B	1984	4	62	3.6	Flail	S13	M3
89-7074	Ford	5610	1989	4	72	4.2	Flail	S7	M7
89-7069	Ford	5610	1989	4	72	4.2	Flail	S9	
89-7075	Ford	5610	1989	4	72	4.2	OTR	S14	M10, M14
90-7162	Massey Ferguson	383	1990	4	81	4.1	Flail	S11	M8
90-7160	Massey Ferguson	383	1990	4	81	4.1	Flail		M5
94-7030	Case IH	695	1994	4	73	3.5	Flail		M6
95-7084	Case IH	4210	1995	4	72	3.9	Flail	S3	
95-7071	Case IH	4210	1995	4	72	3.9	Flail	S6	M12
95-7081	Case IH	4230	1995	4	84	4.4	Double Flail	S8	
04-7039	New Holland	TL90A	2004	4	90	4.5	Batwing	S10	M11
04-7041	New Holland	TL90A	2004	4	90	4.5	None	S15	
04-7042	New Holland	TL90A	2004	4	90	4.5	OTR		M9

* The data from Mobile Test 2 and 15 is unusable

The testing procedure was divided into stationary and mobile tests. Fifteen stationary tests were conducted on fifteen different tractors. Fifteen mobile tests were conducted on fourteen tractors (Tractor 89-7075 was tested twice on the mobile test on two separate days). Due to logistical reasons, only eight individual tractors were tested successfully using the stationary test and mobile test, providing a total of 18 different tractors that were tested in either the stationary and/or the mobile test.

The tested tractors included nine equipped with side-bar flail mowers, two sickle bar/flail mowers, three tractors with batwing mowers, three tractors with over-the-rail (OTR) mowers, and one tractor with no equipped mower. None of the tractors were equipped with cabs, airconditioning or other large auxiliary loads. Table 2 includes additional information on the hours of operation recorded before the beginning of the first test, as well as the weight of the tractors. Figure 1 provides a rear view of a NYSDOT tractor equipped with a side-wing flail and rear flail mower before beginning mowing on the side of the highway. Additional pictures of tractors are given in next section.

Table 2. Additional Tractor Descriptions

Equipment ID	Make	Model	Year	Cyl.	Engine Hp	Displ [L]	Hours of Operation	Weight of Tractor (lbs)
83-7091	Ford	5610	1983	4	72	4.2	4023	5800
83-7110	Ford	5610	1983	4	72	4.2	3268	5800
84-7118	Ford	2910	1984	3	40	2.9	5340	4650
84-7107	Ford	2910	1984	3	40	2.9	2775	4650
84-7152	John Deere	401B	1984	4	62	3.6	3436	4452
84-7153	John Deere	401B	1984	4	62	3.6	3161	4452
89-7074	Ford	5610	1989	4	72	4.2	3939	5800
89-7069	Ford	5610	1989	4	72	4.2	4014	5800
89-7075	Ford	5610	1989	4	72	4.2	2132	5800
90-7162	Massey Ferguson	383	1990	4	81	4.1	3104	6400
90-7160	Massey Ferguson	383	1990	4	81	4.1	2580	6400
94-7030	Case IH	695	1994	4	73	3.5	1216	5660
95-7084	Case IH	4210	1995	4	72	3.9	2163	5800
95-7071	Case IH	4210	1995	4	72	3.9	220	5800
95-7081	Case IH	4230	1995	4	84	4.4	862	6100
04-7039	New Holland	TL90A	2004	4	90	4.5	757	7275
04-7041	New Holland	TL90A	2004	4	90	4.5	651	7275
04-7042	New Holland	TL90A	2004	4	90	4.5	199	7275

Figure 1. Example of Real-world mowing conditions

3.2 Mower Equipment

Each mower type has varying power requirements that affects the energy and emissions output. From personal correspondence with Rich Boeltz, NYSDOT Region 9 Production Manager, the tractors are all operated to run at 540 rpm for the Power-take-off (PTO)to power the mowers. Some of the mowers (Case International 4210/4230 and New Holland TL90A) have capabilities to run the PTO at 1000 rpm, however the mowers used by the NYSDOT are all ran at 540 rpm. The majority of the mowers used by the NYSDOT are produced by Alamo Industrial, with several produced by Schulte Industries. The numbers from current Alamo (http://www.alamo-industrial.com/), and a Schulte batwing mower (http://www.schulte.ca/) are summarized in table 3 below. Because the mowers used by the NYSDOT are older than the current models, these values should give approximations for the power output and performance of the mowers currently used by the NYSDOT. However, they provide insight into the specifications, power needs, and benefits of each type of mower.

Table 3. Mower Descriptions and Requirements from Alamo Industrial and Schulte Industries

Mower Type	Tractor requirements	Cutting Requirements	Mowing Width
Alamo Switch Blade® Sickle Bar (Sickle Bar)	25 HP, 3,000 lbs minimum (Bar weighs 500 lbs)	½" grass and weeds,	5'and 6'
Alamo Super Heavy Duty Flail 88" Rear and 74" Side wing (Flail)	50 HP (Depending on model)	1 " diameter brush 62" to 96" width	12'2"
Alamo Eagle 15™ Flex Wing Rotary (Batwing)	50 HP	4" diameter vegetation	15'
Schulte FX180 Rotary Cutter (Batwing)	50 HP, (batwing weights 4500 to 5050lbs)	4" vegetation	15'
Alamo Rear Mount Boom with Flail-Axe® Brush Cutter (Over-the-Rail)	65 HP, 5000 lbs (OTR weighs 4,700 lbs)	4" vegetation	4'

(http://www.alamo-industrial.com/ and http://www.schulte.ca/)

The mowers tested in the project were characterized according to type, and not the manufacture or model year. The in-field notes refer to the mowing type as the Sickle Bar, Flail and Batwing, and Over-the-Rail. Each tractor-mower configuration is now discussed in detail.

3.2.1 Sickle Bar Mower

Two tractors configured with the "Sickle Bar" mower were tested: 84-7107, and 84-7118. Both tractors were 1984 Ford 2910 Tractors. The tractors equipped with the sickle bar mower also have a rear flail. The tractors had 6' wide sickle bar, and a 7'4 wide rear flail. Assuming that the sickle bar and side flail overlap 1'4" (the same as the side-flail tractors, Alamo Industrial), the total mowing width should be 12'. Figure 2 contains a front angled view of one of the sickle-bar mowers. The advantage of the sickle bar mower is the lower power and weight requirements, so it can be used on smaller tractors. The Ford 2910 equipped with the sickle bar mower has the smallest rated HP than all of the other tested tractors.

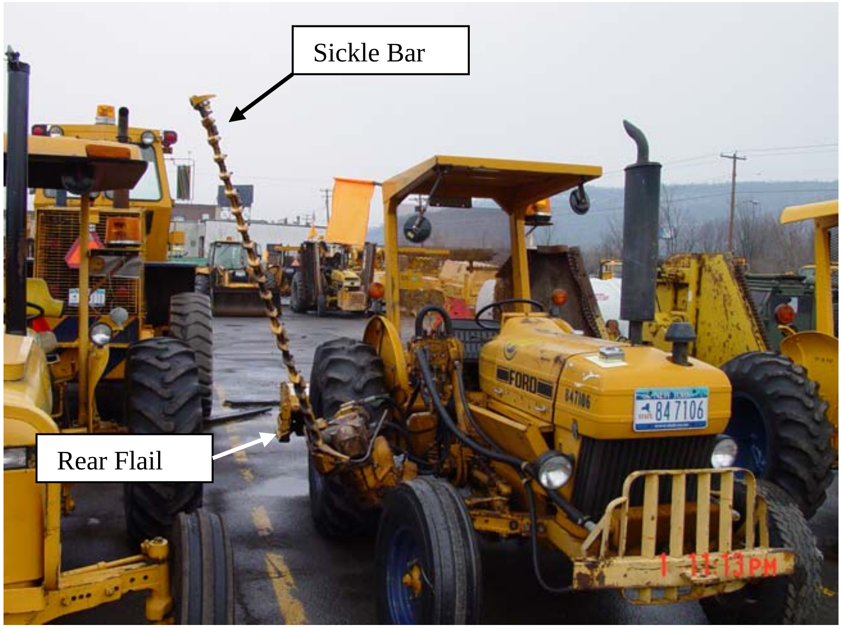

Figure 2. 1983 Ford 2910 Tractor Equipped with a Sickle Bar with Rear Flail Mower.

3.2.2 Flail Mower

The tractors referred to as "Flail" mowers in this report and project were tractors that were equipped with both a side-wing flail and a rear flail. Flail mowers use a series of cutting axes attached to a rotating shaft to provide a clean and sharp grass cut. Flail mowers are often used when the aesthetics of the mowing job are a priority. Eight out of the eighteen tested tractors were equipped with a side wing flail and a rear flail. The rear flail width is 7'4 (88") and the side flail is 6'2" (74"). The mowers have a 16" overlap so that no gaps in mowing will occur while the tractor is turning. With a 16" overlap the total the mowing width for these tractors is 12'2."

Figure 3. 1995 Case IH 4210 Tractor Equipped with a Side-Wing Flail and Rear Flail Mower.

Tractor 95-7081 (a 1995 Case IH 4230 tractor pictured in Figure 4) was equipped with a double-wing flail mower. If both of the side flails are engaged than this tractor has a mowing width of 17'. This is the only double-wing flail mower in Region 9, and it was only tested using a stationary test.

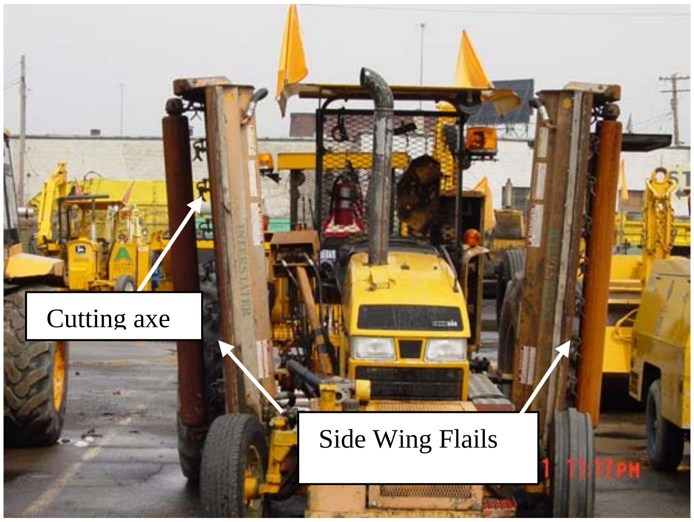

Figure 4. 1995 Case IH 4230 Tractor Equipped with a Double Wing Flail and a Rear Flail Mower.

3.2.3 Batwing Mower

"Batwing" mowers are rotary mowers with flexible wings that can be raised. Three of the tested tractors were equipped with Batwing Mowers: a 1983 Ford 5610, the 1984 John Deere 401B shown in Figure 5, and a 2004 New Holland TL90A. The batwing mowers provide a wide cutting width, and are able to cut through larger diameter brush. The older tractors are equipped with Alamo batwing mowers, while the 2004 New Holland tractors are equipped with 2004

Schulte batwing mowers. From the specifications on the manufactures' websites the horsepower requirements for the two types of batwings appears to be the same.

Figure 5. 1984 John Deere 401B Tractor Equipped with a Batwing Mower.

3.2.4 Over-the-Rail Mowers

"Over-the-Rail" (OTR) mowers are named because they are used to cut vegetation over guide-rails on the side of highways. The OTR mowers have a rear mount boom that is attached to a mower head, which typically is a rotary or a flail mower head. Three tractors were tested which were equipped with OTR mowers: a 1983 Ford 5610, a 1989 Ford 5610, and a 2004 New Holland TL90A. Each of these tractors was equipped with an Alamo rear mount boom with Alamo flail mower head. The 2004 New Holland tractor was equipped with an older mower taken from an older tractor. Thus the load requirements and performance of the mowers should be equal across the different types of tractors. Pictures of an OTR mower configuration and flail mower head are shown in Figures 6 and 7. Note that Tractor 84-7153 pictured in Figure 6, was tested during the study, but was equipped with a side-wing flail during the testing period instead of the OTR mower.

Figure 6. 1984 John Deere 401B Tractor Equipped with a Over-the-Bar Mower.

Figure 7. Flail-Axe head on the Over-the-Bar Mower.

The mowing width for the tractor mower configurations from the provided assumptions and measurements are summarized in Table 4.

Table 4. Mowing Width of NYSDOT Mower Configurations on Tested Tractors

Mower Type	Combined Mowing Width
Sickle Bar (side) and Rear Flail	12'
Side Wing and Rear Flail	12'2"
Double Side Wing Flail and Rear Flail	17'
Batwing	15'
Over-the-Rail	4'

4. Overview and Quality Assurance of Collected Data

4.1. Stationary Tests

The purpose of the stationary test was to provide a baseline comparison among the different tractors. The stationary tests were conducted for several reasons: (1) The stationary tests were conducted before the mobile tests were performed to inform researchers of what to expect during the mobile tests. Ranges of acceptable fuel/emission levels were collected to ensure that the emissions measurement equipment was functioning properly in the field during mobile tests. (2) More difficulties were expected in measuring emissions data during the mobile tests, so the stationary tests were conducted to guarantee that at least some high-quality data was obtained on 15 different NYSDOT tractors. (3) The stationary tests could be conducted under identical testing conditions among the different tractors eliminating confounding effects that were introduced during mobile tests from variables such as operator type, mower type, road type, vegetation type, vegetation growth, slope, soil type, etc.

The stationary tests involved running the engine at five different engine speed levels (Idle, 1000, 1500, 2000, and the maximum allowed for the engine) for two minutes each. When the engine had warmed up, the test was then repeated. An example of the varying engine speed level procedure for a cold start emission test is shown in Figure 8.

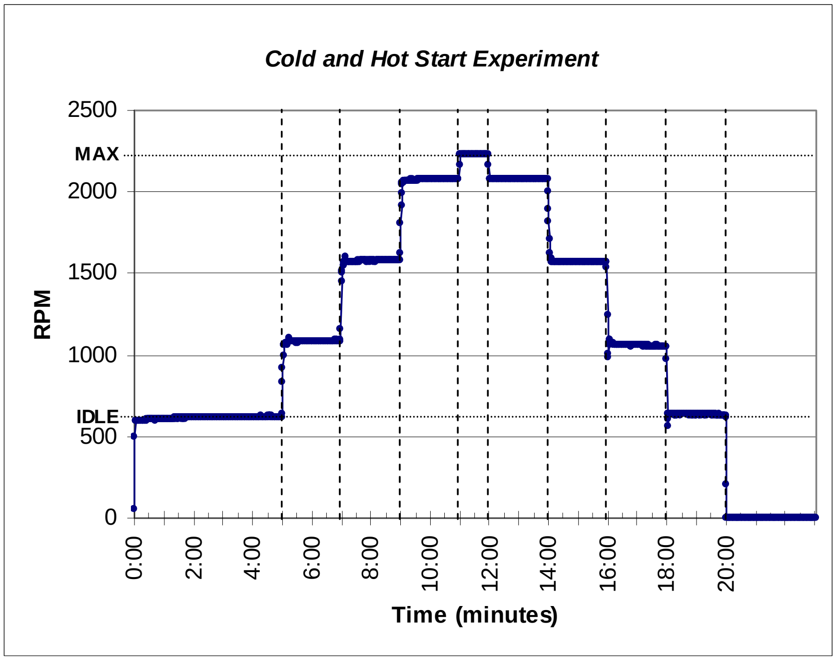

Figure 8. Engine Speed measured during the cold start of Stationary Test 2. Test conducted on a 1984 Ford 2910 on May 28, 2009.

After the cold start and hot start tests, the tractor was revved up to its maximum engine speed with the Power-Take Off (PTO) disengaged and then again with the PTO engaged. In all but one of the cases, the PTO was engaged to an attached mower. When the PTO was engaged, the tractor would power the hydraulic and mechanical operation of the attached mower. The PTO test was used to examine the effect of operating the mower on fuel consumption and emission rates, and to better simulate real mowing engine operation. In the rest of the report, the PTO test conducted during the stationary test is referred to as the stationary mower test. Figure 9 records the engine speed measurements for the first stationary mower test conducted on May 28, 2009.

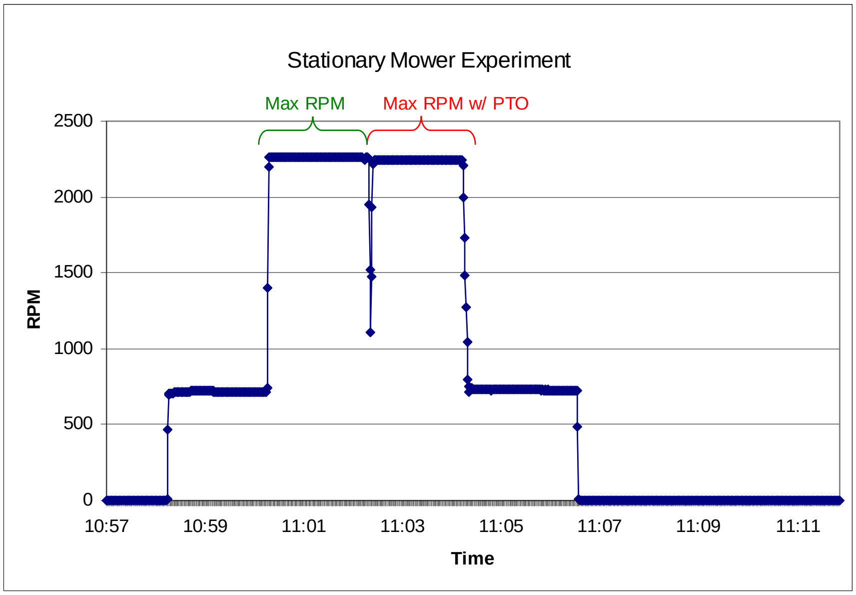

Figure 9. Engine Speed measured during the Mower Test of Stationary Test 1. Test conducted on a 1983 Ford 5610 on May 28, 2009.

The next figure displays the fuel consumption measured during the Stationary Mower test for Test 1. The fuel consumption is slightly higher when the PTO is engaged during the maximum engine speed. The resistance (also known as torque) on the engine crankshaft, increases when the PTO is engaged. However the Axion system is not capable of measuring engine torque (an engine dynamometer would be needed). Power is the work performed per time, which can be calculated in terms of torque multiplied by engine speed:

$$Power = Torque \cdot \frac{Rotations}{\min} \cdot 2\pi = Torque \cdot Engine\ Speed \cdot 2\pi$$

(Goering, 1989)

The power produced during a test cannot be calculated without both the torque and the engine speed. However, the fuel rate is measured, which should increase monotonically at higher engine power. As shown in Figure 10, the fuel rate increases when the Power-Take Off is engaged. The engine speed is roughly equal, so the increased load was due to the higher torque occurring when the PTO is engaged.

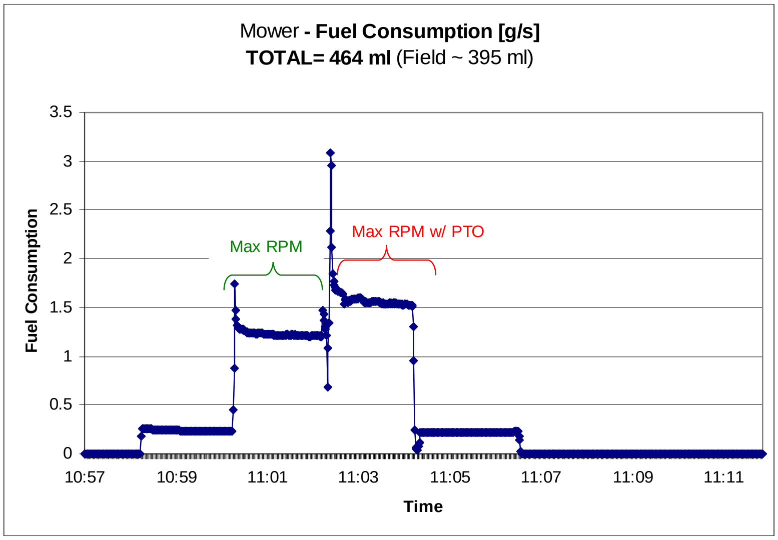

Figure 10. Fuel Consumption measured during the Mower Test of Stationary Test 1. Test conducted on a 1983 Ford 5610 on May 28, 2009.

Beginning after Stationary test 4 (June 8, 2009), the mower test procedures were changed to have an idling interval between the two maximum engine speed segments. This was done because the NYSDOT tractor operators suggested that the PTO should only be engaged from idle, making the test safer and easier to perform. The engine speed levels for the mower test from Stationary test 4 (June 8, 2008) are shown below. For this specific test, the PTO was engaged during the first maximum engine speed interval, and the PTO was disengaged during the second maximum engine speed interval.

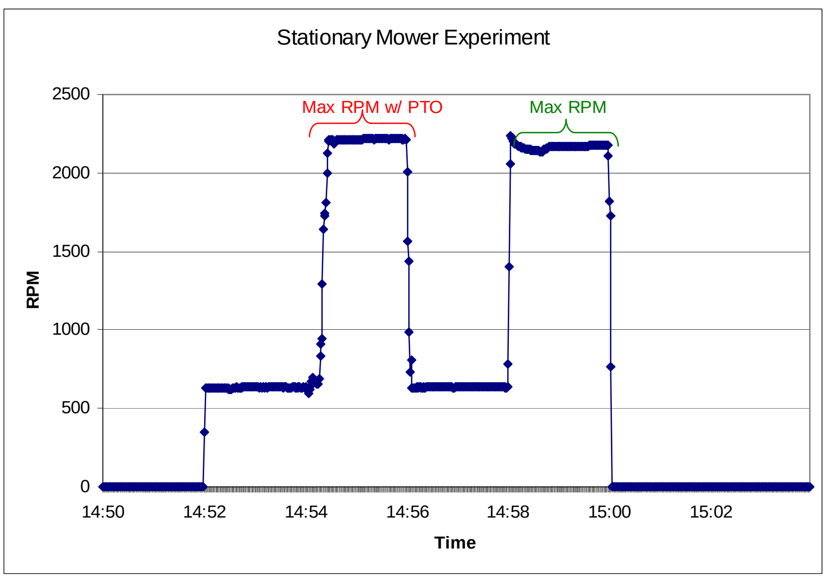

Figure 11. Engine Speed measured during the Mower Test of Stationary Test 4. Test conducted on a 1984 Ford 2910 Tractor on June 8, 2009.

As shown in Figure 11, the fuel consumption is higher with the PTO engaged and the mower activated, indicating the larger engine loads occurring when activating the mower. The measurement of the increase in fuel consumption with the PTO engaged, gives initial confidence that the fuel rate measurements from the Axion system are correct.

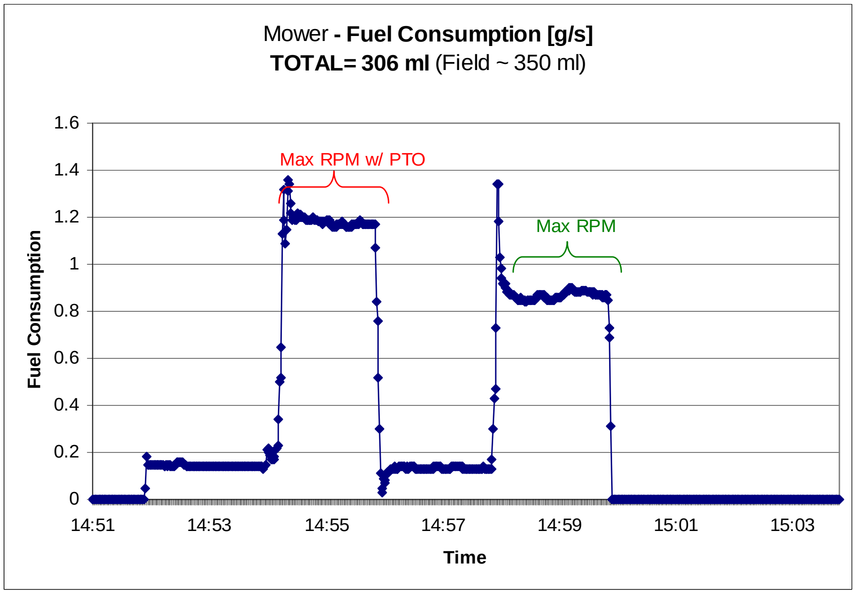

Figure 12. Fuel Consumption Rate measured during the Mower Test of Stationary Test 4. Test conducted on a 1984 Ford 2910 Tractor on June 8, 2009.

The validity of the fuel and emission data collected from the Axion system during the stationary tests was evaluated and quality assured through several means. First, the fuel consumption data measured from the Axion system was compared with volumetric measurements made in the field. During the stationary tests, volumetric measurements were made at three times during the test. The fuel tank was filled before testing began. Than after the cold start, hot start, and mower portions of the test, the tank was refilled and the fuel needed to refill the tank was measured. The volumetric measurements provide real world measurements to the amount of fuel consumed by the tractors. However, the volumetric measurements were rough measurements made in the field and are anticipated to contain a good deal of measurement error. In summary the volumetric fuel measurements should be reasonably accurate but not precise.

The Axion system measured the fuel rate at second-by-second intervals, and the total fuel consumption over each testing interval was summed to compare with the volumetric measurements. For example, in Figure 12 the total fuel consumption during the mower test measured by the Axion system was 306 ml, while the field measurements were approximately 350 ml. The Axion system should have precise measurements of fuel consumption. However, measurement errors such as miscalibration, could bias the results. Therefore, comparisons with the volumetric measurements were used to determine if the Axion measurements were also accurately measuring the fuel consumption.

35 volumetric field measurements were made of the cold, hot, and mower portions of the stationary tests. These fuel rates are compared in Figure 13. As shown, there is a strong correlation among the measurements, and the Axion measurements are on average slightly smaller than the volumetric field measurements. When weighting the measurements by tractor

type, the Axion measurements are 6% smaller than the volumetric field measurements. These differences are small compared to the variability in the test measurements. A paired t-test showed that the two fuel measurements are not significantly different (p-value = .1450 at the 10% confidence level. Thus, the Axion measurements appear to be both precisely and accurately measuring fuel consumption during the stationary tractor tests.

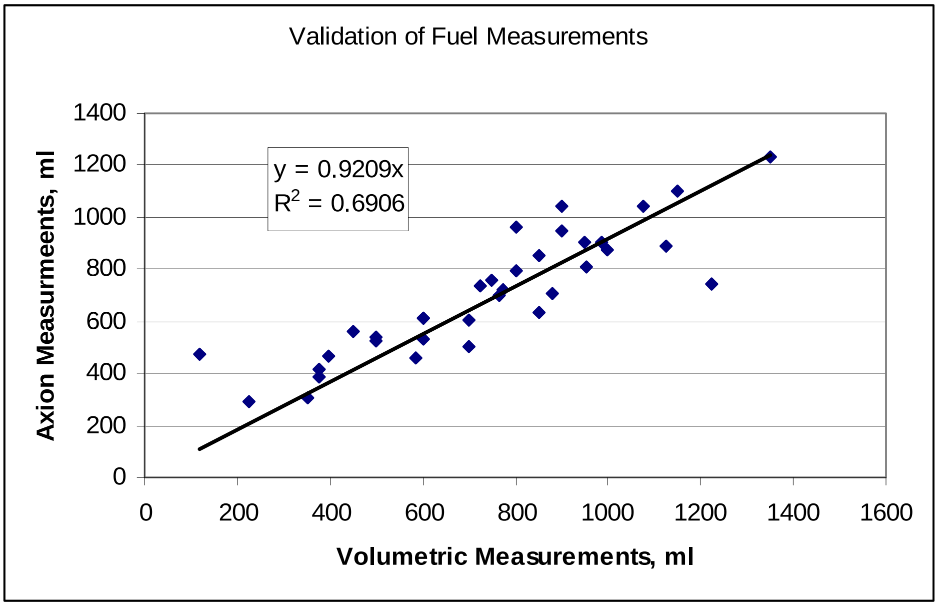

Figure 13. Comparison of Axion Measurements with Volumetric Measurements.

Second, the validity of the Axion data was also evaluated by examining the responsiveness of fuel consumption and emission rates to operating conditions from the stationary mower tests. The mean and median fuel consumption and emission rates were computed for each stationary test under two conditions: (1) the two-minute period with maximum engine speed with the PTO disengaged, (2) the two-minute period with maximum engine speed with the PTO engaged. The details from this analysis are included in Section 1 in the appendix, however the main results are summarized here:

- Fuel consumption consistently increased for all the tractors tested in the stationary test when the PTO was engaged.
  - The only exception was stationary test S2, which had known problems and the data was removed from analysis from the stationary mowers test results.
  - Excluding the stationary test S2, the average increase in the median fuel consumption was 33%.
- NOx emissions were consistently higher when the PTO was engaged. On average the median NOx emission increased by more than 2 times.
- PM emissions were generally higher with the PTO engaged. On average the PM emissions were 15% higher with the PTO engaged. However, one of the stationary tests had suspect PM data. When that test was excluded, the PM emissions were 20% higher and were significantly different according to a one-sided t-test at the 5% confidence level (p-value = 0.049).
- Neither the Hydrocarbon nor Carbon Monoxide emissions were clearly influenced by the engagement of the PTO. No clear difference in emissions among the tractors is

observed hydrocarbon and carbon monoxide emissions when the PTO is engaged. T-tests detect no significant difference between the emissions with the PTO engaged. This observation does not mean the hydrocarbon and carbon monoxide emission rates are inaccurate. Previous tests on diesel emission vehicles have shown less sensitivity of HC and CO emissions to operating mode (Frey, et al. 2008a).

Third, the validity of the Axion data was evaluated by comparing the fuel and emission rates to published results on tractors fuel consumption and emissions available in the literature. Lindgren et al. (2003) measured the fuel consumption and NOx, HC, and CO emissions from two European tractors while in real-world mowing operation. A summary of the results converted into comparable units for this study is shown in Table A19 in the Appendix. The fuel consumption rates and NOx emission rates are comparable to those obtained from the tractors tested. The CO and HC emission rates for the tractors tested in their study are substantially lower than those obtained in the present study.

In summary, the Axion fuel measurements appear to be quite accurate and are used in the rest of the report from both the stationary and mobile tests. The Axion fuel measurements compare well with the volumetric fuel measurements made when refueling the tractors. Additionally, the fuel rates consistently increase during the stationary mower test, as expected during higher loads when the PTO is engaged to activate the mower. The emissions data also appears to be valid. The NOx and PM emissions are responsive to operating conditions during the stationary mower test. The fuel consumption and NOx emission rates compare well with values in the literature. The CO and HC emissions are not responsive to increases in load, and do not compare well with values in the literature. No conclusions from the CO and HC are made in the report and the measured values are only reported in the Appendix.

4.2. Mobile Tests

The purpose of the project was to quantify the amount of emissions and energy produced during mowing operations. The mobile tests were designed to evaluate the emission rates under real mowing conditions. These tests were performed in the field, during true mowing operations. Figure 14, shows a picture of the emissions measurement equipment being setup on one of the NYSDOT tractors in the field. The Axion equipment was setup onboard the tractor, a short version of the stationary test was conducted, and a 10-minute trial run was conducted to assure that collection of data was occurring during tractor operation. Then the tractor operated the tractor for three 30-minute segments, on its normal route along the side of the highway. During the runs the equipment was visually monitored from a following vehicle while a video camera recorded the tractors' activities. After each run the equipment and tractor were thoroughly inspected to ensure the measurement equipment and tractor was functioning appropriately. Notes were kept in the field to keep track of anomalies such as break-downs, equipment malfunctions, and operating breaks for each of the mobile tests. As noted in Table 1 all but two of the 15 mobile tests were successfully able to collect at least some fuel and emissions data.

Figure 14. Preparing the setup of emissions equipment on a tractor in real-mowing conditions.

The test run for the first mobile test (M1) is shown below in Figure 15. This test was conducted on the Tractor 83-7091, a 1983 Ford 5610 Tractor that was also tested in (S1). As shown previously in S1, the maximum engine speed achieved was around 2250 rpm. As shown in Figure 15 for the Mobile test, the tractor tends to operate near the maximum engine speed level when it is engaged in mowing action. The tractor is operating near 2200 rpm in the real-world operation. Comparable graphs for the mobile tests are given in the Data CD for each of the successful mobile tests conducted.

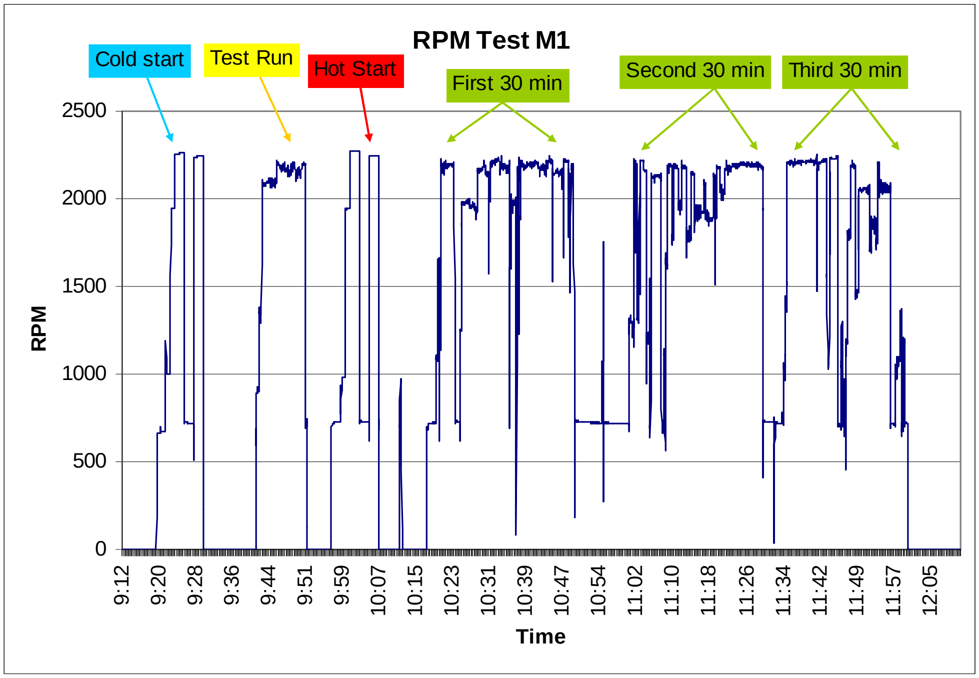

Figure 15. Engine Speed Trajectory for Mobile Test 1, conducted on a 1983 Ford 5610 on June 16, 2009

One way to validate the data from the mobile tests was to compare the data from the stationary tests on the same tractors. The testing conditions of the stationary tests were inherently quite different than the real-world operations. The only loads that could be sustained on the tractors during the stationary tests were the engine resistance and PTO/mower resistance from running the tractor at different engine speed levels. No loads were placed on the tractors to simulate the torque needed to operate the tractors in real-world operating conditions. However, the stationary tests were able to be conducted while the emission, fuel, and engine measurements were being taken under close supervision to assure that the data were collected correctly.

Section 2 in the Appendix outlines comparisons between data collected on the stationary mower tests with the mobile tests. As discussed previously, the stationary mower test collected data from a 2-minute period, with full-engine speed and the Power-Take Off engaged to power the attached mower. The stationary mower test was determined as the most representative of operating conditions during the stationary test to compare with the mobile operation. The mobile operation was chosen from a 10-minute period within one of the 30-minute tests that was consistently loaded and had valid fuel and emission measurement data. The intervals chosen for each 10-minute period are located in Table A6. The median fuel consumption rate and emission rates were chosen from both of these tests for comparison. The median was chosen to be a more stable value that is not highly influenced by outliers that may due to measurement error.

The details from this analysis are included in Section A2 the appendix, however the main results are summarized here:

- Fuel consumption rates among tractors are quite consistent between the stationary mower test and the mobile tests.

- The median engine speed is slightly lower in the mobile test than during the stationary mower test.
- The NOx emissions are generally higher in the mobile test. The trend among tractors is similar for both the stationary mower test and the mobile test.
- The PM emissions are generally lower in the mobile test. Differences in the trend for later model year tractors (1995 and 2004), give evidence that the fuel to air ratio changes significantly between the stationary mower test and the real-world operation for these tractors.
- No strong trends for HC and CO are observed between the two tests.

Overall, the trends in fuel consumption rates are quite similar among tractors between the stationary mower test and the mobile operation test. The fuel and emissions data appear to be valid from the evaluated data. For later model tractors (1995 and later), it appears there is a larger difference between engine operation in the stationary test and the mobile tests. Care must be taken not to make conclusions about emissions in real-world conditions based solely on the stationary tests.

5.0 Data Analysis

In the previous sections, we have explained and explored the data collected from the tractor tests. The previous section identified valid and invalid data. In this section we attempt to leverage the data to compare the energy and emissions from all 18 of the NYSDOT tractors tested in this study.

Due to the large amount of data collected, the data could be summarized and analyzed in many different ways. To compare all the tractors, we chose to compare the tractors on three separate data values to assure that each tractor was compared in at least one data value. Although, complete stationary and mobile tests were not conducted on all 18 tractors, at least some valid data was collected from each tractor. In this section, we leverage the valid data to make conclusions about the energy and emissions of each tractor tested.

To do so, each of the 18 tractors is compared using at data from at least one set of data:

1) Stationary test at maximum engine speed, without the PTO

As shown in Section 2.2, in real-world mowing conditions, the tractors often operate near maximum engine speeds. Because the tractor is not moving, nor is the Power Take Off loaded or engaged, the engine load should be much less than the real operating conditions. However, this data point can give us a comparison between tractors that is not confounded by different mower types that are used on the tractors. Additionally, this is the only data set that includes all 18 tractors.

2) Stationary mower test at maximum engine speed, with the PTO engaged

This data was collected when the tractor is operated at maximum engine speed, with the PTO engaged to power the mower attached to the tractor. This test is often referred to as the “stationary mower test.” The engine load will be lower than during real-mowing conditions, however it can better approximate real-world conditions than the stationary test without the PTO engaged. The stationary mower test provides a compromise between realistic and repeatable measurements. The PTO is engaged to partially simulate real-world conditions, yet there should no be no variability introduced by the tractor operator mowing style, or different mowing conditions which should have a very strong effect on the fuel and emissions.

3) 10-minute period of real mowing conditions

This data set is the most useful of the tests because it provides actual fuel and emissions data when the mower is engaged in real-world conditions. However, we were only able to measure limited real-world emissions data in our study. The 10-minute periods were selected when the tractor was operating during typical mowing conditions, with steady loads and fuel consumption rates. Another criteria was that accurate measurements were taken from each of the tractors. 10-minute averages were taken from all of the tests except mobile test 11, which only had 6 minutes of valid data collected.

No tractors were able to be tested on identical mowing conditions. Additionally, the 15 mobile tractor tests were accomplished by 13 different tractor drivers. Thus, it is difficult to distinguish the impact of the tractor type, mower type, the operating conditions (length of grass, slope of highways, area of mowing), and the style of the tractor driver. We have provided the previous two data points in order to provide a reference between the different tractors and mowers. These can be used to discuss the potential impacts of each of the factors.

5.1 Data Set Comparisons

As mentioned previously, not all the tests were able to be successfully completed on each vehicle. In order to compare all of the tractors and to leverage the collected data, the fuel consumption and emission rates for the three tests are plotted side-by-side in the following Figure 16 through 20. The numerical values are included in Tables A20 through A23 in Section 3 of the Appendix. If no such test was made for a particular tractor or there is a known measurement error, then it is not plotted in the following figures nor reported in the tables.

5.1.1 Fuel Consumption

Figure 16 contains the fuel consumption data for the 18 tractors. All of the tractors were at least tested with a stationary test at maximum engine speed test. For the three tractors that did not have a dedicated stationary test (they were only tested with a mobile test), a short stationary test was included in the mobile tests. Also, the stationary test data from M13 was used to substitute the stationary test data from test S2, which had known problems during the stationary mower test.

Only the 04-7042 2004 New Holland test was not tested with stationary mower test. This is because this tractor was tested at the Equipment Maintenance Shop in Binghamton, NY and was not equipped with a mower during the time of testing. Otherwise all of the other tractors were tested in a stationary test with and without the PTO engaged. As shown, the median fuel consumption consistently increases in the stationary test when the PTO is engaged. The increase in fuel consumption for the stationary mower test is notably higher for the New Holland tractors then the other tractors.

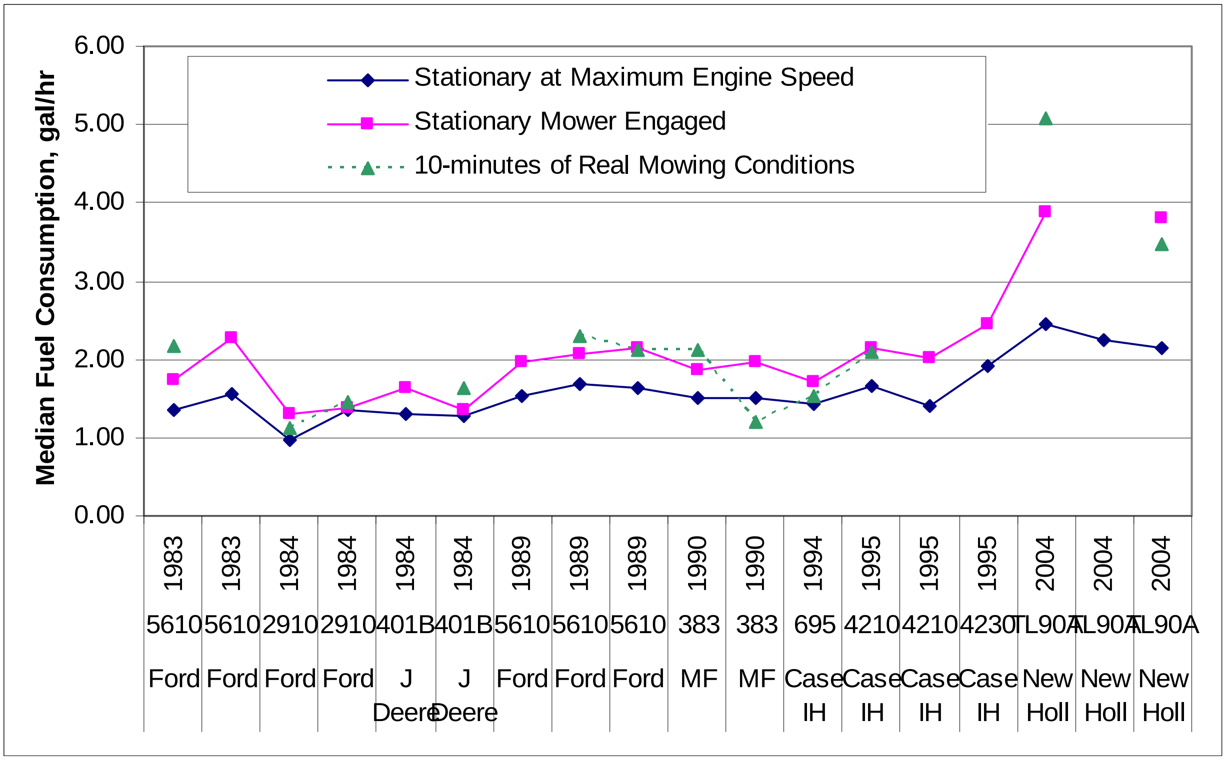

Figure 16. Fuel Consumption of Tractors on according to the three evaluated tests.

The median fuel consumption rates for the real mowing conditions are also plotted on Figure 16. These values are obtained from 13 successful mobile runs. Only twelve values are listed on Figure 16, because two of the mobile runs (M10 and M14) were both conducted on the same tractor (89-7075 Ford 5410). The values from M10 and M14 were averaged as shown in Table A22.

As expected, the values from the real-world mowing tests contain more variability than the other tests. Even mobile tests conducted on the same tractor model can be substantially different. This is apparent with the two 1990 Massey-Furgeson 383 Tractors, as well as the tested 2004 New Holland TL90A tractors.

Generally, the real-world fuel consumption rates are similar to the rates obtained from the stationary mower tests. If the tractor is not tested in a mobile test, such as the only 1995 Case IH 4230, then we would suggest using the stationary mower test with the PTO engaged as a useful surrogate for estimating the fuel consumption rate. The mean fuel consumption rate, as opposed to the median, is also evaluated for the same set of data (Figure A19). The mean values are quite similar to the median values, and the same trends persist.

5.1.2 Nitrogen Oxides (NOx) Emissions

The emissions of NOx are evaluated in Figure 17. The stationary mower tests have NOx emissions consistently higher than the stationary test at maximum engine speed. The 1994 and 1995 Case IH Tractors have a very large increase in NOx emissions during the stationary mower tests. For the most part, the real mowing conditions produce NOx emissions that are close to, or higher than the stationary mower test results.

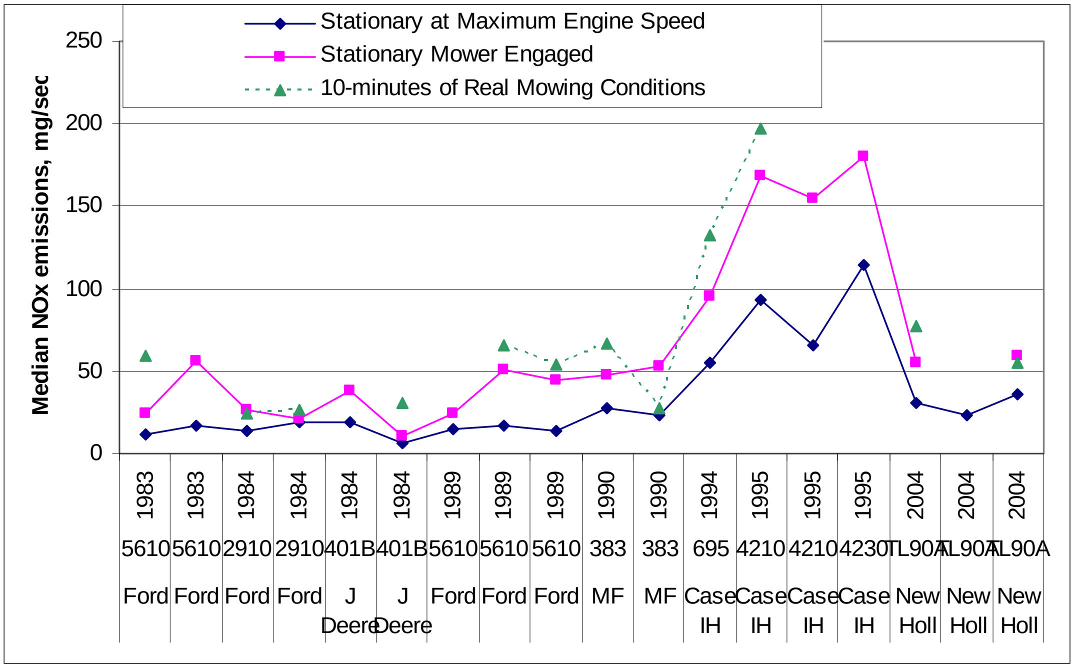

Figure 17. NOx Emissions of Tractors on according to the three evaluated tests.

5.1.3 Particulate Matter (PM) Emissions

The Particulate Matter emissions are evaluated in the Figure 18. The PM is not reported for the 1994 Case IH 695 tractor due to unreasonably low readings that are believed to be due to data collection problems during Mobile Test 6. Overall, the PM emissions are more variable than the NOx emissions. For most cases, the PM emissions are highest with the PTO engaged. The real-world PM emissions are highly variable, and can occasionally be the highest or the lowest. Interestingly, Tractor 95-7084 (1995 Case IH 4210), had the lowest real-world PM emissions, while it had the highest real-world NOx emissions (Figure 16). There is a known tradeoff between PM and NOx emissions in diesel engines. This tradeoff is discussed more in the discussion of results.

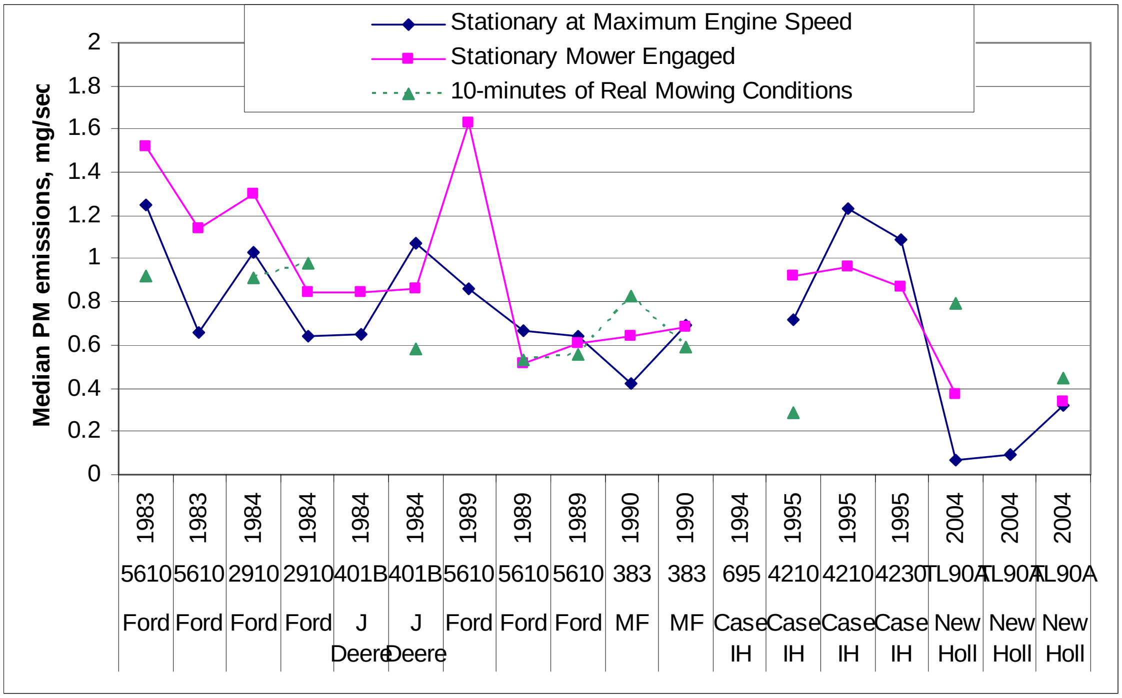

Figure 18. PM Emissions of Tractors on according to the three evaluated tests.

Whereas the fuel consumption rates were quite consistent across the three types of tests, the emissions seem to be more variable across the different tests. The emission rates for HC and CO are included in the appendix. The HC are quite consistent across the tests, whereas the CO are quite variable among the different tests and tractors. These results are included in the Section 3 of the Appendix for the interested reader.

5.1.4 Fuel-Based Emission Rates

The emission rates can also be calculated in terms of emissions per unit of fuel burned. Fuel-based emission rates account for the fact that some runs will have been run at different fuel rates. Additionally, fuel-based emission rates can be used to estimate total emissions when the total amount of fuel used is known. Figure 19 contains the NOx fuel-based emission rates, and Figure 20 contains the PM fuel-based emission rates.

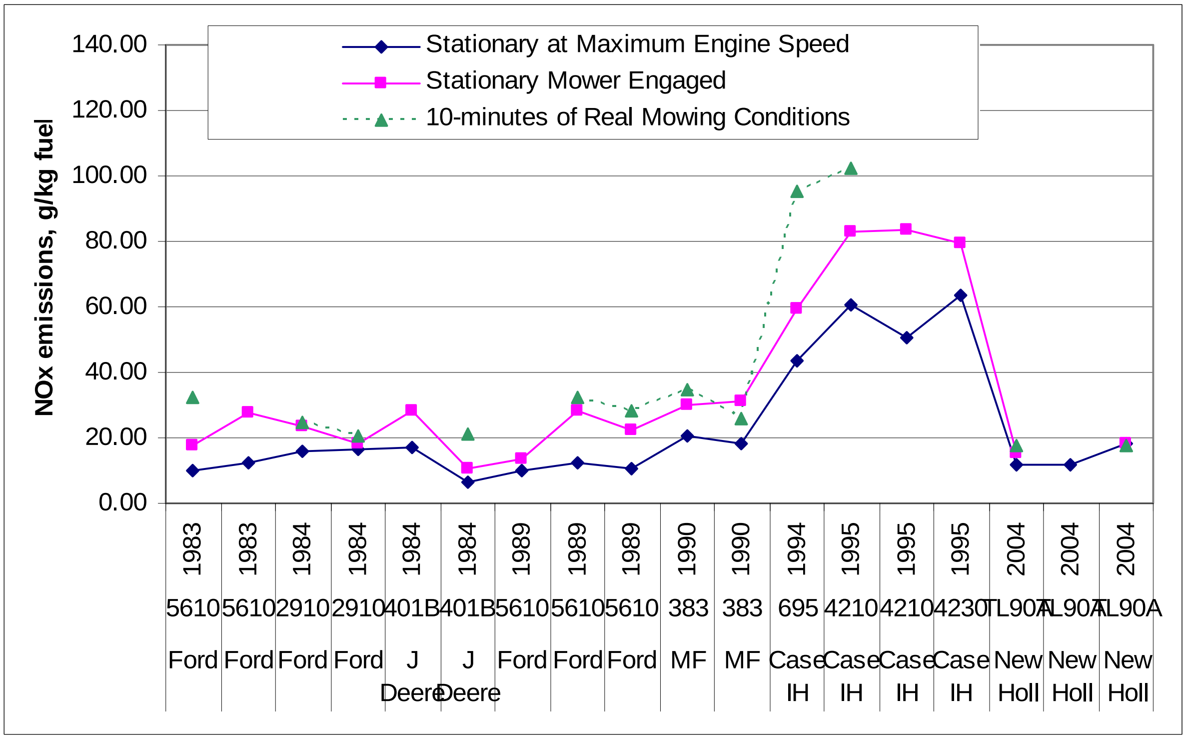

Figure 19. Fuel-based NOx Emission Factors of Tractors on according to the three evaluated tests.

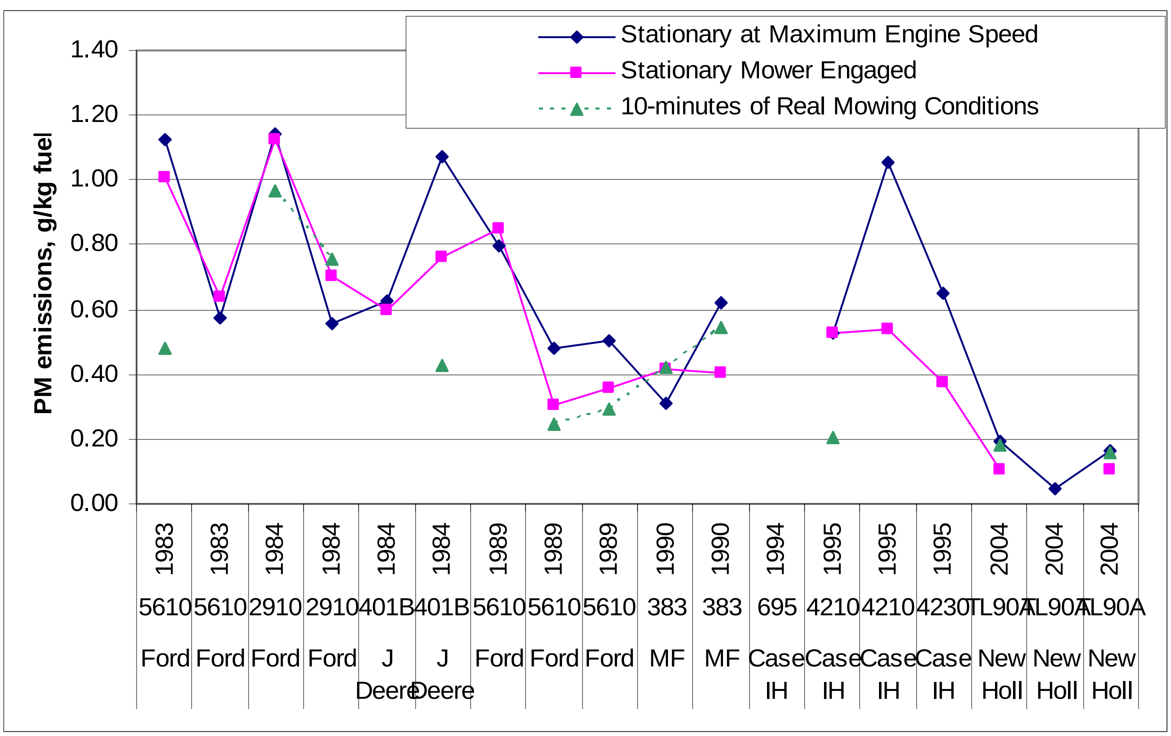

Figure 20. Fuel-based PM Emission Factors of Tractors on according to the three evaluated tests.

5.2 Tractor Fuel Consumption Comparison

Because each tractor was equipped with different mowers and operated in different conditions and operators during the mobile tests, comparing the fuel and emissions characteristics of each tractor is not straightforward. Each mower type has different power requirements, so that the larger tractors are used to operate the largest power requirements, and the smaller tractors operate mowers that have smaller load requirements. To compare the baseline emissions and fuel usage, the tractors can be compared from the stationary test at maximum engine speed. These results are shown below in Figure 21. There is a noticeable difference in the tractors running at maximum engine speed without the PTO.

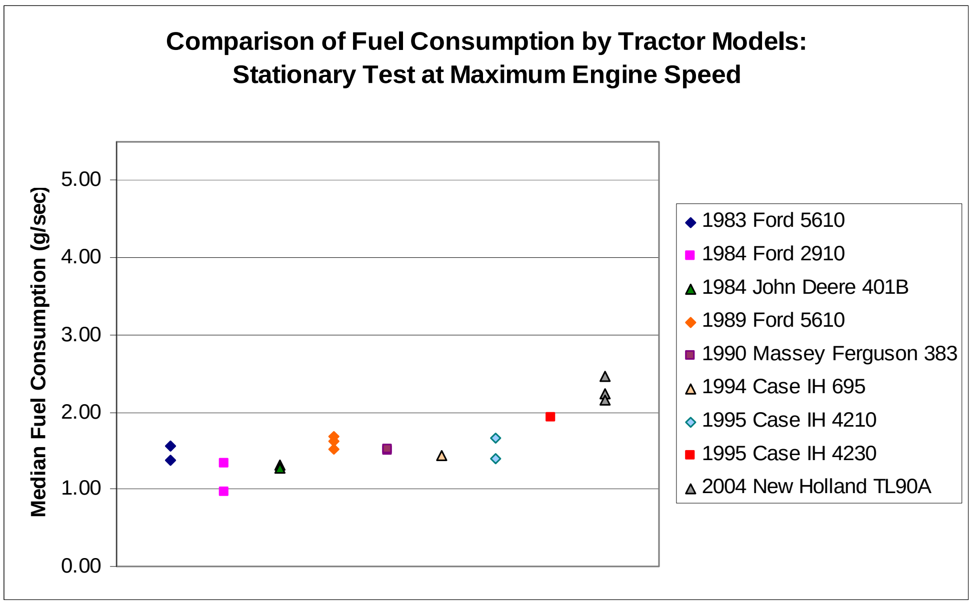

Figure 21. Comparison of Fuel Consumption for Stationary Tests at Maximum Engine Speed without Power-Take Off (PTO).

The fuel consumption data from the stationary mower test is reported in Figure 22. As noted previously, the fuel consumption increases for all the tractors when the PTO is engaged. In comparison to the other tractors, the 2004 New Holland TL90A tractors have a much larger increase in fuel consumption due to the engagement of the PTO.

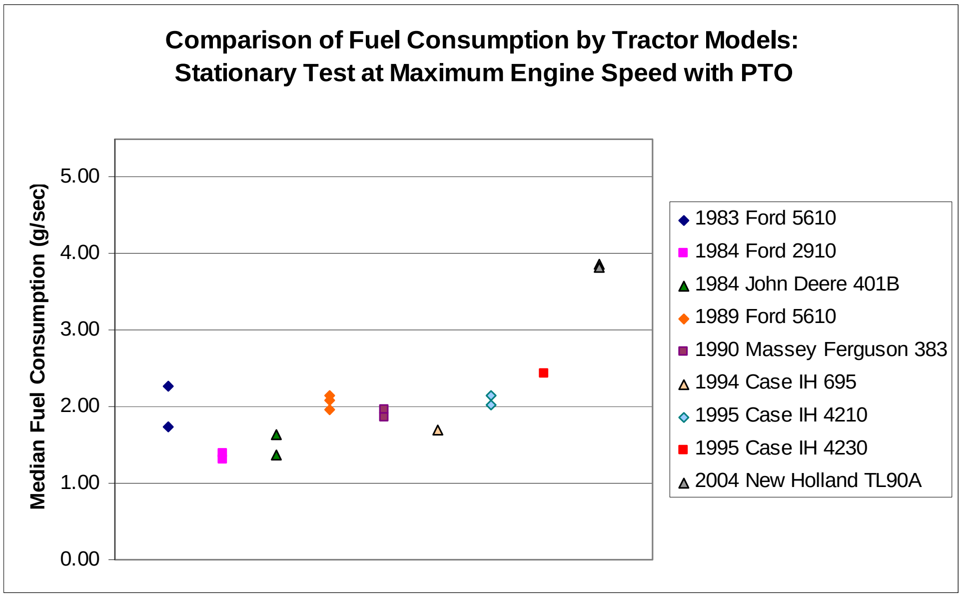

Figure 22. Comparison of Fuel Consumption for Stationary Tests at Maximum Engine Speed with Power-Take Off (PTO).

Figure 23 displays the real-world fuel consumption rates. The New Holland fuel consumption rates are much higher compared to the other tractors, as occurred during the stationary mower test with the PTO engaged. For some tractors, the stationary test without PTO, may be a useful surrogate for emissions and energy use. However, for one of the New Holland tractors, the operation of the New Holland engine appears to be substantially different between the stationary mower test and real-world conditions.

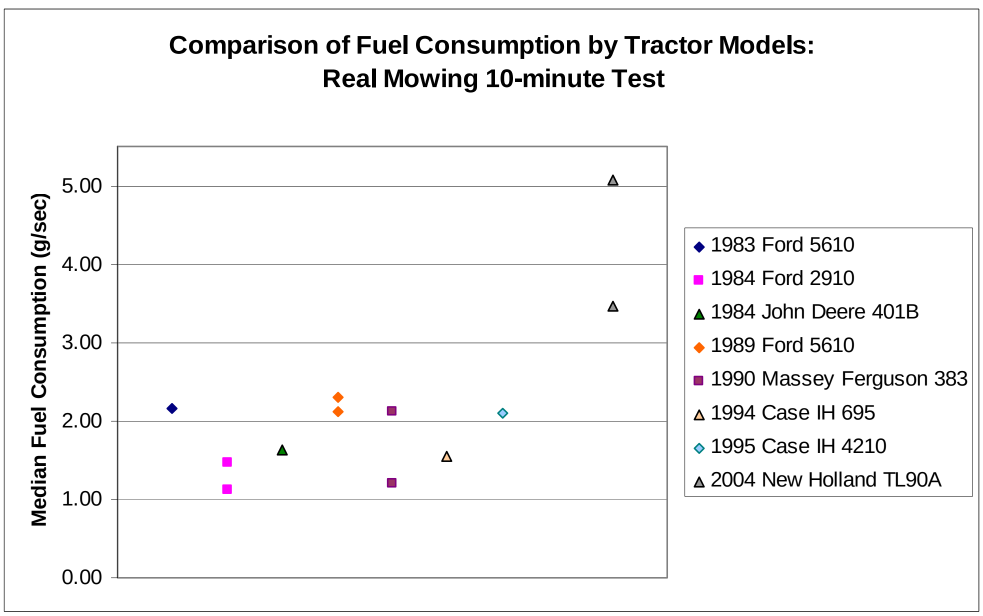

Figure 23. Comparison of Fuel Consumption for the 10-Minute Real Mowing Tests.

The 2004 New Holland tractors have the largest rated engine HP and tractor weight then the other tractors. Figures 24 and 25, plot the fuel consumption rates according to rated engine HP and tractor weight. Given the same technology, the fuel consumption should increase for a larger HP engine and for a moving a larger tractor. Figures 24 and 25, qualitatively evaluate the variability in fuel consumption that could be explained according to these factors. In both cases, there is an increasing trend in fuel consumption between the two variables as expected.

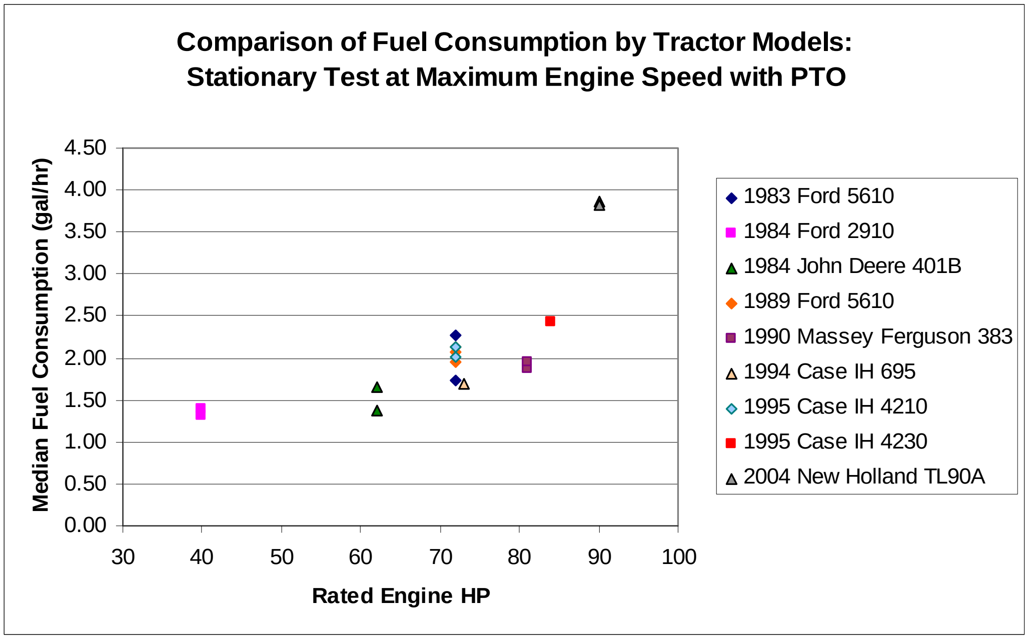

Figure 24. Comparison of Fuel Consumption for Stationary Tests at Maximum Engine Speed with Power-Take Off (PTO) evaluated according to rated engine HP.

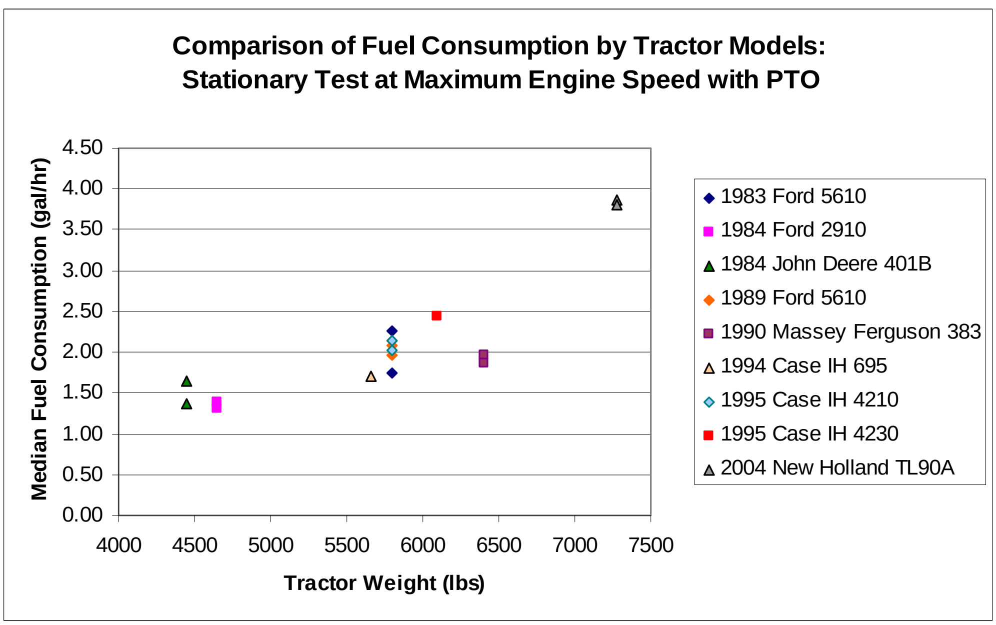

Figure 25. Comparison of Fuel Consumption for Stationary Tests at Maximum Engine Speed with Power-Take Off (PTO) evaluated according tractor weight.

5.3 Mower Fuel Consumption Comparison

The type of mower should influence the fuel consumption for the tractors in the mower test and especially real-world conditions. In this section, we focused on estimating the energy consumption demands of each mower. To do so, we evaluated the energy consumption of the same tractor model that was equipped with different types of mowers. Secondly, we compared all the tractors equipped with mowers, keeping in mind that the tractor model can have an enormous impact on the fuel consumption rates.

Table 5 compares the five Ford 5610 tractors that were tested in the stationary mower test in the study. The tractors were equipped with Batwing, Flail, and OTR mowers. None of the individual tractors were tested under different mower types. However, the data can be used to evaluate the energy and power requirements of the different mower types using one tractor model. The fuel consumption increase is defined as the percentage increase in the fuel consumption rate from the stationary maximum engine speed test, and the stationary mower test. The percentage increase in fuel consumption was evaluated in order to incorporate the fact that an individual mower may have a lower baseline fuel consumption rate, and to incorporate measurement/test differences (i.e. the tractor operator may have not completely opened the throttle on the tractor during the test).

The horsepower and engine loads should be seen as very rough approximations, and should only be used for qualitative comparisons within the Ford 5610 tractors. Several rough approximations were used in order to compare our measured data with the Nebraska Tractor Testing Laboratory tests used to estimate power. Thus, the magnitude of the power should not be compared between different types of tractors. Further details are discussed in the Nebraska Tractor Testing Laboratory Section located in the Appendix.

Table 5. Fuel Consumption and Power Requirements of Mowers Operated on the Ford 5610

Equipment ID	Year	Mower Type	Fuel Consumption, gal/hr	Fuel Consumption Increase, %	Approximation of Power during test, Hp	Approximation of Engine Load %
83-7091	1983	Batwing	1.74	27%	11.0	18%
89-7074	1989	Flail	2.08	23%	19.1	31%
89-7069	1989	Flail	1.96	29%	16.3	26%
89-7075	1989	OTR	2.14	32%	20.6	33%
83-7110	1983	OTR	2.26	45%	23.5	38%

The two Ford 5610 tractors tested with the OTR mowers had the largest fuel consumption, power needs, and relative increase in fuel consumption. This supports the claim in Table 3 that the OTR mower has the highest HP requirements of the evaluated mowers. The flail-equipped tractors had higher fuel rates and power consumption rates than the batwing-equipped tractor. However the relative fuel consumption increase for using the batwing and the flail falls in the same range (23-29%). It is difficult to determine if the flail mower has higher fuel and power demands, because the lower fuel use may be due to the specific tractor tested, or the variability of the test.

A John Deere 401B tractor model was also tested with both a Flail and Batwing Mower as shown in Table 6. In this case, the batwing-equipped tractor had a higher fuel consumption than the flail-equipped tractor. The batwing also has a higher percentage increase compared to Flail mower.

Table 6. Fuel Consumption of Mowers Operated by two 1984 John Deere 401B Tractors.

Equipment ID	Mower Type	Fuel Consumption, gal/hr	Fuel Consumption Increase
84-7152	Batwing	1.64	26%
84-7153	Flail	1.36	7%

* Power was not calculated because the John Deere 401B was not tested by the Nebraska Tractor Test Laboratory.

Two New Holland Tractors were successfully tested in the stationary mower test test. One was equipped with a Batwing mower, while the other was equipped with an OTR mower. These tractors had similar fuel consumption values for the two mowers. The relative fuel increase is substantial for both tractors. Both the fuel consumption increased by over 50% when the PTO was engaged. These results are shown in Table 7. Relative to the baseline, the fuel consumption increased more for the OTR mower.

Table 7. Fuel Consumption of Mowers Operated by two 2004 New Holland TL90A Tractors.

Equipment ID	Mower Type	Fuel Consumption, gal/hr	Relative Fuel Increase, %
04-7039	Batwing	3.87	57%
04-7042	OTR	3.82	78%

The power approximated by using the Nebraska Tractor Test Laboratory was deemed unreasonably high and so are not included. Details are included in the appendix.

Overall, the data is not clear on the relative fuel demands of the batwing and flail in the stationary mower test. There is not enough evidence to refute Table 3 which states that the Flail and Batwing Mowers have similar power requirements. The 5610 Ford tractors show higher fuel consumption and power requirements for the OTR mowers compared to the batwing and flail mowers. However, when the two New Holland tractors were equipped with a Batwing and OTR mower, they show similar fuel requirements. This analysis stresses the difficulty in showing the difference in tractors due to the many confounding variables. Even under stationary tests, there are uncontrolled variables such differences in tractors, mowers, tractor operators, and measurement error

In Table 8 all of the fuel consumption data for the Stationary Maximum Engine Speed with PTO, are reported for each of the tractors, sorted according to the mower type.

Table 8. Fuel Consumption of Mowers Operated during the Stationary Mower Test with PTO.

Mower Type	Equip ID	Make	Model	Year	Rated engine hp	Displ (L)	Weight of Tractor (lbs)	Stationary PTO Test: Fuel Consumption (gal/hr)
Sickle Bar	84-7107	Ford	2910	1984	40	2.9	4650	1.31
	84-7118	Ford	2910	1984	40	2.9	4650	1.39
Flail	84-7153	J Deere	401B	1984	62	3.6	4452	1.36
	89-7069	Ford	5610	1989	72	4.2	5800	1.96
	89-7074	Ford	5610	1989	72	4.2	5800	2.08
	90-7160	M F	383	1990	81	4.1	6400	1.87
	90-7162	M F	383	1990	81	4.1	6400	1.96
	94-7030	Case IH	695	1994	73	3.5	5660	1.70
	95-7071	Case IH	4210	1995	72	3.9	5800	2.14
	95-7084	Case IH	4210	1995	72	3.9	5800	2.02
Double Flail	95-7081	Case IH	4230	1995	84	4.4	6100	2.44
Batwing	83-7091	Ford	5610	1983	72	4.2	5800	1.74
	84-7152	J Deere	401B	1984	62	3.6	4452	1.64
	04-7039	New Holl	TL90A	2004	90	4.5	7275	3.87
OTR	83-7110	Ford	5610	1983	72	4.2	5800	2.26
	89-7075	Ford	5610	1989	72	4.2	5800	2.14
	04-7042	New Holl	TL90A	2004	90	4.5	7275	3.82

Figure 26 summarizes the data in Table 8 by plotting the median fuel consumption data according to mower type. For the seven tractors operated the flail mower, there is good agreement in the fuel consumption data. These tractors have HP ratings that range from 62 to 81.

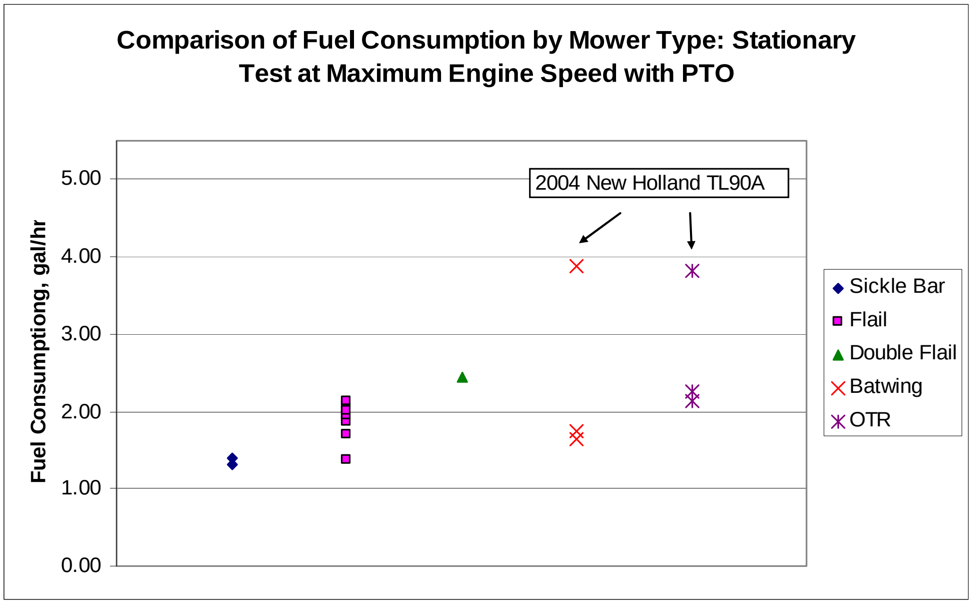

Figure 26. Fuel Consumption of Tractors plotted Operated during the Stationary Mower Test with PTO, organized according to mower type.

For the Batwing and OTR mowers, the 2004 New Holland TL90A had much higher fuel consumption rates than the other tractors that were equipped with the Batwing and OTR mowers. The 2004 New Holland was outfitted with an older OTR mower that had been previously used by other NYSDOT mowers. Thus, the OTR mower used by the 2004 New Holland TL90A is of the same model and age as the OTR model used by the two Ford 5610 tractors.

The batwing mower on the 04-7039 New Holland TL90A is a Schulte rotary mower, while the other batwing mowers are Alamo rotary mowers (Correspondence with Rich Boeltz, Region 9). From discussion with Rich Boeltz, and referring to the manufacturer information (Table 3), the power requirements for the batwing mowers used on the different tractors should be similar. The higher fuel consumption for both of these New Holland tractors is believed to be due to the tractor and not the mower.

Next, the median fuel consumption for the real-world operation of the mowers is presented. The real-world fuel consumption should be different for several reasons. (1) The tractors are operating under much higher engine loads, due to the power needed to cut the vegetation and power the tractor forward. (2) The mowers are operated much differently in real-operating conditions. In real mowing conditions, the mowers are typically not operated 100% of the time. For example, near obstacles such as a guide-rail, a flail-equipped mower, will frequently raise the side-wing flail and only operate the rear flail. Additionally, tractors periodically turn off the mowers to navigating obstacles or travel to the next section for mowing. Other confounding effects are introduced, because the mowing conditions are different for each test, as well as the tractor operator. However, it is informative to compare the fuel consumption rates for actual use in the field. Table 9 contains the median fuel consumption values measured from the 10-minute intervals taken from the real-world tests organized by mower type.

Only the tractors that were tested with valid mobile tests are presented in Table 9. The value for the sickle bar and flail mowers are quite similar to the stationary mower tests. The fuel consumption for the batwing-equipped tractors increased by 24% (Ford 5610) and 31% (New Holland TL90A) when the batwing was operated in the field. In contrast, the OTR-equipped mowers showed slight decreases in the fuel consumption of -1% (Ford 5610) and -9% (New Holland TL90A) when operating in the real mowing conditions. The difference is likely related to the length of the analysis period for the mobile test. In real operating conditions, the batwing mowers can run continuously for the 10-minute period of analysis. The OTR mowers typically operate using several passes, and the mower is not engaged while the tractor is backing up to make a second pass. Thus, over a 10-minute period the batwing mower would likely be used more consistently than the OTR mowers. The median fuel consumption for the mower types from real-operating conditions are plotted in Figure 27.

Table 9. Fuel Consumption of Mowers Operated during the Real Mowing Conditions.

Mower Type	Equip ID	Make	Model	Year	Rated engine hp	Displ (L)	Weight of Tractor (lbs)	Mobile Test: Fuel Consumption (gal/hr)
Sickle Bar	84-7107	Ford	2910	1984	40	2.9	4650	1.12
	84-7118	Ford	2910	1984	40	2.9	4650	1.47
Flail	84-7153	John Deere	401B	1984	62	3.6	4452	1.63
	89-7074	Ford	5610	1989	72	4.2	5800	2.29
	90-7160	M F	383	1990	81	4.1	6400	2.13
	90-7162	M F	383	1990	81	4.1	6400	1.21
	94-7030	Case IH	695	1994	73	3.5	5660	1.54
	95-7071	Case IH	4210	1995	72	3.9	5800	2.10
Batwing	83-7091	Ford	5610	1983	72	4.2	5800	2.16
	04-7039	New Holl	TL90A	2004	90	4.5	7275	5.08
OTR	89-7075	Ford	5610	1989	72	4.2	5800	2.11
	04-7042	New Holl	TL90A	2004	90	4.5	7275	3.47

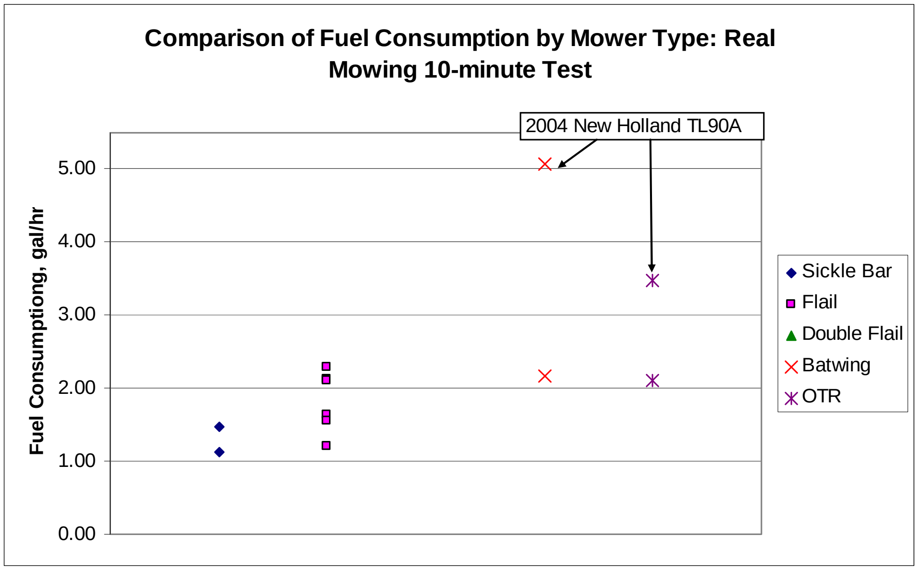

Figure 27. Fuel Consumption of Mowers Operated during the Real Mowing Conditions.

5.4 Emissions Comparison

5.4.1. Tradeoff in PM and NOx emissions

For the most part, the emissions data from the stationary mower test corresponded with the real mowing tests. The stationary mower test data was first analyzed because it includes a larger sample size of tractors. In the previous analysis, there appeared to be a trade-off in PM and NOx emissions. Lower PM, HC, and CO emissions can generally be achieved by increasing the air to fuel ratio. In contrast, NOx emissions are favored when combustion conditions are near stoichiometric that increase exhaust temperatures (Yanowitz et al., 2000; Clark et al., 2002). The PM-NOx tradeoff was compared in depth by plotting the median PM and NOx emissions for each tractor in the stationary mower test. These results are shown in Figure 28.

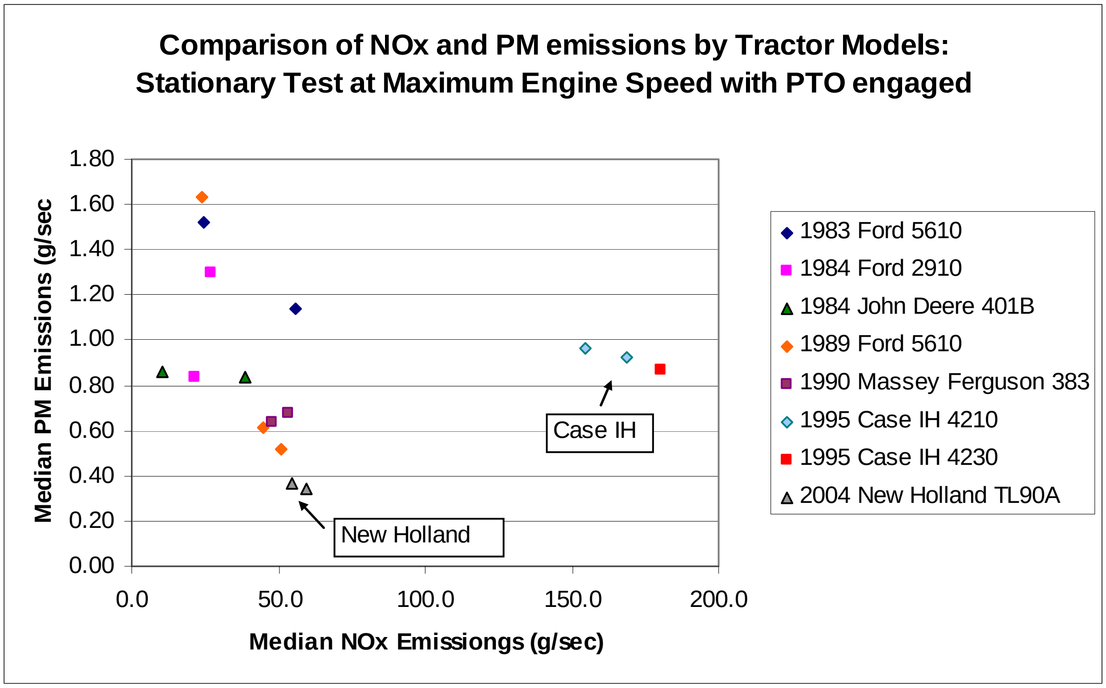

Figure 28. Comparison of NOx and PM Emissions by Tractor Models: Stationary Test at Maximum Engine Speed with PTO engaged.

Figure 28 shows that on a per-second basis, the 2004 New Holland has the lowest PM emissions when operating in stationary mower test. The PM emissions from the other tractors varied considerably. For example, the Ford 5610 had instances of both low PM emissions measurements and high PM emission measurements. Most of the tractors had NOx rates less than 60 mg/sec. The Case IH tractors were identified for having substantially higher NOx emissions than the other tractors, while having moderate PM emissions. In Figure 29 a qualitative tradeoff-curve between PM and NOx is drawn on the graph. The tractors with the best emissions performance should be as close to the line as possible. In context of the two most important emissions from diesel engines (PM and NOx), the Case IH tractor performed quite poorly in the stationary mowing test.

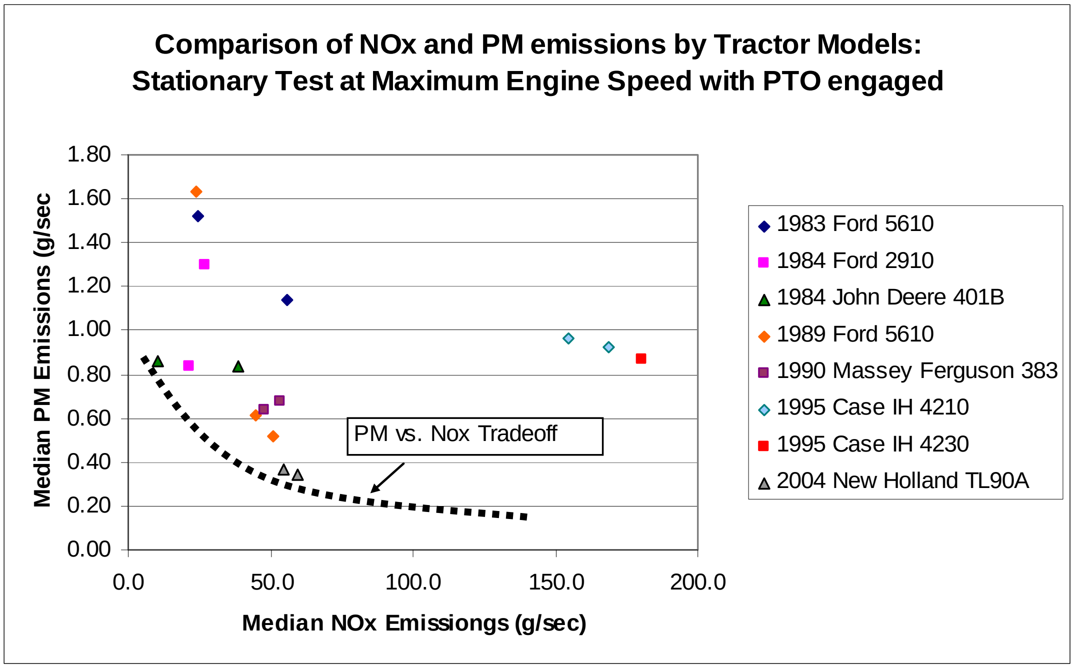

Figure 29. Comparison of NOx and PM Emissions by Tractor Models: Stationary Test at Maximum Engine Speed with PTO engaged with qualitative tradeoff curve.

Next, the tractors that had successful mobile test are evaluated. Figure 30 plots the median PM and NOx emission rates for the 10-minute real mowing tests. The sample size is reduced from seventeen tractors to eleven and the 1995 Case IH 4230 is no longer represented because a mobile mowing test was not conducted with this tractor.

Some differences are noted in the emissions from the stationary mower tests. First, the New Holland tractors no longer had the lowest PM emissions. The New Holland tractor with PM emissions near 0.8 g/sec is the tractor that was operated with the batwings and had a high fuel rate. The 1995 Case IH 4210 has the lowest PM emissions of the tractors tested, and a very high NOx emission rate. For real-world operation, it appears that the Case IH 4210 has been optimized to have low PM emissions, while permitting high NOx emissions. This could be because the Case IH is running a lean fuel to air ratio (near stoichiometric conditions), which is favorable for NOx emissions, but can decrease PM emissions. The Ford 2910 has the highest PM emissions, with the lowest NOx emissions. A trade-off in PM and NOx emissions does appear to be more apparent in the real-world tests among the different tractor models. A qualitative PM-NOx tradeoff curve is included in Figure 31.

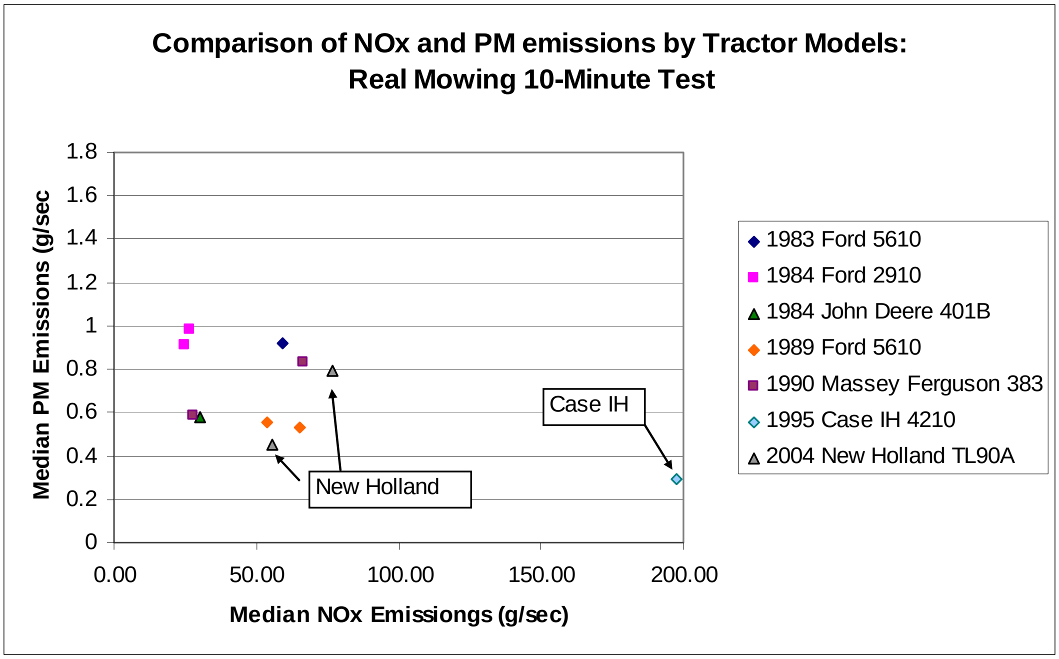

Figure 30. Comparison of NOx and PM Emissions by Tractor Models: Mobile Test.

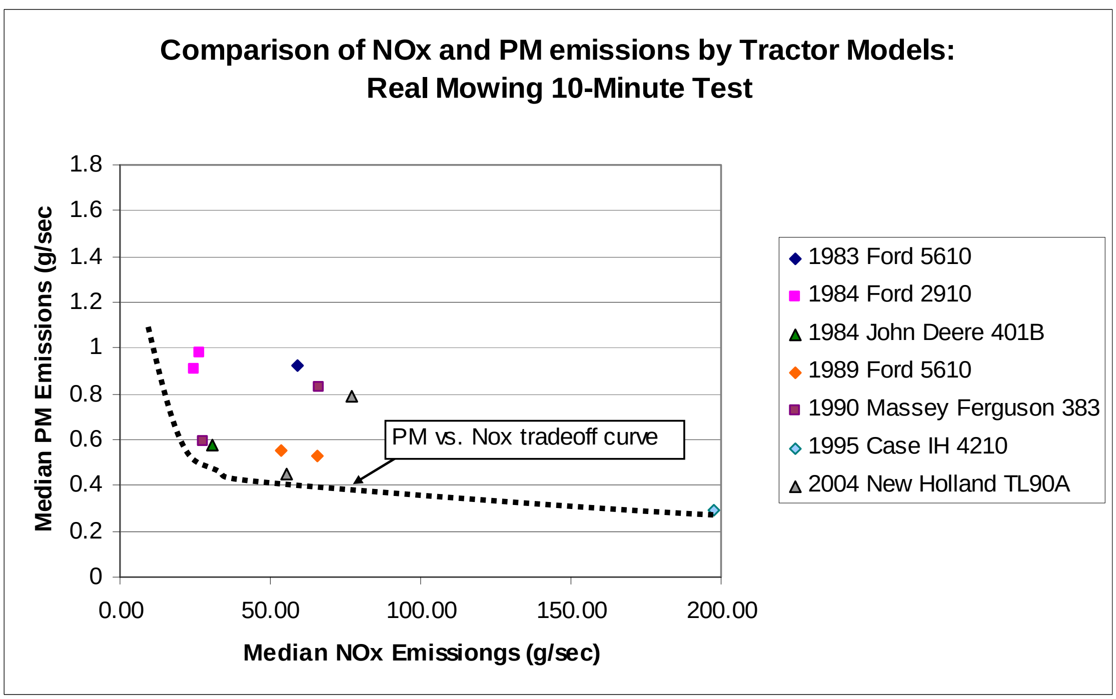

Figure 31. Comparison of NOx and PM Emissions by Tractor Models: Mobile Test with Tradeoff curve.

5.4.2 Fuel-based Emission Factors

The US EPA regulates off-road diesel engines and heavy-duty on-road diesel vehicles in units of grams per brake-horsepower-hour (g/bhp.hr) (Clark et al. 2002). Thus, engines that produce more work can emit higher emissions per unit of time. Measurements of brake-horsepower were not obtained in the study. Assuming that the tractor engines have similar work-based fuel economy then fuel rate can be used as a surrogate for work-based emission factors. On their own, fuel based emission factors are useful to estimate the amount of emissions from the amount of fuel used. Fuel-based emission rates also account for the fact that some tests runs are more power and fuel intensive than others, which can be the cause for higher emission rates. The fuel-based emission rates for PM and NOx are given in Figure 32 for the stationary mowing test. The fuel-based emission factors for the stationary mower test show much the same trend as the time-based (mg/sec) emission factors for the stationary mower test the New Holland Tractors have the lowest PM emission rates, and the Case IH tractors have the highest NOx emission rates. The New Holland tractors have some of the lowest fuel-based NOx emission rates.

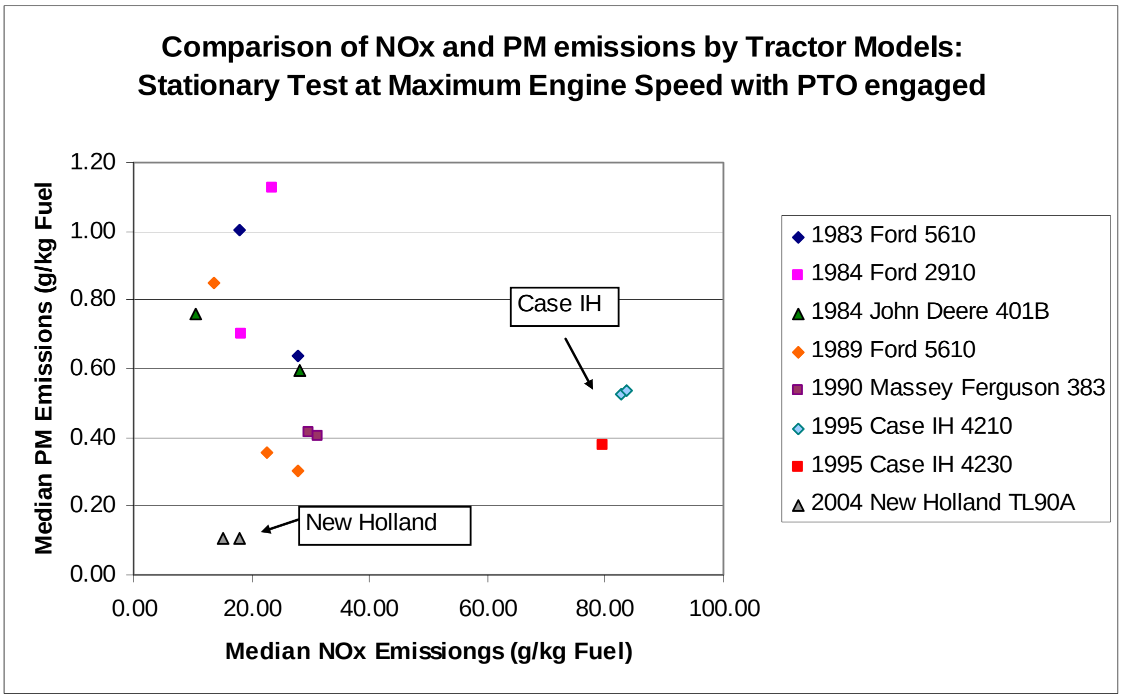

Figure 32. Comparison of NOx and PM Fuel-based Emissions Factors by Tractor Models using the Stationary Mower Test Data.

Figure 33 evaluates the fuel-based emission measurements for the mobile tests. In terms of fuel-based emission rates, the 2004 New Holland has the lowest PM and NOx emission rates. The Case IH also has a low PM emission rate, but has high NOx fuel-based emission rates.

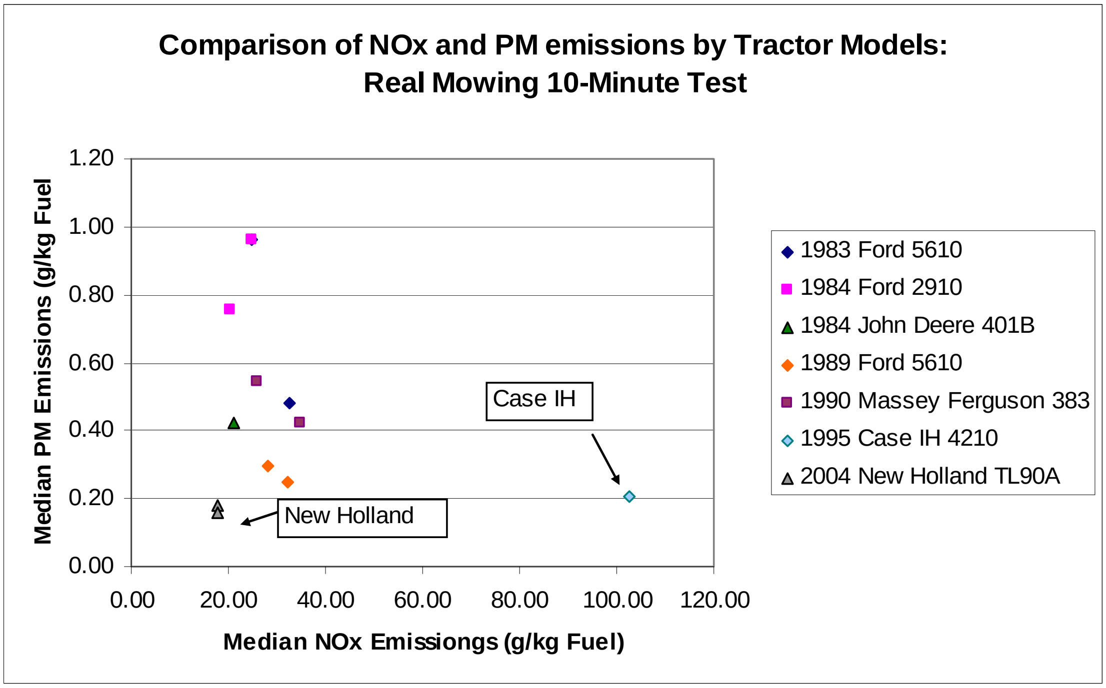

Figure 33. Comparison of NOx and PM Fuel-based Emissions Factors by Tractor Models using the Mobile Test Data.

6.0 Mobile Tests Analysis

The previous section compared the tractors in time-based units (gal/hr, and grams/sec). However, more useful comparisons can be made when evaluating the amount of useful work accomplished. In this section, we analyzed the data according the miles and acres mowed.

10-minute snapshots were chosen that were deemed representative of typical mowing conditions. In some instances the same intervals as used in Section 5 were used, while in others they were changed. The intervals from section 5 were primarily chosen if the engine was operating in a steady state and that good emissions data was being collected. However, in this section we are also concerned that the tractor is mowing a representative amount of vegetation during the 10-minute period. The following tests had revised 10-minute periods: M4, M8, M9, M10, M13, and M14. Some of the 10-minute periods were revised because the previous periods had excessive time traveling on the roadway, small mowing width, and mowing problems that were not deemed representative.

The following criteria were used to select the 10-minute periods.

1. Valid fuel and emissions data
2. Availability of GPS and/or video data provided information on the activity of the tractor.
3. Full mowing conditions. 10-minute periods were typically chosen that had consistent mowing conditions using either the full or partial mower.
4. In some cases the mower covered one segment measured in shoulder miles. This was not generally the case, but it did influence the choice of the 10-minute segment.

Overview of the 10-minute periods are given in the following table. The 10-minute periods are referred to as "snapshots" because they give a relatively small data set of the total possible operation of the mower in real-world operation. All of the snapshots of the mobile tests were 10-minutets except Test M11 due to an equipment failure that occurred 6-minutes into the test. Additional data including the specific time intervals used, distance traveled on roadway, etc. are included in Table A25 and A26 in the Appendix.

The summary of the mobile tests is given in Table 10. The miles mowed per hour was calculated as the total amount of miles mowed during the 10-minute period, divided by the 10-minutes (or 6-minutes in case of M11). The miles mowed was calculated from the GPS the using the total miles, and estimates of the distance traveled when the tractor was not mowing (such as traveling on the roadway). The weighted mower width was calculated to take into account that sometimes only one of the mowers is used on the sickle bar and flail tractor mowers. Using the miles mowed per hour, and the weighted mowing width, the acres mowed per hour was also calculated.

Table 10. Mobile Test Descriptions and performance evaluations.

Mower Type	Equip. ID	Make	Model	Mobile Test	Average Speed (mph)	Miles mowed per hour	Weighted Mower width (ft)	Acres Mowed per Hour	Mowing description
Sickle Bar	84-7107	Ford	2910	M4	1.7	1.4	8.35	1.42	roadside (partial width)
	84-7118	Ford	2910	M13 (I)	2.8	2.8	12	4.07	roadside (full width)
				M13 (II)	3.2	2.8	12	4.13	roadside (full width)
Flail	84-7153	Deere	401B	M3	2.9	2.5	12.17	3.75	roadside (full width)
	89-7074	Ford	5610	M7	3.40	3.2	12.17	4.75	roadside (full width)
	90-7160	MF	383	M5	2.2	2.2	12.17	3.24	median (full width)
	90-7162	MF	383	M8 (I)	1.1	1.1	6.2	0.82	roadside (partial width)
				M8 (II)	1.4	1.0	8.28	1.04	roadside (full/partial)
	94-7030	Case IH	695	M6	1.7	1.7	12.17	2.51	roadside (full width)
	95-7071	Case IH	4210	M12	2.7	2.7	12.17	3.98	interchange (full width)
Batwing	83-7091	Ford	5610	M1	2.7	2.7	15	4.91	interchange (full width)
	04-7039	New Holl	TL90A	M11	3	3.0	15	5.45	median (full width)
Over-the-Rail	89-7075	Ford	5610	M10 (I)	1.2	1.2	4	0.58	roadside (single-pass)
				M10 (II)	1.2	0.8	4	0.39	roadside (double-pass)
				M14	1.7	1.1	4	0.55	roadside (double-pass)
	04-7042	New Holl	TL90A	M9	1.4	0.9	4	0.45	roadside (double-pass)

As expected, the large Over-the-Rail mowers cover the least amount of miles per hour. Due to the small size of the flail axe on the rear mount boom, they mow the least amount of acres per hour. The two batwing mower tractors had the highest acre mowed per hour rates. This is expected due to the large width of the mowers, which are used to mow flat grassy areas such as near interchanges and roadsides. There was substantial variability within the values obtained for the sickle bar and flail mowers. This emphasizes the large influence of roadside conditions on mowing capabilities. In some conditions, only the side-flail is used to mow the side of the highway, while in other cases, such as in a median, the tractors are able to use both the rear and side mowers, which largely increases the amount they can mow per hour.

The next tables (Table 11 through 13) give the emission and fuel consumption rates for the mobile tests. Table 11 presents emission and fuel consumption rates in time-based units. Table 12 gives emissions and fuel rates per distance-mowed. Table 13 gives the values according to the number of acres mowed.

Table 11. Time-based Emission Rates from Mobile Tests

					Time-based Emission Rates					
Mower Type	Equipment ID	Make	Model	Mobile Test	CO2 (g/s)	CO (mg/s)	HC (mg/s)	NOx (mg/s)	PM (mg/s)	FC (gal/hr)
Sickle Bar	84-7107	Ford	2910	M4	2.8	36.8	6.3	22.2	0.9	1.1
	84-7118	Ford	2910	M13 (I)	4.0	51.0	14.0	26.9	1.0	1.5
				M13 (II)	4.4	100.6	90.5	28.7	1.1	1.7
Flail	84-7153	Deere	401B	M3	4.2	40.1	12.6	28.6	0.6	1.5
	89-7074	Ford	5610	M7	6.3	23.5	8.2	65.0	0.5	2.2
	90-7160	MF	383	M5	5.4	39.4	6.5	64.2	0.8	2.1
	90-7162	MF	383	M8	3.3	25.6	13.9	27.6	0.6	1.2
				M8	3.7	24.3	11.4	37.3	0.6	1.3
	94-7030	Case IH	695	M6	4.1	22.7	7.3	130.3	0.2	1.5
	95-7071	Case IH	4210	M12	5.8	19.2	21.5	189.3	0.4	2.1
Batwing	83-7091	Ford	5610	M1	6.0	48.3	13.4	62.3	0.9	2.1
	04-7039	New Holl	TL90A	M11	12.6	0.4	64.9	71.4	0.7	4.5
Over-the-Rail	89-7075	Ford	5610	M10 (I)	5.7	36.8	74.3	51.4	0.7	2.2
				M10 (II)	5.6	74.7	85.1	48.9	0.6	2.2
				M14	6.5	21.7	31.0	59.6	0.6	2.3
	04-7042	New Holl	TL90A	M9	9.5	16.3	86.8	54.8	0.4	3.4

Table 12. Distance-Mowed Emission Rates from Mobile Tests

Mower Type	Equipment ID	Make	Model	Mobile Test	CO2 (kg/mile)	CO (g/mile)	HC (g/mile)	NOx (g/mile)	PM (g/mile)	FC (gal/mile)
Sickle Bar	84-7107	Ford	2910	M4	7.2	94.6	16.3	57.2	2.2	0.76
	84-7118	Ford	2910	M13 (I)	5.2	65.6	18.0	34.5	1.3	0.52
				M13 (II)	5.6	127.5	114.8	36.4	1.4	0.58
Flail	84-7153	Deere	401B	M3	6.0	56.8	17.8	40.6	0.8	0.60
	89-7074	Ford	5610	M7	7.1	26.2	9.2	72.7	0.6	0.70
	90-7160	MF	383	M5	8.9	64.5	10.7	105.0	1.3	0.93
	90-7162	MF	383	M8	10.9	83.8	45.4	90.5	1.9	1.09
				M8	12.7	83.9	39.4	129.2	2.1	1.26
	94-7030	Case IH	695	M6	8.6	48.1	15.4	276.0	0.4	0.90
	95-7071	Case IH	4210	M12	7.7	25.6	28.6	252.4	0.5	0.77
Batwing	83-7091	Ford	5610	M1	7.9	64.3	17.9	83.0	1.2	0.79
	04-7039	New Holl	TL90A	M11	15.1	0.4	77.9	85.7	0.9	1.49
Over-the-Rail	89-7075	Ford	5610	M10 (I)	17.2	110.5	222.8	154.1	2.0	1.83
				M10 (II)	25.3	336.1	383.2	220.0	2.5	2.73
				M14	20.7	68.8	98.5	189.4	2.1	2.06
	04-7042	New Holl	TL90A	M9	36.5	63.0	334.6	211.4	1.7	3.64

Table 13. Area-Mowed Emission Rates from Mobile Tests

Mower Type	Equiment ID	Make	Model	Mobile Test	Area-Mowed Emission Rates CO2 (kg/acre)	CO (g/acre)	HC (g/acre)	Nox (g/acre)	PM (g/acre)	FC (gal/acre)
Sickle Bar	84-7107	Ford	2910	M4	7.1	93.5	16.1	56.5	2.2	0.76
	84-7118	Ford	2910	M13 (I)	3.6	45.1	12.4	23.8	0.9	0.36
				M13 (II)	3.8	87.7	78.9	25.0	0.9	0.40
Flail	84-7153	Deere	401B	M3	4.1	38.5	12.1	27.5	0.6	0.41
	89-7074	Ford	5610	M7	4.8	17.8	6.2	49.3	0.4	0.47
	90-7160	MF	383	M5	6.0	43.7	7.2	71.2	0.9	0.63
	90-7162	MF	383	M8	14.6	112.2	60.7	121.0	2.6	1.46
				M8	12.6	83.6	39.2	128.6	2.1	1.25
	94-7030	Case IH	695	M6	5.8	32.6	10.5	187.1	0.2	0.61
	95-7071	Case IH	4210	M12	5.2	17.3	19.4	171.2	0.3	0.52
Batwing	83-7091	Ford	5610	M1	4.4	35.4	9.9	45.7	0.7	0.44
	04-7039	New Holl	TL90A	M11	8.3	0.2	42.8	47.1	0.5	0.82
Over-the-Rail	89-7075	Ford	5610	M10 (I)	35.5	228.0	459.5	317.7	4.2	3.78
				M10 (II)	52.2	693.2	790.3	453.7	5.2	5.64
				M14	42.7	141.9	203.1	390.6	4.2	4.25
	04-7042	New Holl	TL90A	M9	75.2	129.9	690.2	435.9	3.4	7.50

The fuel consumption rates (gal/mile) are presented in Figure 34. Per mile mowed, the sickle bar mowers had the smallest fuel consumption, followed by the Flail, Batwing, and the Over-the-Rail Mowers. As shown previously, the 2004 New Holland TL90A tractors had higher fuel consumption rates than the Ford 5610 mowers for both the Batwing and Over-the-Rail mowers.

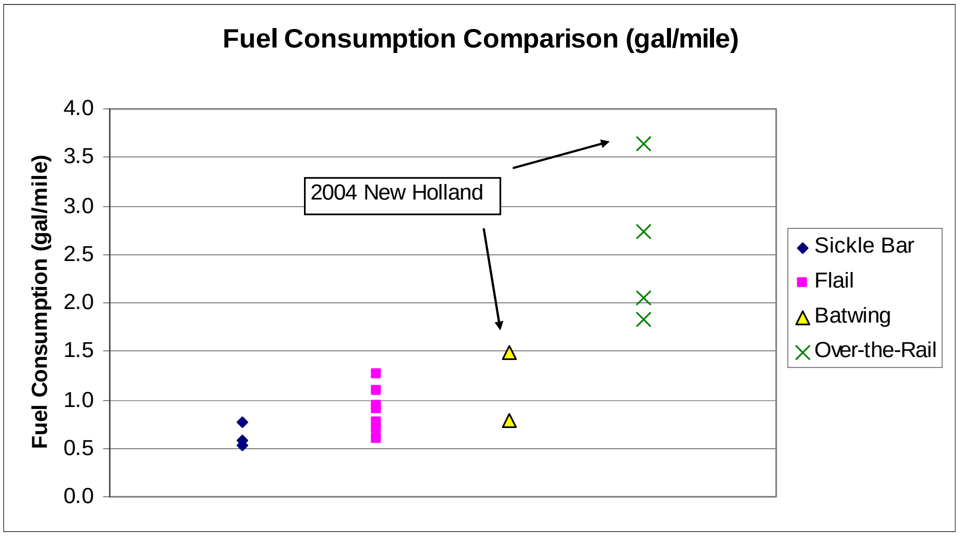

Figure 34. Distance-based Fuel Consumption Rates from Mobile Tests by Mower.

Figure 35 shows the fuel consumption per acre mowed. In this case, the sickle bar, flail, and batwing mowers had similar fuel consumption rates. The flail mowers typically made a wider cut, which made the fuel economy per acre more comparable with the sickle bar. The batwing mowers tractors use substantially more fuel per hour of operation, but because they travel at a high speed and have a large mowing width, they have low fuel consumption rates per acre of vegetation mowed. Because the over-the-rail boom mowers have a small cutting head, they use substantially more fuel per acre mowed.

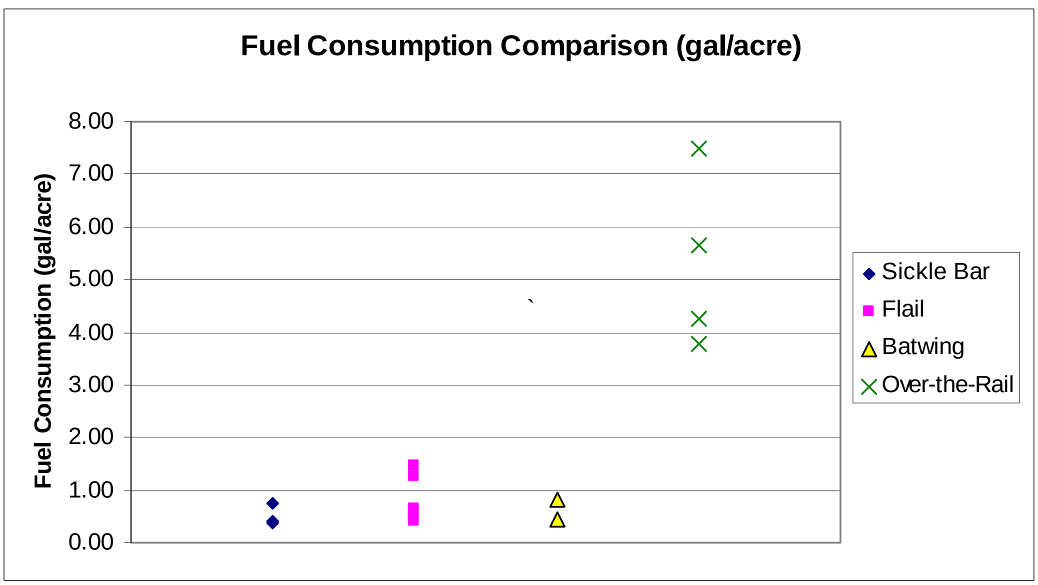

Figure 35. Distance-based Fuel Consumption Rates from Mobile Tests by Mower.

Figure 36 displays the particulate matter emissions in grams per kilometer mowed. The differences in tractor engines were more apparent than with the fuel consumption comparison. As shown the older tractors tend to have the highest particulate matter emissions. The lowest emissions in the flail mower groups are the Case IH tractors. The 2004 New Holland had lower PM emissions than the Ford 5610 when operating both the batwing and over-the-rail mowers.

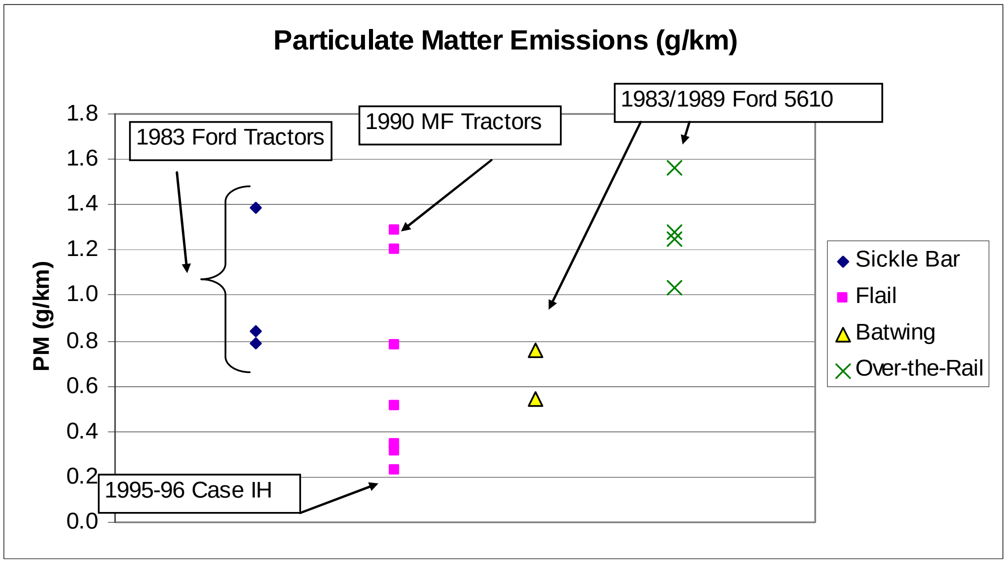

Figure 36. Distance-based Particulate Matter Emission Rates from Mobile Tests by Mower.

Figure 37 displays the particulate matter emissions in grams per acre mowed. The over-the-rail mowers have the largest PM emissions due to the higher fuel consumption needed to mow equivalent acreage.

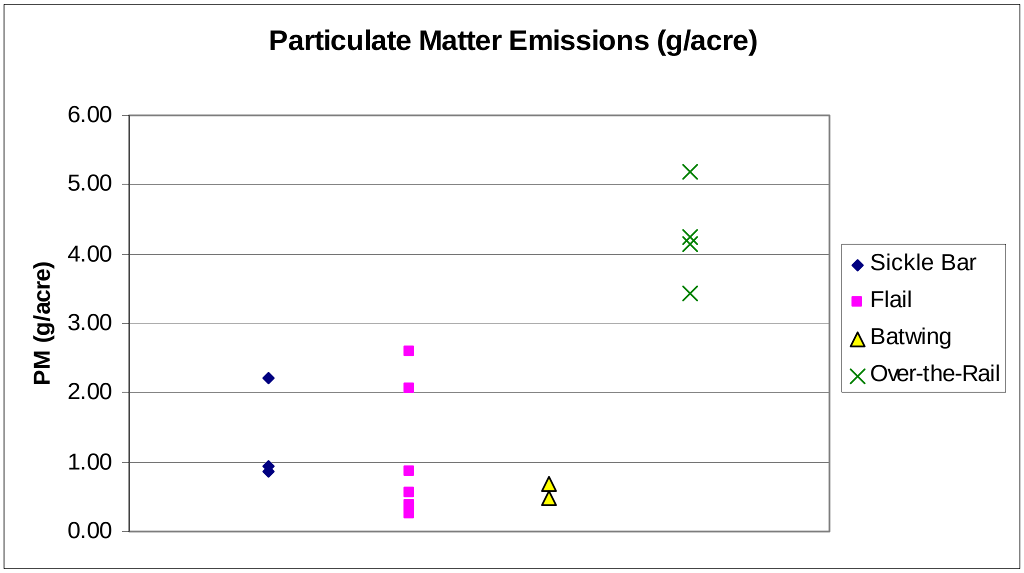

Figure 37. Area-based Particulate Matter Emission Rates from Mobile Tests by Mower.

Figure 38 displays the nitrogen oxide (NOx) emissions in grams per kilometer mowed. The NOx emissions per km tend to follow the trend as the fuel consumption, except for the 1994 Case IH 695 tractor and the 1995 Case IH 4210 tractors which have significantly higher NOx emissions than the other flail tractors. The Case IH tractors were previously shown to have high NOx emissions from the stationary tests.

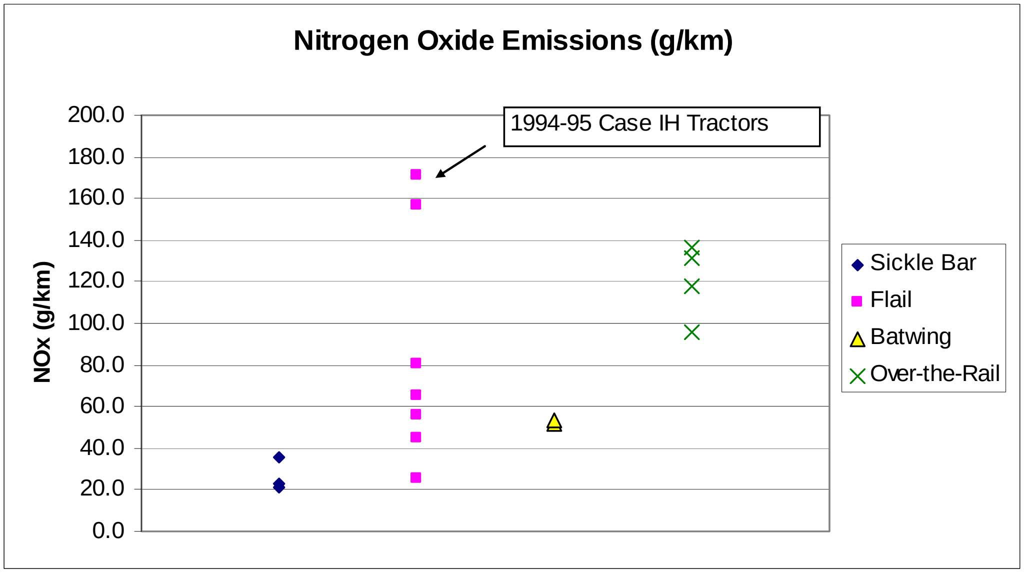

Figure 38. Distance-based Nitrogen Oxide Emission Rates from Mobile Tests by Mower.

Figure 39 displays the nitrogen oxide emissions in grams per acre mowed. In g/acre units, the differences in engine specific NOx emissions are less pronounced. The largest NOx emissions are associated with the most fuel intensive tractor mowers.

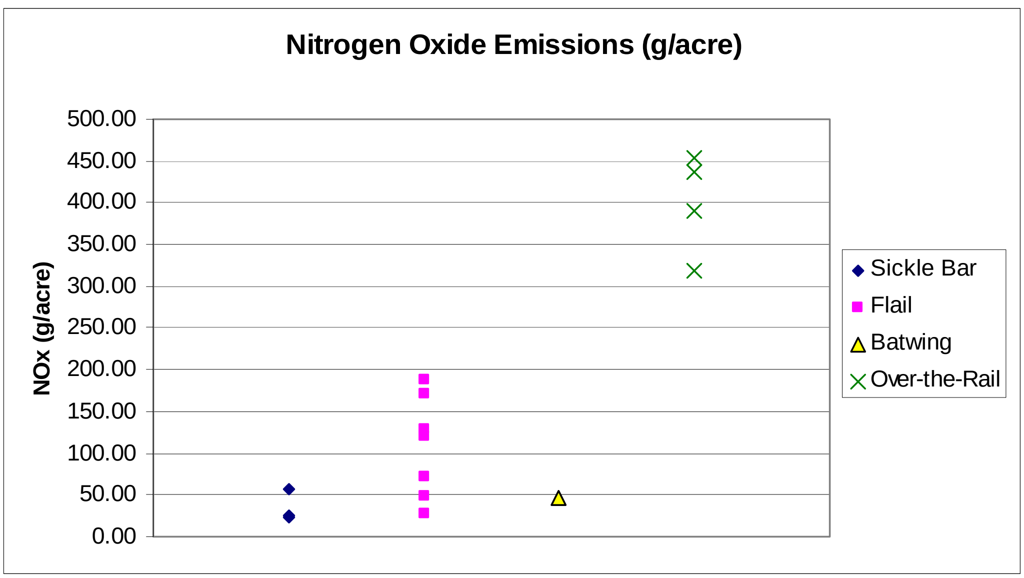

Figure 39. Area-based Nitrogen Oxide Emission Rates from Mobile Tests by Mower.

7.0 Herbicide Truck Emissions Analysis

As part of the study, three herbicide trucks were also tested for emissions in real-world driving conditions. A description of each herbicide truck is listed in Table 14. Each herbicide trucks is equipped with a small 2-cycle gasoline generators which operate the herbicide sprayer. A small gasoline herbicide generator was tested in the summer of 2008, but the test yielded unusable data. Although no valid fuel measurements are available from the herbicide generator, they are anticipated to be rather minor in comparison to the fuel used to operate the trucks.

Table 14. Herbicide Trucks Tested.

Herbicide Test	Date	Location	Truck ID	Make	Model	Model Year	Engine Type	Engine Size (L)
H1	6/24/2009	Hancock	07-5168	Ford	F-250	2007	Gasoline	5.4
H2	8/11/2009	Roseboom	07-5489	Ford	F-350	2007	Gasoline	5.4
H3	8/12/2009	Waterloo	94-5416	Ford	Sintar	1994	Turbo-Diesel	8.3

The fuel usage for herbicide tests H1 and H2 are given in Figures A24 and A25. Unfortunately, test H3 was unsuccessful in collecting valid fuel consumption and energy data. H1 is analyzed according to three sections: driving from the residency, spraying and driving during herbicide application, and returning to the residency after the application of the herbicides. The herbicides are applied under the guide-rails, and under traffic signs along the side of the highway. During the normal operation there are segments of roadway where the truck is not applying herbicides on the roadside. From viewing the speed traces of the normal operation from the GPS data, and viewing the video log, it was estimated that during the normal operation the herbicide truck only was applying herbicide for 75% of the miles traveled. In total this gives an estimate that only 33% of the miles traveled by the truck during the duty cycle were driven while the herbicide was being applied. However, most of the time of the duty cycle occurred while the tractor was applying herbicide (This duty cycle likely had less time for spraying because the truck only sprayed for 1-hour, whereas in the field they would likely apply herbicides for a larger part of the day). Using these assumption, the acres sprayed during the driving cycle for each period is shown in Table 15. For test H2, no data was collected on the driving activity before or after the application of herbicides so it was not included in the analysis. However, it was assumed that 25% of the roadway consisted of segments where no herbicide was applied.

Table 15. Activity Information for Herbicide Trucks.

Herbicide Test	start	end	Elapsed Time (minutes)	Description	Miles traveled	Average speed (mph)	Spray Width (ft)	Percentage of distanced sprayed	Acres sprayed
H1	10:22:53	10:30:30	7.6	Driving from residency	1.7	21.9	4	0	0.0
H1	10:30:30	11:29:00	58.5	Spraying/driving (normal operation)	10.6	11.0	4	0.75	3.9
H1	11:29:00	11:44:46	15.8	Returning to residency	11.5	47.2	4	0	0.0

H1	10:22:53	11:44:46	81.9	Entire Duty Cycle	23.8	17.4	4	0.33	3.9
H2	12:45:00	13:49:45	64.8	Spraying/driving (normal operation)	5	4.6	4	0.75	1.8

The fuel consumption measurements from the Axion system were not validated with volumetric measurements for the herbicide trucks. This is an important issue because the Axion system was only validated on tractor diesel engines, and was not validated to measure fuel consumption accurately for gasoline engines from highway vehicles. The fuel economy (mpg) was estimated for the different driving segments and is presented in Table 16. As shown the fuel economy estimates are rather low.

Table 16. Axion Emissions and Fuel Consumption Measurements for the Herbicide Trucks

Herbicide Test	Elapsed Time (minutes)	Description	Miles traveled	Average speed (mph)	CO2 [kg/mile]	CO [g/mile]	HC [g/mile]	NOx [g/mile]	FC (gal/mile)	Fuel Economy (mpg)
H1	7.6	Driving from residency	1.7	21.9	1.44	3.04	0.26	0.07	0.16	6.2
H1	58.5	Spraying/driving (normal operation)	10.6	11.0	2.97	-0.14	1.29	0.02	0.33	3.0
H1	15.8	Returning to residency	11.5	47.2	1.03	3.91	0.17	0.04	0.11	8.7
H2	64.8	Spraying/driving (normal operation)	5	4.6	6.12	0.15	2.53	0.21	0.68	1.5

The EPA model MOVES was used to estimate fuel consumption and emission rates for the light-duty trucks used in herbicide application. The model was used to estimate the fuel and emissions for a 2007 commercial light-duty gasoline-fueled truck traveling on average 10 mph on rural highways with unrestricted access. Emission rates were estimated for typical weather conditions in upstate New York during July. These results are shown in Table 17.

Table 17. US EPA MOVES estimates for 2007 light-duty commercial truck traveling 10 mph on rural highways.

Pollutant	Units	Emission Rate
Fuel Consumption	gal/mile	0.114
PM	g/mile	0.005
CO2	g/mile	1049
NOx	g/mile	0.54
CO	g/mile	2.65
HC	g/mile	0.08

The PM and NOx emission rates are quite low, which was similar to the Axion measurements made on H1 and H2. However, the emission rates on CO and HC differ significantly, which reinforces the low confidence we had in these emission rates reported from the Axion system during the project. Most importantly, the fuel consumption rate from MOVES output is 0.114 gal/mile. On test H1, while spraying and traveling on average of 11 mph, the measurements made by the Axion yielded fuel consumption of 0.33 gal/mile. Thus, it appears that the Axion fuel consumption measurements are likely three times larger than expected for the H1 truck. The Axion fuel consumption measurements from H2 appear even less credible.

When traveling at 45 miles her hour, MOVES estimates a fuel economy of 17.9 mpg, while the Axion measurements estimated a fuel economy of 8.7 when traveling an average speed of 47.2. Overall, the emission rates and fuel consumptions from the MOVES model do not compare well with the Axion measurements. Fortunately, the herbicide trucks are standard commercial trucks, and using the MOVES model can be a reliable source to obtain energy and emissions use of herbicide trucks in New York State.

Using the MOVES data, we estimated fuel consumption and emission emitted when applying herbicide data with the 2007 light-duty commercial trucks. The herbicide is assumed to have been applied over a distance of 4-feet, and that herbicides are applied for 75% of the distance traveled during real-world application. The results are shown in Table 18 and 19.

Table 18. Fuel Consumption of 2007 Commercial light-duty truck during application of herbicides with average speed of 10 mph.

Fuel Consumption per shoulder mile (gal/mile)	Fuel Consumption per mile applied herbicide (gal/mile)	Emission Rate per acre applied herbicide (gal/acre)
0.114	0.152	0.314

* Differences in the per should mile and per mile applied herbicide are due to the assumption that 75% of the roadway during application is applied with herbicide.

Table 19. Emission rates of 2007 Commercial light-duty truck during application of herbicides with average speed of 10 mph.

Pollutant	Emission Rate per shoulder mile (g/mile)	Emission rate per mile applied herbicide (g/mile)	Emission Rate per acre applied herbicide (g/acre)
PM	0.005	0.007	0.014
CO2	1049	1398	2884
NOx	0.54	0.73	1.497
CO	2.65	3.53	7.28
HC	0.08	0.10	0.213

8.0 Shadow Truck Emissions Analysis

Shadow trucks are used to protect the safety of road-users and the employees operating the mowing tractors and applying the herbicides. The shadow trucks follow the tractors and herbicide vehicles and have an arrow board to alert drivers of the vehicles ahead and/or signal the drivers to change lanes. The shadowing trucks used by Region 9 are small dump trucks, such as the International 4700 and Ford F650 diesel trucks. No energy/emission measurements were taken from the NYSDOT shadow trucks during mowing operation. Many of the NYSDOT International 4700 trucks are model year 1996, and many of the Ford 650 trucks are model year 2007. The US EPA MOVES emission model was used to estimate the aggregate emission rates for 1996 and 2007 short-haul diesel-fueled trucks traveling on average 10 mph on rural highways. The results are shown in Table 20 and 21. As shown the fuel consumption rates are 0.22 gal/mile for both model years. This equates to a 4.5 miles per gallon fuel economy. Similarly, CO_2 emissions are practically the same between the two model years. The estimates of the criteria air pollutants: HC, CO, NOx, and PM10 are greatly different between the two model years. The 2007 model year vehicles were required to meet more stringent federal emission standards for PM, HC, and NOx emission standards (US EPA, 2001). MOVES estimated that PM10, CO, and HC decreased by more than 90%, while the emissions for NOx decreased by over 75% between the 1996 and 2007 short-haul diesel truck fleet.

Table 20. US EPA MOVES estimates for 1996 diesel-fueled Short-Haul Truck traveling 10 mph on rural highways.

Pollutant	Emission Rate	Units
Fuel Consumption	0.22	gal/mile
PM 10	2.34	g/mile
CO2	2349	g/mile
NOx	29.51	g/mile
CO	8.43	g/mile
HC	3.01	g/mile

Table 21. US EPA MOVES estimates for 2007 diesel-fueled Short-Haul Truck traveling 10 mph on rural highways.

Pollutant	Emission Rate	Units
Fuel Consumption	0.22	gal/mile
PM	0.03	g/mile
CO2	2369	g/mile
NOx	6.44	g/mile
CO	0.63	g/mile
HC	0.24	g/mile

9.0 Discussion of Results

9.1 Energy Use of Tractors

In terms of gal/hr of operation, the most fuel efficient tractors were the lightest tractors with the smallest engines. The 1983 Ford 2910 was the smallest tractor with a rated engine of 60 Hp, and a tractor weight of 4650 lbs. This tractor had the lowest in-use fuel consumption of 1.1 and 1.5 gal/hr. The hourly fuel rate increased along with the engine size of the tractor. The 2004 New Holland 04-7039 tractor had the largest weight of 7275 lbs and a rated engine of 90 HP. The New Holland was observed during the 10-minute "snapshop" of real-world mowing conditions of having in-use fuel consumption of 3.47 and 5.08 gal/hr. Per-hour, the New Holland was using more than 3 times as much fuel as the smallest NYSDOT tractor.

When the fuel consumption of the tractors was evaluated in terms of gal/mile mowed, the specific operating conditions of the roadway and the equipped mower became a more important factor. For example, the batwing equipped tractors operated in medians and near exits, where they could mow continuously. Some of the flail-equipped tractors such as tractor 90-7162 mowed along the side of a rural highway that required frequent stops, to avoid culverts, traffic signs, driveways and other obstacles. The OTR equipped mowers traveled at a low average speed, and typically made multiple passes, making them less efficient when comparing gal/mile metrics. While the operating conditions have a larger impact when evaluating the fuel consumption in terms of gal/mile-mowed instead of gal/hr-operated, the gal/mile-mowed metric still favored the smallest tractors.

In terms of gal/acre-mowed, the sickle bar, flail, and batwing mowers had similar fuel economy. When using gal/acre-mowed the operating conditions and the mower type become the dominant factors influencing fuel economy. The flail mowers performed well because they often used both the rear flail and side-wing flail simultaneously, which made them more efficient at cutting large acreage of vegetation per hour. The batwing mowers, while powered by larger tractors, have the largest cutting width, and perform very well using the gal/acre-mowed metric. Because the OTR mowers only have a 4' cutting head, and the mowing conditions require them to make multiple passes, they use substantially more fuel than the other mowers per acre-mowed.

Within the batwing and over-the-rail equipped mowers there was substantial variability in fuel consumption between the older Ford 5610 tractors and the newer New Holland TL90A tractors. The New Holland TL90A tractors are substantially larger, weighing 1,475 lbs more and having an additional 0.3 L of engine displacement. The larger size of newer tractors follows a nation-wide trend to manufacture larger tractors (Liljedahl et al. 1989).

The fuel consumption of the Ford 5610 and New Holland TL90A tractors is compared to the Nebraska Tractor Test Laboratory data to evaluate the causes for the increase in fuel consumption. The Nebraska Tractor Test Laboratory provides valuable test data to compare the performance and fuel economy of agricultural tractors. Most of the tractors used by the NYSDOT have been evaluated by the Nebraska Tractor Tests, including the New Holland TL90A and the Ford 5610. One of the Nebraska Tractor Tests is the Varying Power and Fuel Consumption Test. In this test, the tractor is tested operating the PTO under different loads. The maximum power is recorded, as well as the fuel rate at different power levels (Nebraska Tractor Test Laboratory).

The fuel consumption rates (gal/hr) from the Varying Power and Fuel Consumption Test are given in Figure 40 for the Ford 5610 and New Holland TL90A Tractors. In terms of fuel consumption rates, more fuel efficient vehicles will have a lower fuel consumption for the same power of output. As shown, the fuel consumption rate increases as the engine works at a higher rate of power. The maximum power of the PTO for the Ford 5610 occurs around 60 HP, while the maximum PTO power for the New Holland TL90A is higher, and occurs just above 80 HP. For loads occurring between 20 and 60 HP, it is apparent that the Ford 5610 can perform an equal amount of work, with substantially less fuel (0.5 to 0.8 less gallons per hour).

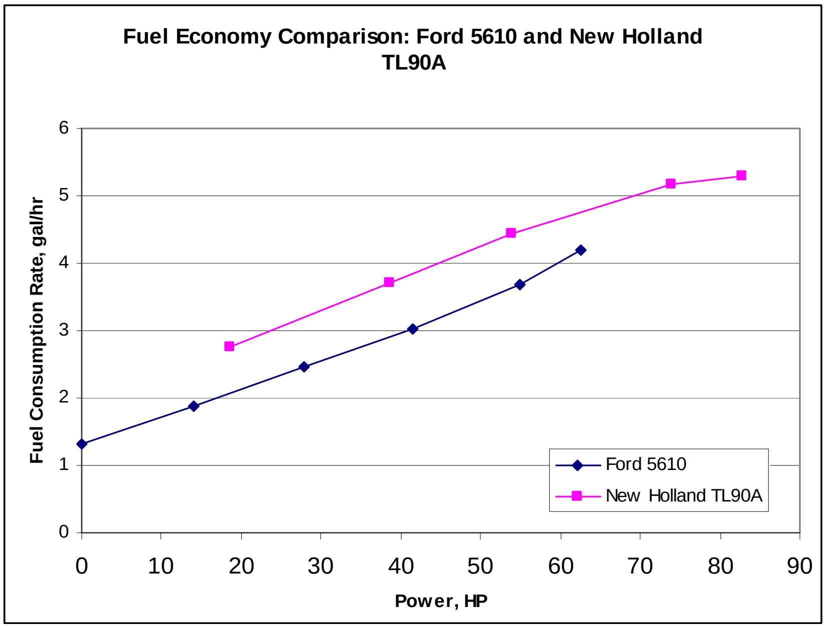

Figure 40. Fuel Consumption Rate Comparison between the Ford 5610 and New Holland TL90A. (Nebraska Tractor Test Laboratory).

Fuel economy for a tractor can also be evaluated in the work performed per gallon, similar to the miles per gallon metric used by passenger automobiles. In this case, higher values reflect more fuel efficient tractors, since they are performing more work for the same gallon of fuel. Figure 41 plots the fuel economy for the Ford 5610 and New Holland TL90A tractors in terms of Hp.h/gal. As shown, the fuel economy peaks for the Ford 5610 around 55 HP, whereas the fuel economy for the New Holland TL90A occurs at the maximum power output of 83 HP. When operating at its highest power output, the 2004 New Holland TL90A has a better work-based fuel economy than the Ford 5610 tractor. However, if the operating loads are less than 60 HP, the Ford 5610 can produce more power for the same amount of fuel consumed as the New Holland TL90A.

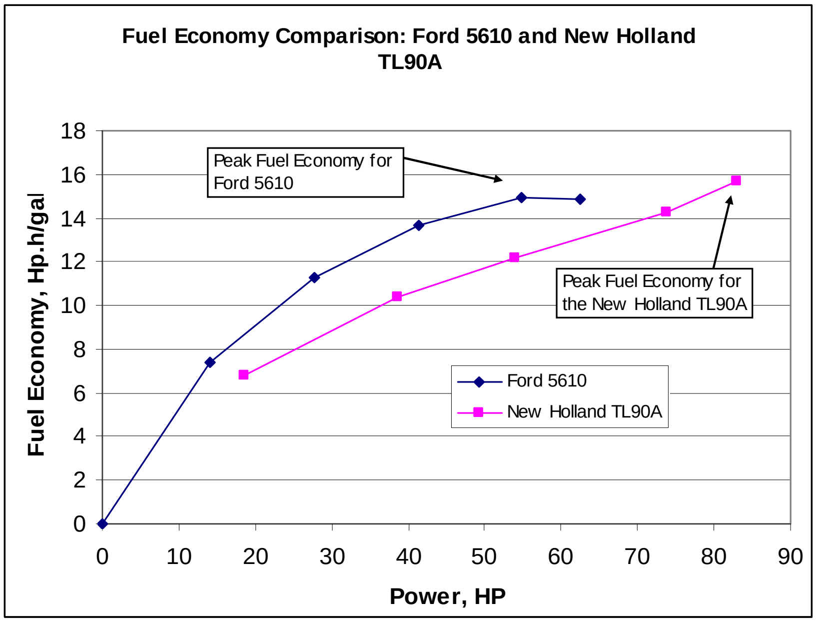

Figure 41. Fuel Economy Comparison between the Ford 5610 and New Holland TL90A. (Nebraska Tractor Test Laboratory).

The Ford 5610 had a fuel consumption rate of 2.16 gal/hr in real mowing conditions when operating the batwing mower and 2.1 gal/hr with the over-the-rail mower. Using Figure 41, at these fuel rates the Ford 5610 would output 20.5 Hp and 19.4 Hp respectively.

Table 22. Median Fuel Consumption of the Ford 5610 in real mowing conditions, along with estimated HP.

Equipment ID	Model	Test	Mower	FC (gal/hr)	Estimated Power (Hp)
83-7091	Ford 5610	M1	Batwing	2.2	20.5
89-7075	Ford 5611	M14	OTR	2.3	24.6

For the New Holland Tractors to operate at the same horsepower output (20.5 and 19.4) used to run the same mowers as the Ford 5610 Tractors, they would be expected to use 2.8-3.0 gal/hr (Using the Nebraska Tractor Test Data in Figure 42). This is a 30-32% increase in fuel consumption from the from Ford 5610 Tractors as shown in Table 23.

Table 23. Estimated Fuel Consumption of the New Holland TL90A to produce the same power as in Table 22.

Equipment ID	Model	Mower	Power (Hp)	Estimated FC (gal/hr)	Increase in Estimated FC from Ford 5610
04-7039	New Holl TL90A	Batwing	20.5	2.8	32%
04-7042	New Holl TL90A	OTR	24.6	3.0	30%

The actual median fuel rates of New Holland TL90A tractor was 4.48 gal/hr when operating the batwing mower and 3.40 gal/hr when operating the OTR. The true percentage increase in fuel rates between the Ford 5610 tractors and the New Holland Tractors is 107% and 46%.

Table 24. Actual Fuel Consumption of the New Holland TL90A to operate similar mowers as Ford 5610 Tractors.

Equipment ID	Model	Test	Mower	FC (gal/hr)	Estimated Power (Hp)	Increase in FC compared to Ford 5610	Difference explained by Nebraska Tractor Data (assuming equal power)
04-7039	New Holl TL90A	M11	Batwing	4.48	55.3	107%	30%
04-7042	New Holl TL90A	M9	OTR	3.40	28.1	46%	67%

The differences in fuel economy at 20 HP as recorded by the Nebraska Tractor Test data is able to explain most of the observed differences in fuel economy for the New Holland tractor equipped with the OTR mower. The inefficiency of the larger engine to output the same power at 25 Hp, explains a most of the observed 46% increase in fuel consumption. The remaining 16% of the fuel consumption is likely explained by the additional power needed to move the larger New Holland tractor. Additional differences are likely due to the different operation conditions, operators, and uncontrolled factors. Figure 42 plots the Nebraska data alongside the estimated and actual fuel consumption rates.

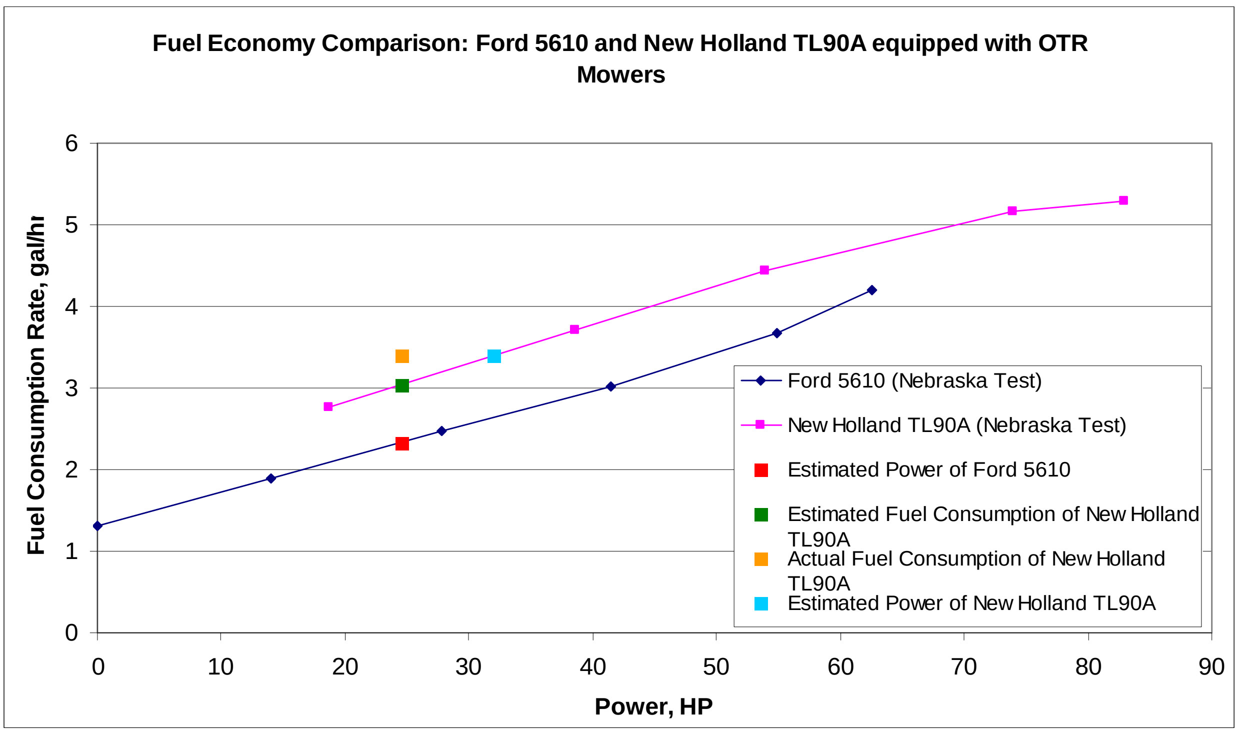

Figure 42. Comparison of Fuel Consumption of OTR-equipped Mowers using both measured data and Nebraska Tractor Test Data.

For the batwing mowers, the Varying Power and Fuel Consumption Test from the Nebraska Laboratory can only be used to explains a small portion of the observed increase in fuel consumption when using the New Holland tractors. When using the batwing mower, the New Holland tractor was measured using 107% more fuel than the Ford 5610 tractor. However, differences in fuel economy at 20.5 Hp only explain a 32% increase. There are several potential reasons for the discrepancies:

(1) The "Varying Power and Fuel Consumption Test" from the Nebraska test is performed while the tractor is stationary and only loaded with the PTO. When pulling the batwings, the tractors are traveling on average around 3 mph, and has significant loads from pulling the mower. Thus, using the PTO test to estimate load is not as accurate for the batwing mowing activities.

(2) The New Holland is heavier is traveling faster than the Ford 5610 when using the batwing (3 mph compared to 2.7 mph). This will require much more power to pull a larger tractor at a higher speed.

(3) There were known problems on mobile test 11, when the New Holland was tested. The test had to be stopped after 6 minutes due to data problems.

These reasons may be used to explain some of the differences in the high fuel consumption observed from the New Holland tractor. However, even in the stationary mower tests, the fuel rate is significantly higher than would be expected if they were producing the same load. During the stationary mower tests, the larger weight of the tractor, and different operating modes should not come into play. Thus, the specific New Holland equipped with the batwing mower appears to be using even more fuel than would be estimated from the Nebraska data.

9.2 Tractor Emissions

The 2004 New Holland tractors are the only tractors that were manufactured after the full phase in of the Tier 1, 2, and 3 off-road diesel regulations. Because the 2004 have the lowest Fuel-based PM and NOx emissions in real-world conditions, the data suggest that the off-road diesel engine regulations have achieved effective results.

Although the 2004 New Holland has the lowest fuel-based emission standards of the tested fleet due to the high fuel rates, the emissions of the New Holland tractors can be quite similar, and sometimes worse than the older tractors. For example, the New Holland TL90A equipped with a batwing mower (Tractor 04-7039), had very high fuel consumption rates in the field (4.5 gal/hr). Even though, it had very low fuel-based PM emission rates, (0.18 g/kg) (Table A23), in terms of PM/hr the emission rate was comparable to some of the older tractors (Figure 30).

Thus, the effectiveness of the tighter emission standards given by the Environmental Protection Agency (EPA) in terms of grams per brake-horsepower-hours (g/bHP.hr) are somewhat reduced due to the fact that larger tractors were purchased. This follows a nation-wide trend, as tractors continue to be built with higher power output (Liljedahl et al 1989). It appears the benefit obtained by tighter g/bHp.hr emission based standards has been partially off-set by replacing older tractors with newer larger tractor that use more fuel. The introduction of the Tier 4 for off-road vehicles standards in 2013, (EPA, 2004e), emissions will decrease emissions from these engines by more than 90 percent (EPA, 2004e). This effect may have been seen during the implementation of the Tier 1 -3 standards which had more modest decreases in emission standards. The introduction of 2013 off-road engines will have a dramatic decrease in vehicle emissions, regardless of size, due to the implementation of much tighter PM and NOx emission standards. To lower emissions, tractors are often forced to use more fuel (Personal Correspondence, Prof. Roger Hoy, Director of the Nebraska Tractor Test Laboratory). For example, retarding the fuel injection can be an effective means to lower NOx emissions, but will cause a drop in fuel economy (Clark et al. 2002). Thus, there can be a tradeoff in using older more fuel efficient tractors, and purchasing newer tractors that have less harmful emissions, yet are less fuel efficient.

9.3 Comparison of mowing and herbicide fuel usage and emissions

Table 25 provides "ballpark" estimates of the fuel usage for certain mileage activities. The values are given according to the mower type and the mowing conditions. These values should be considered "ballpark" estimates because they were estimated from the 10-minute "snapshots." They do not provide estimates from the entire range of conditions encountered by the NYSDOT mowers, nor are they weighted according to the distribution of tractor mowers within the NYSDOT fleet. These estimates were obtained by averaging the fuel consumption rates across the 10-minute mobile tests that were conducted in similar conditions. Averaging was conducted in order to provide an aggregate number with which to compare to the herbicide data. The fuel consumption is given in units of gallons per mile-mowed, and gallons per acre-mowed.

Table 25. Estimates of fuel usage from a range of mowing conditions using real-world data.

Mower Type:	Sickle Bar and Rear Flail	Rear and Side Flail	Rear and Side Flail	Batwing	Over-the Rail	Over-the Rail
Mowing conditions:	Full Width	Full Width	Partial Width	Full Width	One Pass	Two Passes
FC (gal/mile)	0.55	0.78	1.18	1.14	1.83	3.02
FC (gal/acre)	0.38	0.53	1.36	0.63	3.78	6.22

The herbicide fuel consumption rates obtained from section 7 are reproduced in Table 26.

Table 26. Consumption of 2007 Commercial light-duty truck during application of herbicides with average speed of 10 mph.

Fuel Consumption per mile applied herbicide (gal/mile)	Emission Rate per acre applied herbicide (gal/acre)
0.152	0.314

Disregarding the fuel used to power the herbicide generator (which is used in the herbicide application) and the shadow trucks (which can be used in both applications), the in-use fuel consumption used in herbicide application is less than the mowing operations, in units of gal/mile and gal/acre. The fuel consumption rates are 21% to 100% more for the gal/acre when comparing the conventional tractors (sickle bar, flail, and batwing) mowing in full-cut conditions. However the fuel consumption is significantly less when compared to the over-the-rail mowers, or to flail tractors mowing with only one side-flail. The "ballpark" emissions for the different mower types are given in Table 27 and 28. The estimates from the herbicide application are reproduced in Table 29.

Table 27. Estimates of Emissions (g/mile) from mowing conditions using real-world mowing data.

Mower Type	Mowing conditions	CO_2 (kg/mile)	CO (g/mile)	HC (g/mile)	Nox (g/mile)	PM (g/mile)
Sickle Bar and Rear Flail	Full Width	5.4	96.6	66.4	35.5	1.3
Rear and Side Flail	Full Width	7.7	44.2	16.4	149.3	0.7
Rear and Side Flail	Partial Width	11.8	83.9	42.4	109.8	2.0
Batwing	Full Width	11.5	32.4	47.9	84.4	1.1
Over-the Rail	One Pass	17.2	110.5	222.8	154.1	2.0
Over-the Rail	Two Passes	29.7	132.7	287.7	208.0	2.0

Table 28. Estimates of Emissions (g/acre) from mowing conditions using real-world mowing data.

Mower Type	Mowing conditions	CO_2 (kg/acre)	CO (g/acre)	HC (g/acre	Nox (g/acre)	PM (g/acre)
Sickle Bar and Rear Flail	Full Width	3.7	66.4	45.6	24.4	0.9
Rear and Side Flail	Full Width	5.2	30.0	11.1	101.3	0.5
Rear and Side Flail	Partial Width	13.6	97.9	49.9	124.8	2.3
Batwing	Full Width	6.3	17.8	26.3	46.4	0.6
Over-the Rail	One Pass	35.5	228.0	459.5	317.7	4.2
Over-the Rail	Two Passes	61.3	273.7	593.4	429.0	4.1

Table 29. Emission rates of 2007 Commercial light-duty truck during application of herbicides with average speed of 10 mph.

Pollutant	Emission rate per mile applied herbicide (g/mile)	Emission Rate per acre applied herbicide (g/acre)
PM10	0.007	0.014
CO_2	1398	2884
NOx	0.73	1.497
CO	3.53	7.28
HC	0.10	0.213

The estimated vehicle emissions from a 2007 the herbicide vehicle are much less than the tractor on a per-mile and a per-acre basis. The comparison of emission rates between the tractors and herbicides should be done with qualifications. The confidence in the Axion-measured CO and HC emission rates were suspect. Additionally, the PM from the Axion system can only be used qualitatively with other values. However, we would expect a 2007 highway vehicle to have much lower emissions than the largely unregulated vehicle emissions from the off-road tractors. The data does appear to confirm this point, but the magnitude of the differences should not be used from these reported values.

10. Life-Cycle Analysis

In order to evaluate the energy consumption and pollution produced during mowing and herbicide application a life-cycle analysis of both operations was done (Shretha, 2010). Life-cycle analysis includes an objective and transparent evaluation of "environmental burdens associated with a product, process, or activity by identifying and quantifying energy and material uses and environmental releases …[and] includes the entire life cycle of the product, process or activity, encompassing extraction and processing raw material; manufacturing, transportation, and distribution; use, reuse and maintenance; recycling; and final disposal (Allenby, 2003)."

Life cycle analyses can be quite complex. In this study a simplified approach was taken and applied in the same way to mowing and herbicide operations. The simplified approach addresses only the direct energy consumption required to perform both tasks. Only energy costs, and not financial costs, were evaluated. The costs of fuel extraction, processing and transportation were not specifically evaluated, but it is a reasonable to assume that these costs would affect mowing and herbicide application in a proportionally similar way.

The following parameters were evaluated for both:

1. The energy cost of manufacturing based on an estimated energy consumption per unit weight of equipment. The same estimated energy consumption could be used for tractors, trucks and mower attachments.
2. The amount of fuel used to accomplish the operation. This consisted of gallons of diesel fuel used in the tractors during a days work and the gallons of fuel used to operate the herbicide trucks.
3. The energy cost of manufacturing the herbicide based on reported values in the literature.

One of the difficulties encountered during this analysis is the variety of tractors, mowers and trucks used as well as the variety of herbicides applied to the ROW. The life cycle energy requirements calculated using this simplified methodology should be considered as ranges of values and not taken as a hard and fast number.

The life cycle analysis used in this report considered the energy use per unit area of the ROW. Typically Departments of Transportation use linear miles to describe the operations performed along highways. Maintenance of the ROW is better described, however, in area rather than linear units. Although both mowing and herbicide application have a linear dimension they also have a width dimension that varies considerably depending on which type of mower is used and what type of spray pattern is applied. Using only linear miles when comparing mowing and herbicide application significantly distorts any conclusions.

10.1 Mowing

The energy per unit area used during mowing was calculated by evaluating tractor type, mowing equipment and amount of diesel used. Six tractors were used to calculate life cycle energy requirements for mowing (83-7091 - 1983 Ford 5610 with batwing mower; 84-7107 - 1984 Ford 2910 with sickle bar mower; 84-7153 – 1984 John Deere 401B with flail mower; 89-7069 – 1989 Ford 5610 with flail mower; 90-7162 – 1990 Massey Ferguson with flail mower; and 94-

7030 – Case IH 695 with flail mower). These tractors are listed, among others, in Table 1. The weight for each of the tractors is listed in Table 2. Table 30 summarizes the tractors, mowers (various widths), fuel used and distance driven used to calculate the energy cost of mowing per unit area. The energy usage from these tractors was calculated using the total distance traveled and the total fuel used during the mobile test, rather than evaluating a 10-minute "snapshot" of the mowing activity as was done in the other sections of the report. The values in Table 30 should represent more aggregate operating conditions, however the information on the tractor activity (i.e. are both the rear and side mower being used?) is more approximate.

Gliessman (2007) reports that it takes 18000kcal/kg to manufacture agricultural machinery. Mikkola and Ahokas (2010) report that it takes 18000 kcal/kg to manufacture a diesel Volkswagen, and slightly more energy (19402 kcal/kg) to manufacture a gasoline Volkswagen. Multiplying the default value of 18,000 kcal/kg by the weight of each tractor (supplied by the manufacturer) the energy cost to manufacture each tractor used in this study can be calculated.

The energy used to manufacture the tractor needs to be distributed across the expected life of the tractor. The expected operating life span of a tractor in NYS DOT is 10,000 hours. Therefore, the number of hours the tractor was operated during the study was divided by 10,000, and this proportion was the fraction of the total energy of manufacturing used. This is called the legacy energy.

The three types of mowing equipment evaluated in the life cycle analysis are sickle bar, flail and batwing mowers. Characteristics about each, including width of the mowing path, are summarized in Table 3. The energy cost to manufacture the mower was not calculated or used in the life cycle analysis.

The total miles driven and the total gallons of fuel used during one day's operation were recorded at the end of each day. We estimated that the tractors were actually mowing about 75% of their travel distance and, therefore, only 75% of the recorded travel distance was used in the life cycle analysis. The area mowed was calculated by multiplying the width of the mowing apparatus by the length of 75% of the travel distance.

The amount of fuel used during each evaluation was measured at the end of the day. The average energy in a gallon of diesel fuel is 139,000 British Thermal Units (BTUs). As indicated in table 30, the BTUs per acre range from 32,268 to 68,199 for the mowing operations evaluated. ~~The OTR mowers used substantially more fuel per acre than the sickle bar, flail and batwing mowers. Using the 10-minute snapshots in Table 13, the OTR mowers had fuel energy usage ranging from 525,579 to 1,043,095 (BTUs per acre). This only considered the fuel energy and does not include the small fraction of legacy energy, however the fuel energy dominated the legacy energy for the tractors.~~

The OTR mowers use substantially more fuel per acre than the sickle bar, flail and batwing mowers. Using the data from Table 25, flail, sickle bar and batwing mowers use an average of 0.725 gallons per acre, but OTR mowers use an average of 2.8 gallons per acre. This assumes one pass by all types of mowers. If the average energy in a gallon of diesel fuel is 139,000 BTUs, then the flail, sickle bar and batwing mowers use an average of

100,775 BTUs per acre of mowing and the OTR mowers use 389,895 BTUs per acre of mowing. If the OTR mowers need to make two passes, as is often the case, they may use up to 695,000 BTUs per acre.

10.2 Herbicide Application

The most widely used herbicide in NYSDOT Region 9 is glyphosate. Glyphosate containing herbicide is made by a variety of companies and sold under a variety of names. Most, but not all, of the glyphosate products used on the ROW contain 41% glyphosate. The product used in these calculations was Razor Pro, registered by Nufarm Specialty Products (EPA Reg No 228-366). It consists of 41% glyphosate and contains 356 grams of the active ingredient as an acid per liter. Multiplying 356 grams by the number of liters (3.785) in a gallon indicates that there are 1381.525 grams, or 1.382 kilograms, of glyphosate per gallon of RazorPro.
Before application on the ROW, Region 9 makes a 5% solution of RazorPro by diluting 5 gallons of the product to make 100 gallons of solution. If there are 1.382 kilograms of glyphosate per gallon, then there are 6.91 kilograms of glyphosate in 5 gallons and, after dilution, 6.91 kilograms in 100 gallons of herbicide solution. Region 9 applies 25 gallons of herbicide solution per acre along the ROW. This equates to 1.73 kilograms of glyphosate per acre (by dividing the total amount of glyphosate in 100 gallons by 4).

The energy used to manufacture herbicides has been evaluated because of the widespread use of herbicides in agriculture. People have been interested in comparing energy consumption associated with more traditional cultivation methods, often using tractors, and herbicide application. Based on the results of these investigations the energy required to manufacture glyphosate is between 108,100 and 108,509 kilocalories per kilogram (Pimentel, 1980 and Clements et al, 1995), respectively.

If we multiply the total mass of glyphosate applied per acre (1.73 kilograms) by the energy cost of manufacturing 1 kilogram of herbicide (108,100 kilocalories), the energy cost of applying RazorPro to 1 acre is 187,013 kilocalories, or 741,111 BTUs per acre. (To convert kilocalories to British Thermal Units (BTUs) it is necessary to multiply by 3.98 because there are 3.98 kilocalories in 1 BTU.)

It is important to remember that the energy cost of 741,111 BTUs per acre is only for the glyphosate. RazorPro contains 14% surfactants which also require energy to manufacture. The rest of the “inert” ingredients in RazorPro are classified as Confidential Business Information and their identities are not readily available, however, they also may require additional energy to manufacture. In addition, the energy cost of the herbicide truck and the fuel to operate the truck are not included in this calculation.

Table 30. Summary of parameters used to calculate energy use during mowing including type and weight of tractor, type and width of mower, miles driven, hours operated and gallons of fuel consumed. The width of the mower and 75% of the miles driven were used to calculate an estimate of the area mowed. The total miles driven during evaluation were not used because during about 25% of the time, although they were moving, the tractors were not mowing.

Equipment configuration	**Type of mower**	**Mowing width**	**Weight of the tractor**	**Miles driven**	**Hours driven**	**Fuel used**	**Area mowed**	**Liters / acre**	**Fuel energy**	**Legacy energy**	**Total energy**
Units		**Feet**	**Kg**	**Miles**	**Hours**	**Liters**	**Acres**	**Liters / acre**	**BTU/ acre**	**BTU /acre**	**BTU /acre**
		(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)
1984 John Deere 401B	Flail	13	2019	4	1.1	8.1	4.7	1.71	62925	1219	64144
1984 Ford 2910	Sickle bar	7.5	2109	2.9	2	1.7	2.0	0.86	31574	2208	33782
1990 Massey Ferguson tractor 383	Flail	13	2903	5	2.5	4.91	5.9	0.83	30515	1753	32268
1983 Ford 5610	Batwing	15	2627	3.5	1.6	7.57	4.8	1.59	58248	1375	59623
1994 case tractor 695	Flail	13	2567	6	2.2	12.87	7.1	1.81	66649	1550	68199
1989 Ford 5610	Flail	13	2627	5.6	1.7	10.56	6.6	1.60	58597	1587	60184

11.0 Conclusions

1. To save energy from highway mowing activities, efforts should focus on purchasing fuel-efficient tractors. From our results, it appears that the New Holland TL90A tractor is oversized for most of the NYSDOT highway mowing activities. This claim is supported from both our collected data and the Nebraska Tractor Test Data. The fuel economy given in Hp.h/gal of the New Holland TL90A does have better fuel economy than the smaller Ford 5610 tractors at maximum load. However the improved fuel economy only occurs when the tractor is operating above 60 Hp. In typical mowing operation, it appears that the Hp requirements are below 60 Hp. Thus, for the ranges of load experienced by NYSDOT tractors, the smaller tractors, such as the Ford 5610, are much more fuel efficient. There may be instances where the higher power output capabilities and larger weight of the New Holland TL90A may be beneficial are necessary for mowing conditions. In future purchasing decisions, the NYSDOT will have to determine if the higher fuel consumption rates of larger tractors are worth the higher power capabilities.

2. For time-based fuel rates and emission rates (i.e. gal/hg, g/sec) there is substantial variability in emissions due to the effect of the technology of each factor. Per acre-mowed, the fuel consumption and emission rates are dominated by the mowing activity. Due to the high fuel intensity of over-the-bar mowing, which requires a large tractor but can only mow a small area of vegetation per hour, the fuel consumption and emission rates per acre are 2 to 4 times higher than the other mowing activities. Per acre, the sickle bar, flail and batwing mowing activities have relatively similar fuel consumption and emission rates.

3. The 2004 tractors are cleaner in terms of NOx and PM emissions per gallon of fuel used, but have relatively similar emission rates in terms of hour of operation. This is because the 2004 tractors use much more fuel per hour of operation, which counteracts much of the gain achieved due to lower fuel-based emissions. Future 2013 off-road tractors will have substantially lower NOx and PM emissions than current tractors, however they will be slightly less fuel efficient than current tractors.

4. When considering only daily fuel use, the herbicide trucks are more efficient in treating an acre of vegetation compared to tractors mowing an acre of vegetation. Likewise the emissions of CO_2, CO, HC, NOx, and PM are less per unit of acre treated when using the herbicide truck. These numbers do not account for additional environmental, energy-related, or financial costs of using the herbicides. This only considers the fuel used to power the mowing tractors and to power the light-duty commercial herbicide truck.

5. ~~When considering the energy needed to manufacture the tractors and the herbicides in a life-cycle analysis, the energy intensity of herbicide application increases significantly. For the sickle-bar, flail and batwing mowers, herbicide application is much more energy intensive per acre of ROW than mowing operations. The OTR mowing operation is much more fuel intensive than the other mowers, and has similar life-cycle energy costs per acre as the herbicide application.~~

5. Flail, sickle bar and batwing mowers use significantly less energy per unit area (100,775 BTUs) than herbicide application (741,111 BTUs). Fuel use by OTR mowers, however, is

almost 4 times higher than other mowers for one pass (389,200 BTUs) and almost 7 times higher for two pass mowing (695,000 BTUs) using the data in Table 25. Although this approaches the energy use for the glyphosate on a unit area comparison, it is important to remember that all the energy requirements are not included in this comparison and it is not a complete life cycle analysis.

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Appendix: Air Quality and Energy Impacts of NYSDOT Highway ROW Management

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Table A1. Detailed information on each tractor tested

Equipment ID	Make	Model	Year	Cyl.	Engine Hp	Displ [L]	Hours of Operation	Weight of Tractor (lbs)	Residency
84-7152	John Deere	401B	1984	4	62	3.6	3436	4452	Castle Creek
90-7162	Massey Ferguson	383	1990	4	81	4.1	3104	6400	Castle Creek
90-7160	Massey Ferguson	383	1990	4	81	4.1	2580	6400	Deposit
94-7030	Case IH	695	1994	4	73	3.5	1216	5660	Deposit
83-7091	Ford	5610	1983	4	72	4.2	4023	5800	Owego
84-7118	Ford	2910	1984	3	40	2.9	5340	4650	Owego
89-7075	Ford	5610	1989	4	72	4.2	2132	5800	Owego
89-7074	Ford	5610	1989	4	72	4.2	3939	5800	Owego
95-7071	Case IH	4210	1995	4	72	3.9	220	5800	Owego
83-7110	Ford	5610	1983	4	72	4.2	3268	5800	Oxford
84-7107	Ford	2910	1984	3	40	2.9	2775	4650	Oxford
84-7153	John Deere	401B	1984	4	62	3.6	3161	4452	Oxford
89-7069	Ford	5610	1989	4	72	4.2	4014	5800	Oxford (EM)
95-7081	Case IH	4230	1995	4	84	4.4	862	6100	Oxford (EM)
95-7084	Case IH	4210	1995	4	72	3.9	2163	5800	Oxford
04-7039	New Holland	TL90A	2004	4	90	4.5	757	7275	Oxford
04-7041	New Holland	TL90A	2004	4	90	4.5	651	7275	EM
04-7042	New Holland	TL90A	2004	4	90	4.5	199	7275	Hancock

* (EM) indicates that the tractor was tested at the Equipment Maintenance Shop in Binghamton, NY.

Appendix 1. Evaluation of Stationary Test Data

Table A2. Tractor Descriptions for the Stationary Test

Test ID	Equipment ID	Make	Model	Year	Cylinders	Engine hp	Displ [L]	Mower Type
S1	83-7091	Ford	5610	1983	4	72	4.2	Batwing
S2	84-7118	Ford	2910	1984	3	40	2.9	Sickle Bar
S3	95-7084	Case IH	4210	1995	4	72	3.9	Flail
S4	84-7107	Ford	2910	1984	3	40	2.9	Sickle Bar
S5	83-7110	Ford	5610	1983	4	72	4.2	OTR
S6	95-7071	Case IH	4210	1995	4	72	3.9	Flail
S7	89-7074	Ford	5610	1989	4	72	4.2	Flail
S8	95-7081	Case IH	4230	1995	4	84	4.4	Flail
S9	89-7069	Ford	5610	1989	4	72	4.2	Flail
S10	04-7039	New Holland	TL90A	2004	4	90	4.5	Batwing
S11	90-7162	Massey Ferguson	383	1990	4	81	4.1	Flail
S12	84-7152	John Deere	401B	1984	4	62	3.6	Batwing
S13	84-7153	John Deere	401B	1984	4	62	3.6	Flail
S14	89-7075	Ford	5610	1989	4	72	4.2	OTR
S15	04-7041	New Holland	TL90A	2004	4	90	4.5	None

The stationary mowing tests were evaluated in the following graphs. The median fuel consumption and emission values were computed for the two-minute maximum engine segments when the PTO was both engaged and not engaged. Comparisons of the median values for each stationary test are shown below. Stationary test 15 was conducted at the maintenance shop, and was not able to be tested with a mower test.

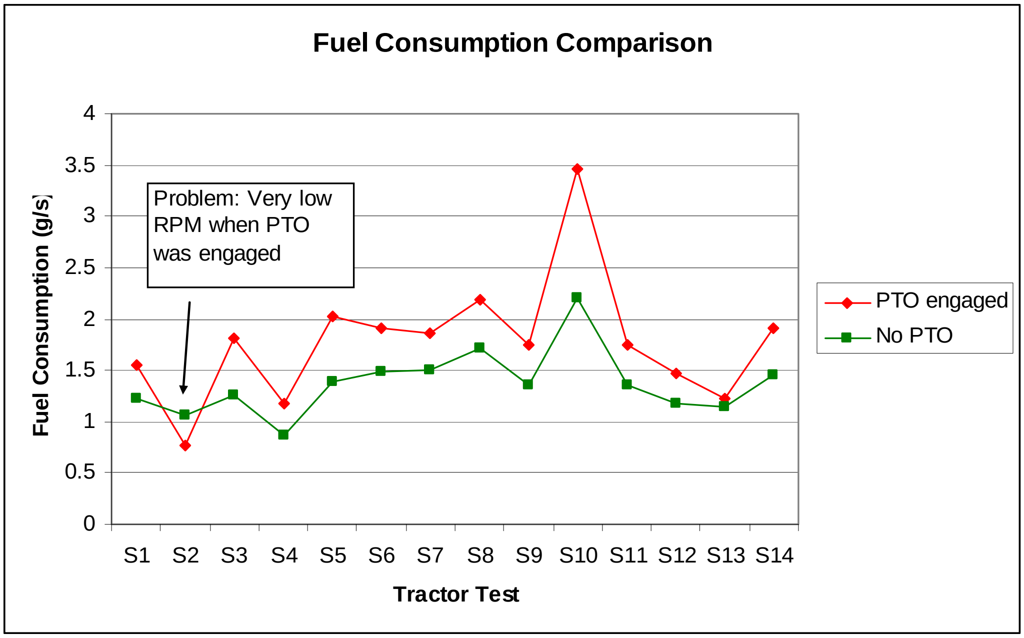

Figure A1. Fuel Consumption Comparison for Stationary Mower Tests.

As should be expected, the fuel consumption is higher when the mower is engaged (PTO engaged). The only exception is Stationary Test 2, which is due to a known problem when conducting the test. For S2, when the PTO was engaged, the loads achieved were substantially lower than when the PTO was not engaged. This is clearly shown in Figure A2, which shows the Crank Shaft Speed Comparison. Excluding Stationary Test 2, the fuel consumption at max rpm with PTO engaged is 33% higher than when the PTO is not engaged. The maximum crank shaft speed is on average (1% higher) higher when the PTO is not engaged. This appears to be detecting a slight "lugging" effect—when the tractors are slightly loaded, the tractors will run at a lower engine speed. The differences in fuel consumption are not due to the crank shaft speed, but are due to the additional loads in powering the PTO. Due to the errors on Stationary Test 2, this test was excluded from further analysis.

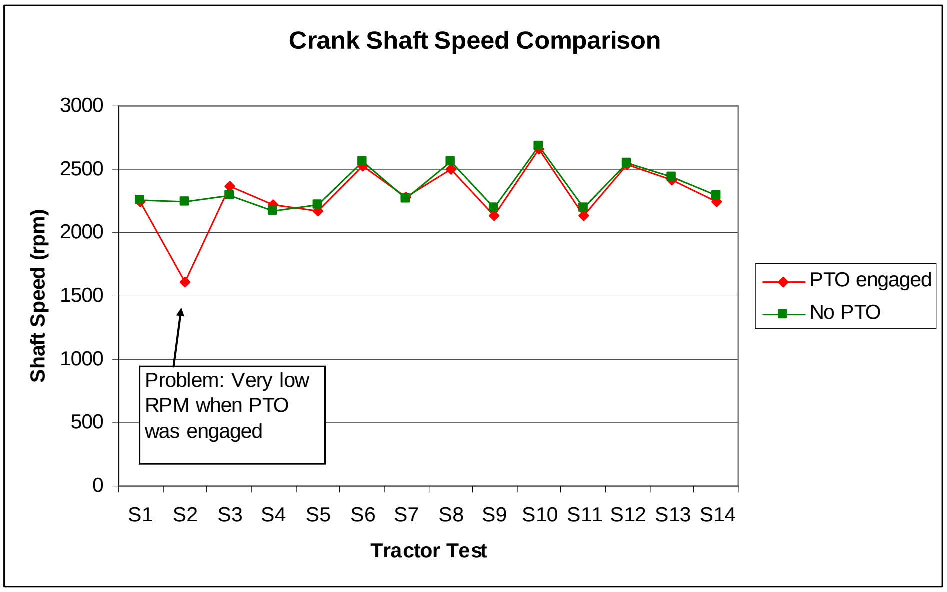

Figure A2. Crank Shaft Speed Comparison for Stationary Mower Tests.

Emissions Comparison

The median emission rates are compared for NOx, PM, CO, and HC emissions. The NOx emissions are consistently higher with the PTO load. On average the median NOx emissions are more than two times higher with the PTO load. S3, S6, and S8 have noticeably higher NOx emissions compared to the other tractors. Each of these tests was conducted on a 1995 Case IH tractor, which showed elevated NOx emissions on both stationary tests.

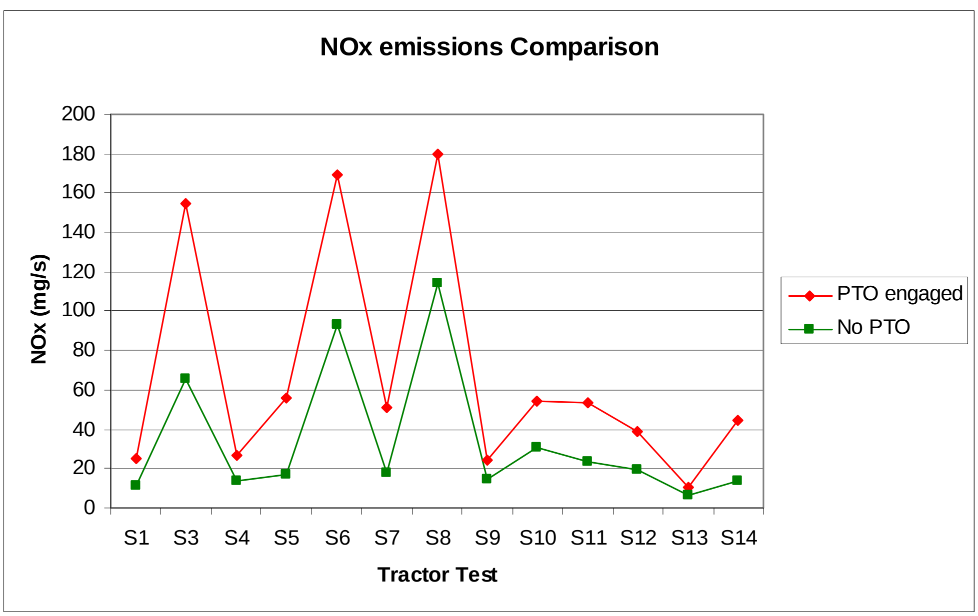

Figure A3. NOx Emissions Comparison for Stationary Mower Tests.

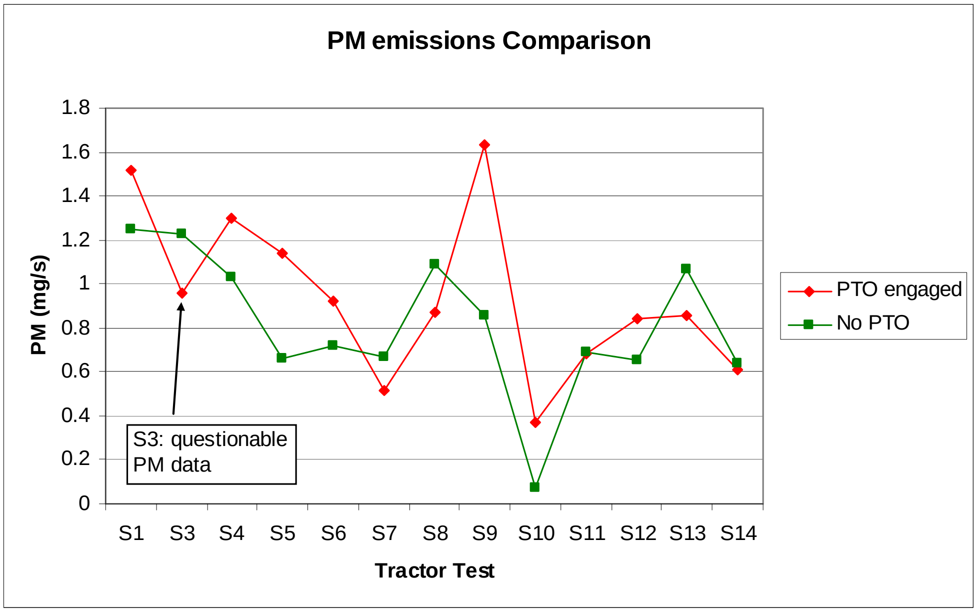

Figure A4. PM Emissions Comparison for Stationary Mower Tests.

The effect of additional loads on PM emissions overall tends to increase PM emissions. One of the major exceptions was Stationary Test 3, which had substantially lower median PM emission rate when the PTO was engaged. However, there are known concerns with the PM data from this test. Even with included the suspect results from S3, the median PM emissions are 15% higher with the PTO engaged, and a paired-t test confirms that the PM is significantly higher with the PTO engaged. When S3 is excluded, the PM median emissions are on average 20% higher when the PTO is engaged.

The highest PM emissions occurred on tractor S9, a 1989 Ford 5610 tractor. This tractor had noticeably low NOx emissions. Conventional diesel engines have a tradeoff between PM and NOx emissions when running rich or lean. This tradeoff will be investigated further across tractors.

Carbon monoxide and hydrocarbon emissions were also evaluated. The figures are shown in Figure A5 and A6. However the trend is unclear for these tests. A two-sided t-test finds that the differences in HC and CO emissions is insignificant at the 95% confidence level. In both cases the average of the median values is slightly lower when the PTO is engaged.

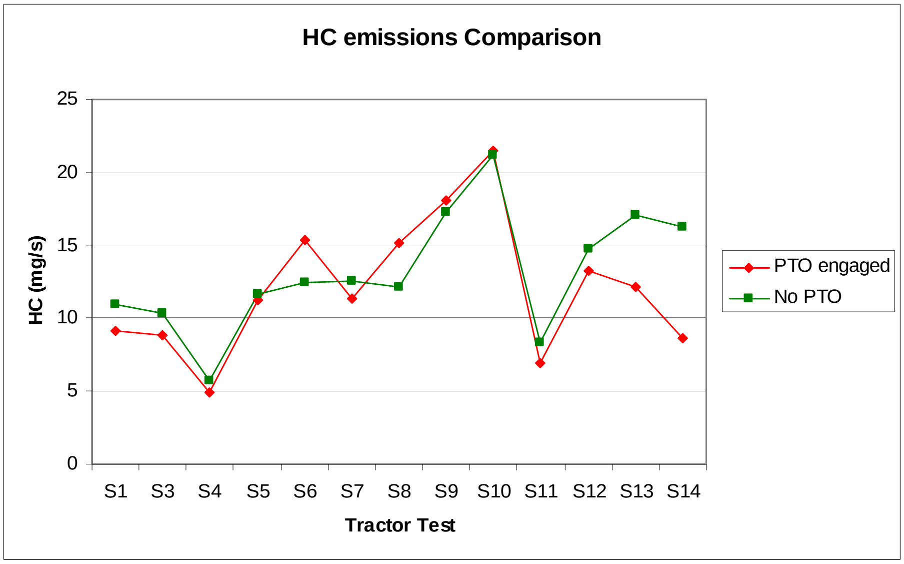

Figure A5. HC Emissions Comparison for Stationary Mower Tests.

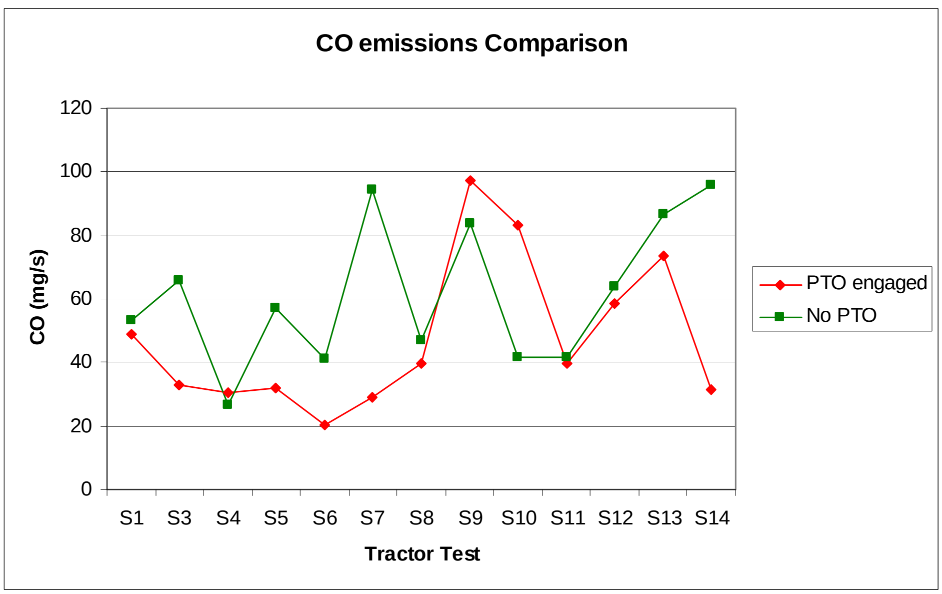

Figure A6. CO Emissions Comparison for Stationary Mower Tests.

More tests would have to confirm the differences in HC and CO emissions. However, the primary concern with emissions from the diesel tractors are PM and NOx emissions. The measurements show that the PM and NOx emission rates are responsive to increases in engine loads. This observation further validates the collected PM and NOx data. Additionally, the effect of the real-world operation on emissions should be further evaluated.

Appendix 2. Comparison of Stationary Tests with Mobile Tests

Table A3. Tractor Descriptions for the Mobile Tests

Test ID	Residency	Equip ID	Make	Model	Cold Start	Hot Start	Stat ID	Usable Data
M1	Owego	83-7091	Ford	5610	Yes	Yes	S1	Yes
M2	Castle Creek	84-7152	JD	401B	No	No	S12	No
M3	Oxford	84-7153	JD	401B	No	No	S13	Yes
M4	Oxford	84-7107	Ford	2910	No	Yes	S4	Yes
M5	Hancock	90-7160	MF	383	Yes	Yes	NONE	Yes
M6	Hancock	94-7030	Case	695	No	Yes	NONE	Yes
M7	Owego	89-7074	Ford	5610	Yes	Yes	S7	Yes
M8	Castle Creek	90-7162	MF	383	Yes	Yes	S11	Yes
M9	Hancock	04-7042	NH	TL90A	No	Yes	NONE	Yes
M10	Owego	89-7075	Ford	5610	No	Yes	S14	Yes
M11	Binghamton	04-7039	NH	TL90A	Yes	Yes	S10	Yes
M12	Owego	95-7071	Case	4210	Yes	Yes	S6	Yes
M13	Owego	84-7118	Ford	2910	Yes	No	S2	Yes
M14	Owego	89-7075	Ford	5610	No	No	S14	Yes
M15	Bainbridge	83-7110	Ford	5610	Yes	Yes	S5	No

Table A4 lists the tractors that had a Stationary Test, but no Mobile Test.

Table A4. Tractors that had a Stationary Test, but no Mobile test.

Stat ID	Residency	Equip ID	Make	Model	Notes
S3	Oxford	95-7084	Case IH	4210	Regular flail mower
S8	Binghamton	95-7081	Case IH	4230	Regular flail mower
S9	Binghamton	89-7069	Ford	5610	Regular flail mower
S15	EM garage	04-7041	New Holland	TL90A	No mower attached

Table A5 lists the tractors that had a Mobile test, but no Stationary Test. Only 14 tractors were tested with the mobile test because mobile tests M10 and M14 were conducted on the same tractor.

Table A5. Tractors that had a Mobile Test, but no Stationary test.

Test ID	Residency	Equip ID	Make	Model
M5	Hancock	90-7160	Massey Ferguson	383
M6	Hancock	94-7030	Case IH	695
M9	Hancock	04-7042	New Holland	TL90A

In order to validate the stationary and mobile tests we evaluated the fuel consumption and engine speeds that occurred during the stationary and mobile tests. Eight tractors were tested successfully using the full stationary test and mobile test. One 1989 Ford 5610 Tractor was tested successfully in twice in the mobile test on two separate days. By using data from both days, we have 9 comparisons between the stationary and mobile test as noted in Table A3.

The data from the stationary mower test and the mobile test were compared. The stationary mower tests data from the 2-minute full-engine speed tests with the Power-Take Off engaged. This was determined as the most representative of operating conditions during the stationary test to compare with the mobile operation.

The mobile operation was chosen from a 10-minute period with "representative" operating conditions. The median was chosen as a more stable value, because it is not influenced by outliers that may due to measurement error. The intervals selected for the mobile tests are listed in Table A6.

Table A6. 10-Minute periods used to Analyze Mobile Test Runs.

Test	Make	Model	Year	Start	End
M1	Ford	5610	1983	10:26:00	10:36:00
M3	John Deere	401B	1984	11:25:00	11:35:00
M4	Ford	2910	1984	14:50:00	15:00:00
M5	Massey F	383	1990	9:50:00	10:00:00
M6	Case IH	695	1994	14:35:00	14:45:00
M7	Ford	5610	1989	11:28:50	11:38:50
M8	Massey F	383	1990	10:30:00	10:40:00
M9	New Holl	TL90A	2004	11:10:00	11:20:00
M10	Ford	5610	1989	11:19:00	11:29:00
M11	New Holl	TL90A	2004	13:36:00	13:46:00
M12	Case IH	4210	1995	9:30:00	9:40:00
M13	Ford	2910	1984	8:50:00	9:00:00
M14	Ford	5610	1989	11:26:00	11:36:00

Figure A7 displays the median fuel consumption for the 8 tractors that were tested both in real-world mowing conditions and in a stationary test with the PTO engaged. As noted, the values typically correspond quite well. The notable exceptions are for Equipment ID 1990 383 Massey-Furgeson Tractor, and the Equipment ID 2004 TL90A New Holland Tractor.

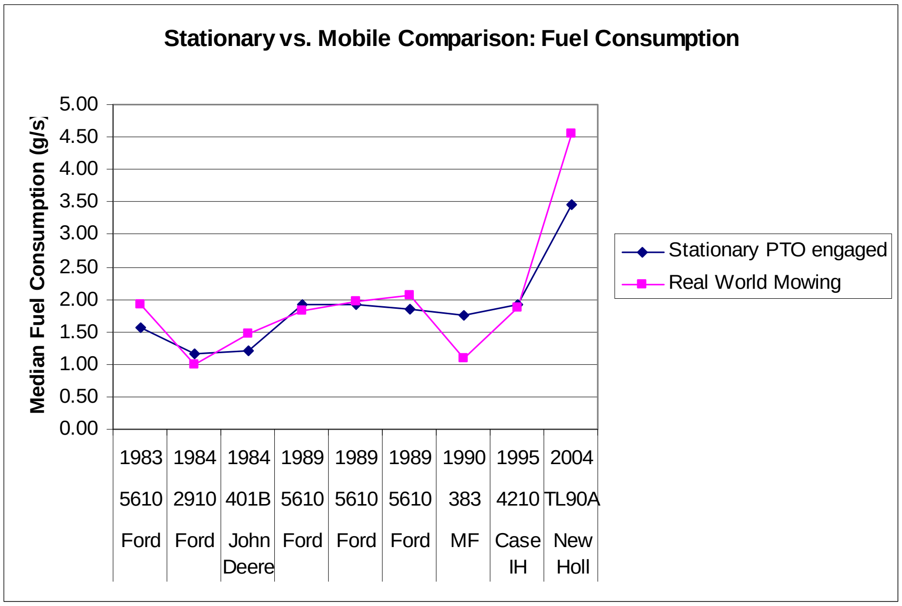

Figure A7. Comparison of the Median Fuel Consumption rate for 9 tractors tested both with a stationary test with PTO-engaged, and in real-world conditions.

To better evaluate the reasons why the discrepancies occurred, the median engine speed measured from the test was compared. Unfortunately, no measure of torque or engine load was made. The work of the engine is computed as:

$$W = Torque \cdot Rotations \cdot 2\pi$$

Power is the work performed per time, so

$$Power = Torque \cdot \frac{Rotations}{\min} \cdot 2\pi = Torque \cdot Engine\ Speed \cdot 2\pi$$

(Goering, 1989)

We can not estimate power without knowing the torque, but by evaluating the engine speed (Figure A8), we can infer the change in torque. The 383 MF tractor has lower engine speed during the real world mowing. This could be due to light engine loads, and substantial idling time, which could lead to the lower observed fuel rate in the real world mowing test. The New Holland has almost equal engine speeds, meaning that the torque on the engine must be significantly higher during the operation of the mower in order to achieve the higher fuel rate.

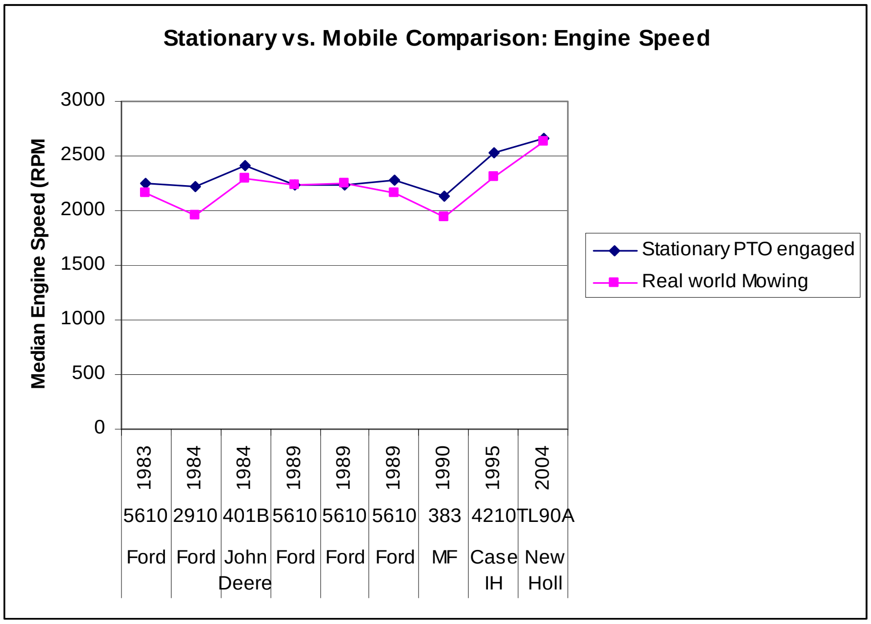

Figure A8. Comparison of the Median Engine Speed for 9 tractors tested both with a stationary test with PTO-engaged, and in real-world conditions.

Comparisons of NOx emissions are given in the Figure A9. The trend among tractors is similar for both the stationary tests and real-world mowing tests. The data shows that the stationary PTO tests can give an approximation of the emissions occurring while mowing. In all but two cases, the NOx emissions are higher in the real mowing than in the stationary tests.

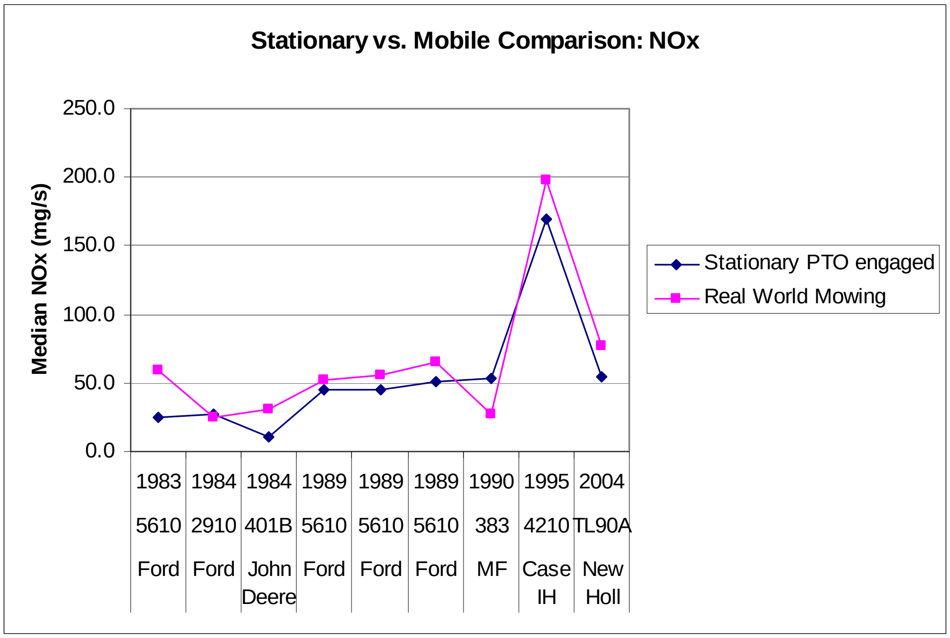

Figure A9. Comparison of the Median NOx emission rates for 9 tractors tested both with a stationary test with PTO-engaged, and in real-world conditions.

The median particulate matter emissions tend to be lower or roughly the same during real-world operation as compared to the stationary test. (Figure A10). The only major exception is the New Holland Tractor which has particulate matter emission rates almost twice as high during the real-world operation. The mean emission rates were also compared in Figure A11. The mean emission rates also demonstrate that the real-world PM are generally lower then those measured during the Stationary PTO-test, with the notable exception of the New Holland TL90A tractor.

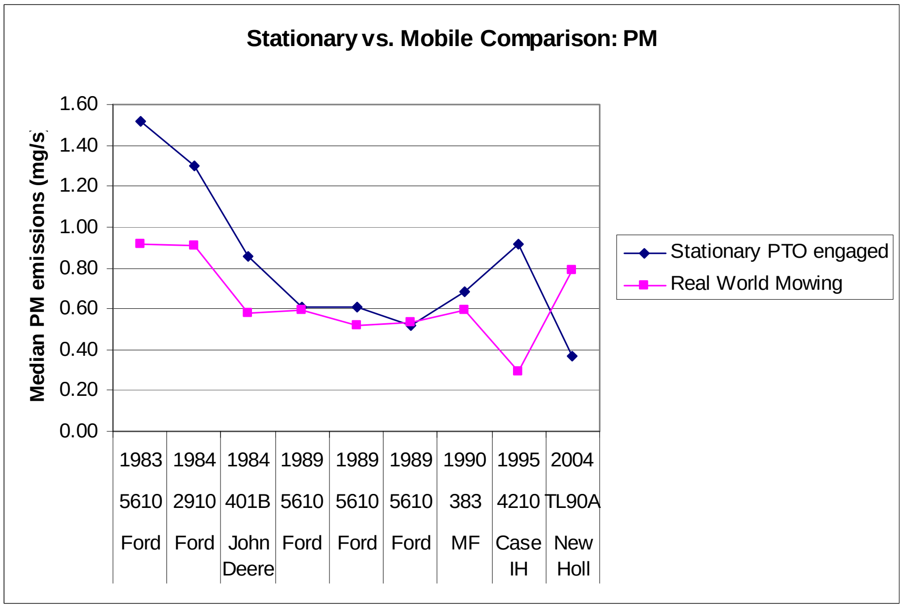

Figure A10. Comparison of the Median PM emission rates for 9 tractors tested both with a stationary test with PTO-engaged, in real-world conditions.

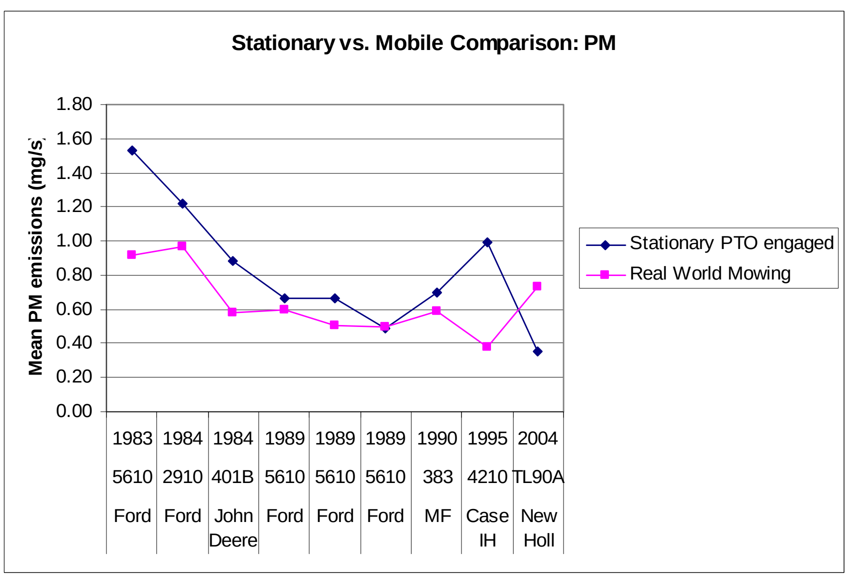

Figure A11. Comparison of the Median PM emission rates for 9 tractors tested both with a stationary test with PTO-engaged, in real-world conditions.

Figure of CO2, CO, and HC emissions are also provided. CO_2 follow the fuel consumption trends. CO do not exhibit any consistent trends among individual tractors for the stationary and real world mowing tests.

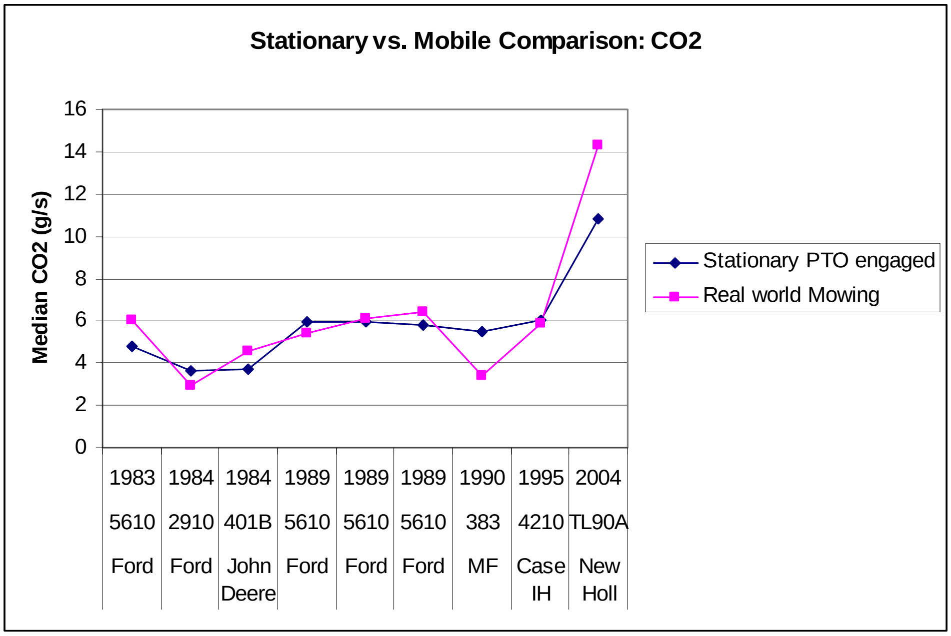

Figure A12. Comparison of the Median CO2 emission rates for 9 tractors tested both with a stationary test with PTO-engaged, in real-world conditions.

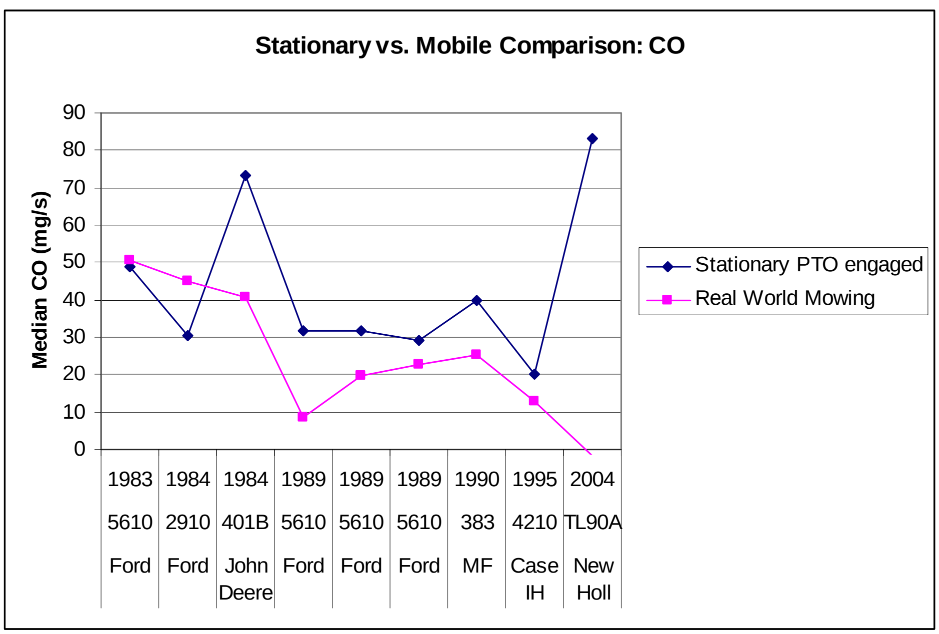

Figure A13. Comparison of the Median CO emission rates for 9 tractors tested both with a stationary test with PTO-engaged, in real-world conditions.

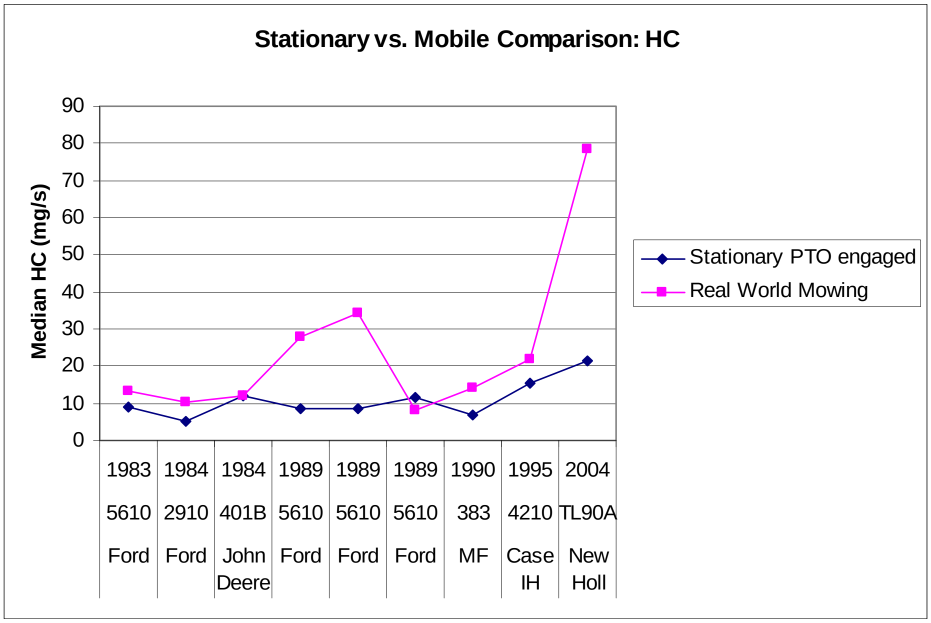

Figure A14. Comparison of the Median HC emission rates for 9 tractors tested both with a stationary test with PTO-engaged, in real-world conditions.

Because the higher emissions are noticed at higher fuel rates, fuel-based emission rates are computed to compare emissions from each of the tractors. The fuel-based emission rates are computed by dividing the total gaseous emission emitted, by the total fuel consumed during the evaluated tests. The resulting statistics is an average rather than a median as presented before. The fuel-based emission rates for NOx are given in Figure A15. In all but one case, the real-world mowing has higher fuel-based NOx emissions.

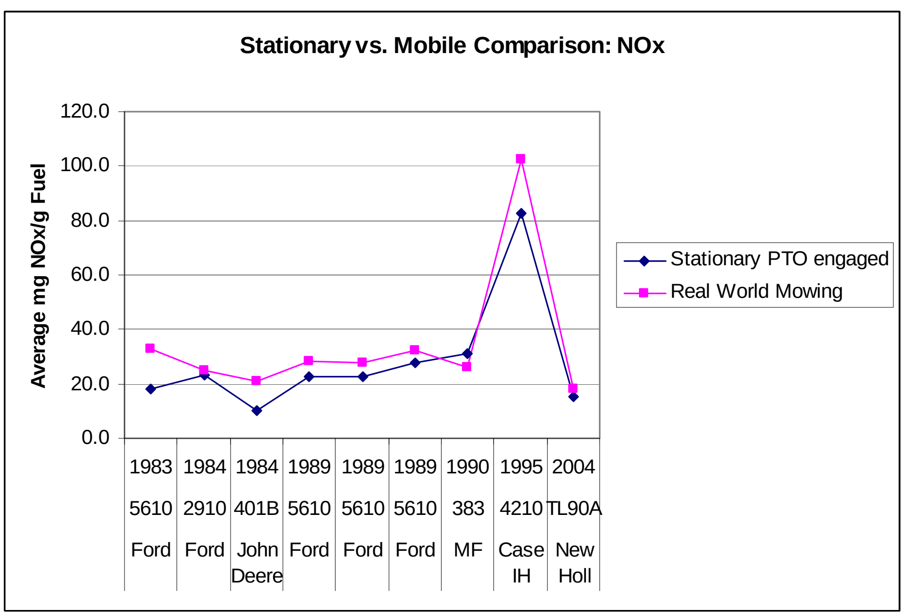

Figure A15. Comparison of the Average Fuel-based NOx emission rates for 9 tractors tested both with a stationary test with PTO-engaged, in real-world conditions.

In contrast to the NOx emissions, the fuel-based PM emission rates tend to be higher for the stationary test. In both cases, the two tests agree better with one another when using the fuel-based emission rates.

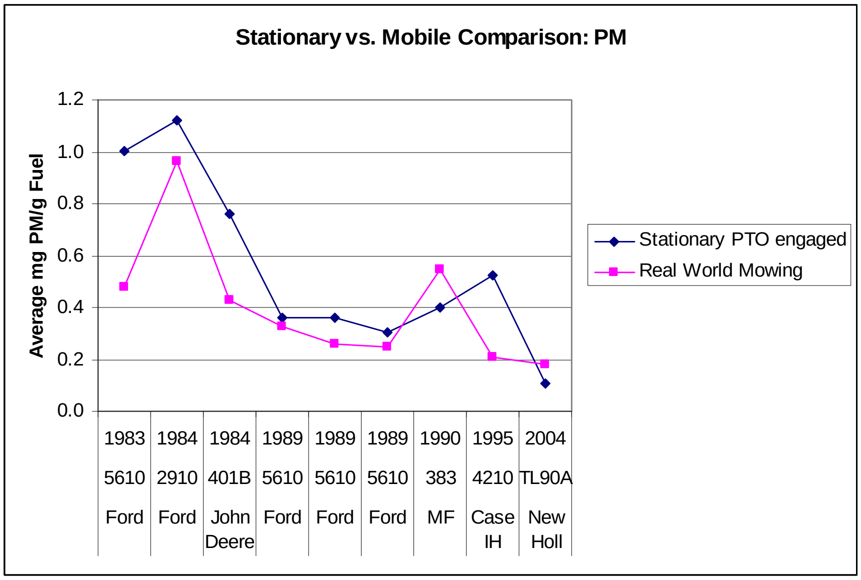

Figure A16. Comparison of the Average Fuel-based PM emission rates for 9 tractors tested both with a stationary test with PTO-engaged, in real-world conditions.

For example, the 1995 Case IH it appears that it runs leaner during real-world conditions, with high NOx emissions and low PM emissions. The 2004 New Holland appears to run richer during real operating conditions, as opposed to the stationary mower test. It has an increase in PM emissions, and a reduction in NOx emissions in real driving conditions. In these cases the fuel to air ratio, likely changes significantly between stationary conditions and loaded conditions.

The fuel-based emission rates are also computed for HC and CO emissions and are included in figure A17 and A18. Again there is substantial variability in these emission rates. Because they are not important sources of emissions from diesel engines, they are included for the interesting reader, but are not discussed in detail.

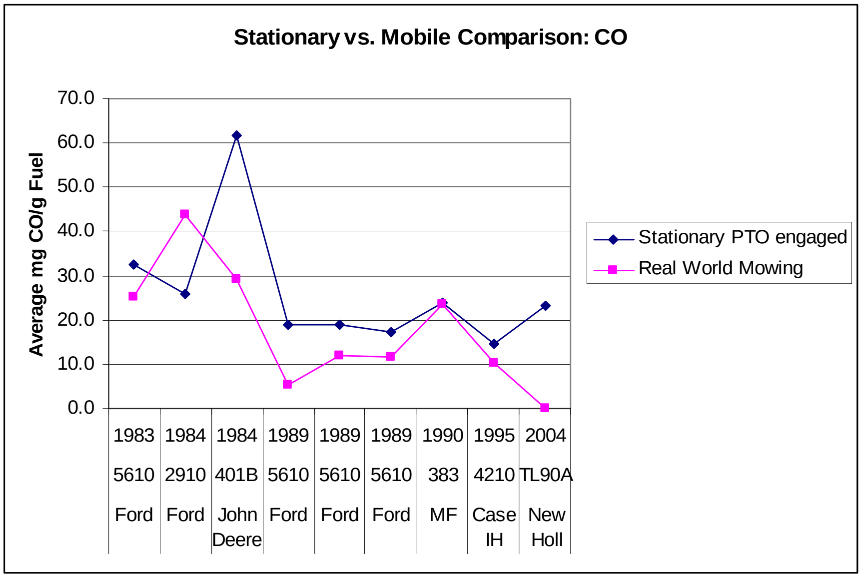

Figure A17. Comparison of the Average Fuel-based CO emission rates for 9 tractors tested both with a stationary test with PTO-engaged in real-world conditions.

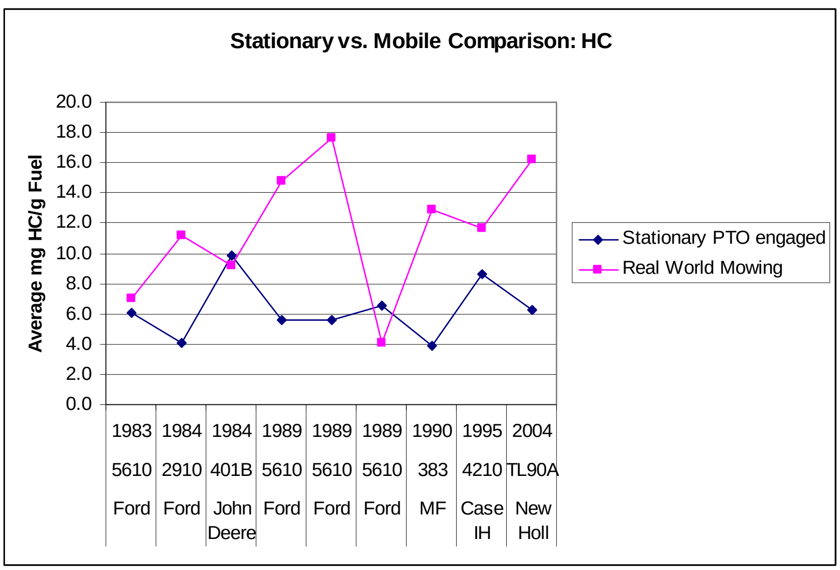

Figure A18. Comparison of the Average Fuel-based HC emission rates for 9 tractors tested both with a stationary test with PTO-engaged, in real-world conditions.

To further validate the emission rates, the emission rates are compared with published data in a tractor study by Lindgren et al. 2004. The summary of his resulsts testing two European tractors in real-mowing conditions is summarized (using similar units) in Table A19.

Table A19. Comparison with numbers emissions/performance of mowing tractors in Lindgren et al. (2004).

Tractor	Model Year	Emissions Reg.	Rated Engine Power (HP)	Mower conditions	% Load	Acre/h	Fuel (gal/h)	CO (mg/s)	HC (mg/s)	NOx (mg/s)
Valtra 6600	1996	None	101	Heavy	79	6.18	4.0	7.2	2.6	142
Valtra 6650	2000	European Stage 1	109	Light	33	3.95	2.1	6.8	2.5	48

Appendix 3: Additional discussion/graphs on Data Analysis Section

Some of the tractors did not have dedicated stationary tests. In these cases, data was taken from two of the mobile tests that conducted a short stationary test before conducting the mobile tests (Mobile Test #5 and Mobile Test#9). For the Case IH 695 (Mobile test #6), and the 04-7041 New Holland Tractor (Stationary Test #15) the two-minute period was not available to be used. So the one-minute period during the maximum engine speed from the hot-start step engine speed test was used. By so doing, this data set included data on all 18 tractors.

Table A20. Mean Fuel Consumption, NOx, and PM Emission Rates for the 18 tractors according to the three evaluated data sets.

	Stationary Maximum Engine Speed			Stationary Mowing Test			10-Minute Real Mowing Test		
Equipment ID	FC (gal/hr)	NOx (mg/s)	PM (mg/s)	FC (gal/hr)	NOx (mg/s)	PM (mg/s)	FC (gal/hr)	NOx (mg/s)	PM (mg/s)
83-7091	1.38	12.29	1.39	1.70	27.17	1.53	2.14	62.26	0.92
83-7110	1.49	16.77	0.77	2.19	54.31	1.25			
84-7107	0.95	13.75	0.97	1.21	25.44	1.22	1.13	24.86	0.97
84-7118	1.34	19.52	0.66	1.42	23.00	0.89	1.47	26.87	0.99
84-7152	1.29	19.28	0.72	1.59	39.81	0.85			
84-7153	1.23	7.18	1.18	1.30	12.11	0.88	1.53	28.62	0.58
89-7069	1.51	13.71	1.08	1.91	23.14	1.45			
89-7074	1.63	18.20	0.70	1.79	44.64	0.49	2.25	65.01	0.50
89-7075	1.52	14.01	0.68	2.09	42.06	0.67	2.09	52.53	0.55
90-7160	1.49	27.13	0.41	1.83	48.93	0.68	2.05	64.17	0.77
90-7162	1.46	23.60	0.81	1.93	53.81	0.69	1.21	28.17	0.59
94-7030	1.40	54.39		1.69	89.64		1.53	130.33	
95-7071	1.63	88.58	0.76	2.11	156.00	0.99	2.07	189.31	0.38
95-7084	1.36	61.61	1.28	1.99	148.71	0.96			
95-7081	1.85	105.40	1.08	2.31	163.93	0.78			
04-7039	2.47	26.58	0.43	3.82	51.61	0.36	4.48	71.43	0.73
04-7041	2.09	21.46	0.09						
04-7042	2.11	34.44	0.31	3.69	59.36	0.34	3.39	53.81	0.48

Table A21. Median Fuel Consumption, NOx, and PM Emission Rates for the 18 tractors according to the three evaluated data sets.

	Stationary Maximum Engine Speed			Stationary Mowing Test			10-Minute Real Mowing Test		
Equipment ID	FC (gal/hr)	NOx (mg/s)	PM (mg/s)	FC (gal/hr)	NOx (mg/s)	PM (mg/s)	FC (gal/hr)	NOx (mg/s)	PM (mg/s)
83-7091	1.37	11.57	1.25	1.74	24.81	1.52	2.16	59.33	0.92
83-7110	1.56	16.71	0.66	2.26	55.88	1.14			
84-7107	0.97	14.01	1.03	1.31	26.72	1.30	1.12	24.64	0.91
84-7118	1.34	19.17	0.64	1.39	21.52	0.84	1.47	26.64	0.98
84-7152	1.31	19.17	0.65	1.64	38.47	0.84			
84-7153	1.28	6.61	1.07	1.36	10.58	0.86	1.63	30.51	0.58
89-7069	1.52	14.90	0.86	1.96	23.94	1.63			
89-7074	1.69	17.46	0.67	2.08	50.70	0.52	2.29	65.55	0.53
89-7075	1.62	14.03	0.64	2.14	44.91	0.61	2.11	53.57	0.56
90-7160	1.50	27.45	0.42	1.87	47.59	0.64	2.13	66.33	0.83
90-7162	1.51	23.32	0.69	1.96	53.18	0.68	1.21	27.51	0.59
94-7030	1.43	55.57		1.70	94.91		1.54	132.15	
95-7071	1.67	93.00	0.72	2.14	168.94	0.92	2.10	197.48	0.29
95-7084	1.40	65.87	1.23	2.02	154.64	0.96			
95-7081	1.92	113.88	1.09	2.44	180.15	0.87			
04-7039	2.46	30.63	0.07	3.87	54.64	0.37	5.08	76.83	0.79
04-7041	2.24	23.66	0.09						
04-7042	2.15	36.13	0.32	3.82	59.48	0.34	3.47	55.39	0.45

Table A22. Average of Median Fuel Consumption, NOx Emission, and PM Emission Rates for Tractor 89-7075 for the two Mobile Runs.

Mobile Test	FC (gal/hr)	Nox (mg/s)	PM (mg/s)
M10	2.04	51.68	0.59
M14	2.19	55.46	0.52
Average	2.11	53.57	0.56

Table A23. Average Fuel-Based NOx, and PM Emission Rates for the 18 tractors according to the three evaluated data sets.

	Stationary Maximum Engine Speed		Stationary with Mower Engaged		10-Minute Real Mowing Conditions	
Equipment ID	NOx (g/kg Fuel)	PM (g/kg Fuel)	NOx (g/kg Fuel)	PM (g/kg Fuel)	NOx (g/kg Fuel)	PM (g/kg Fuel)
83-7091	9.96	1.12	17.88	1.01	32.56	0.48
83-7110	12.55	0.58	27.74	0.64		
84-7107	16.16	1.14	23.48	1.12	24.71	0.96
84-7118	16.30	0.55	18.17	0.70	20.49	0.76
84-7152	16.77	0.63	28.06	0.60		
84-7153	6.55	1.07	10.40	0.76	20.93	0.43
89-7069	10.14	0.80	13.54	0.85		
89-7074	12.46	0.48	27.95	0.30	32.35	0.25
89-7075	10.30	0.50	22.57	0.36	28.13	0.29
90-7160	20.44	0.31	29.87	0.42	34.95	0.42
90-7162	18.10	0.62	31.17	0.40	26.08	0.55
94-7030	43.50		59.47		95.32	
95-7071	60.86	0.52	82.73	0.52	102.49	0.21
95-7084	50.58	1.05	83.59	0.54		
95-7081	63.59	0.65	79.47	0.38		
04-7039	12.02	0.19	15.14	0.10	17.83	0.18
04-7041	11.48	0.05				
04-7042	18.26	0.17	17.99	0.10	17.79	0.16

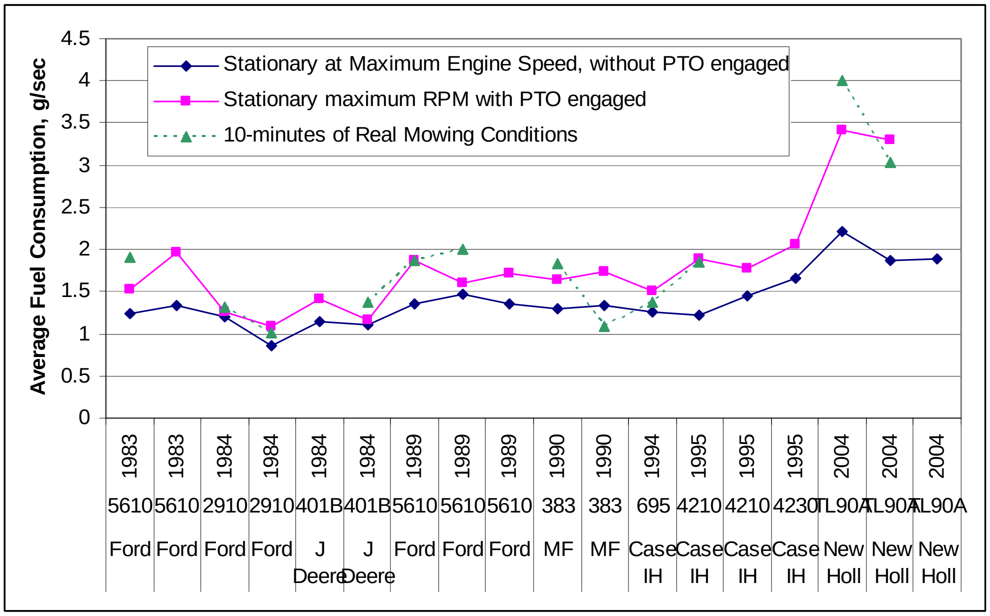

Figure A19. Average fuel consumption comparisons of the tractors in g/sec.

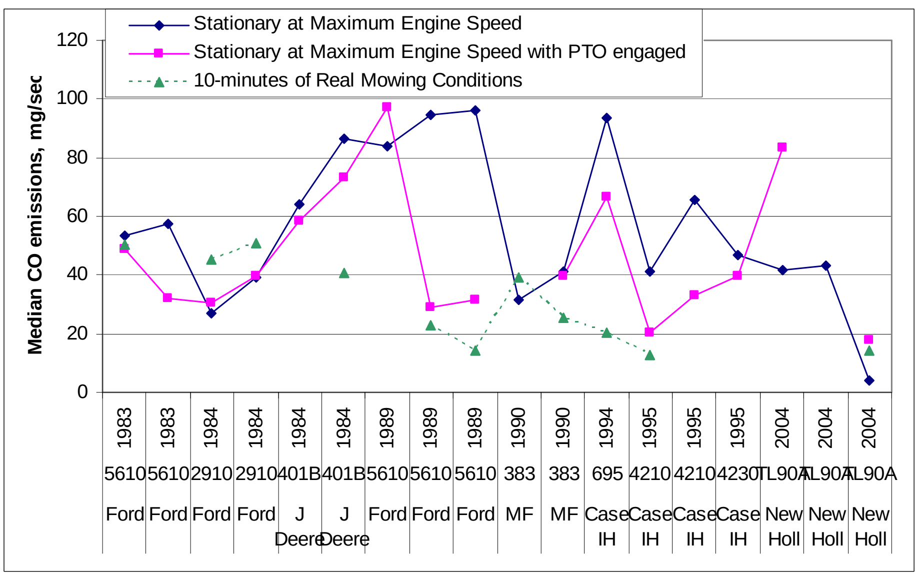

Figure A20. CO Emissions of Tractors on according to the three evaluated tests.

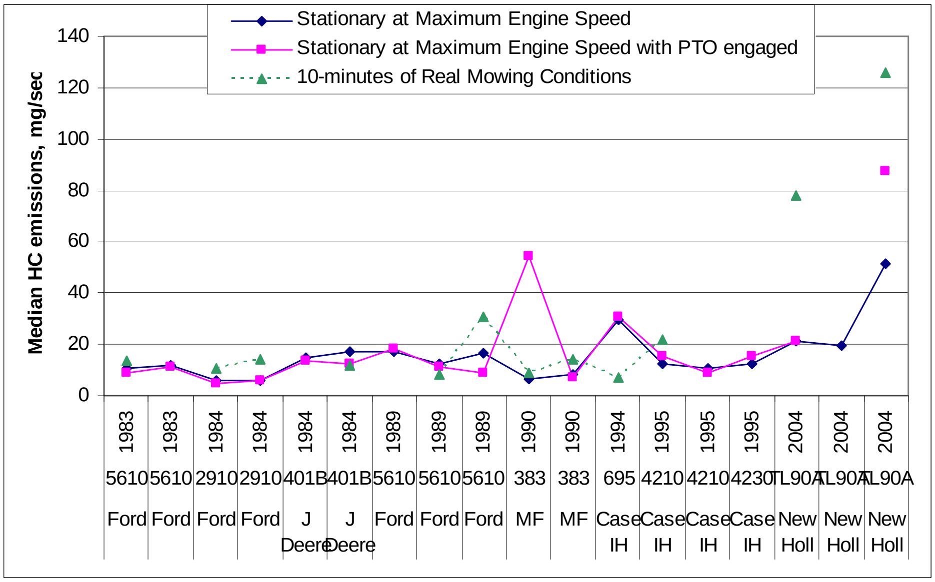

Figure A21. HC Emissions of Tractors on according to the three evaluated tests.

Appendix 4: Nebraska Tractor Test Laboratory

The stationary mowing tests when operating the PTO are assumed to be compared to published testing data. The University of Nebraska Tractor Test Laboratory provides internationally recognized testing data on the performance of agricultural tractors. To validate our results, we compared the engine performance measured of the New Holland TL90 A, which was measured in stationary test 10, to the published results obtained from the Nebraska Tractor Test Laboratory. Figure A22 displays the fuel rate, and engine speed readings, for varying power and fuel consumption tests. In this test, the power-take off is engaged at a constant speed of 1050 rpm. The testing results obtained by the Nebraska, show that at varying fuel consumption and (and Power), the maximum crank shaft speed will change. The median value for fuel rate and the recorded engine speed from the PTO-engaged stationary test from this study is also plotted on the figure. As shown, the measured data point corresponds well to the published data trends.

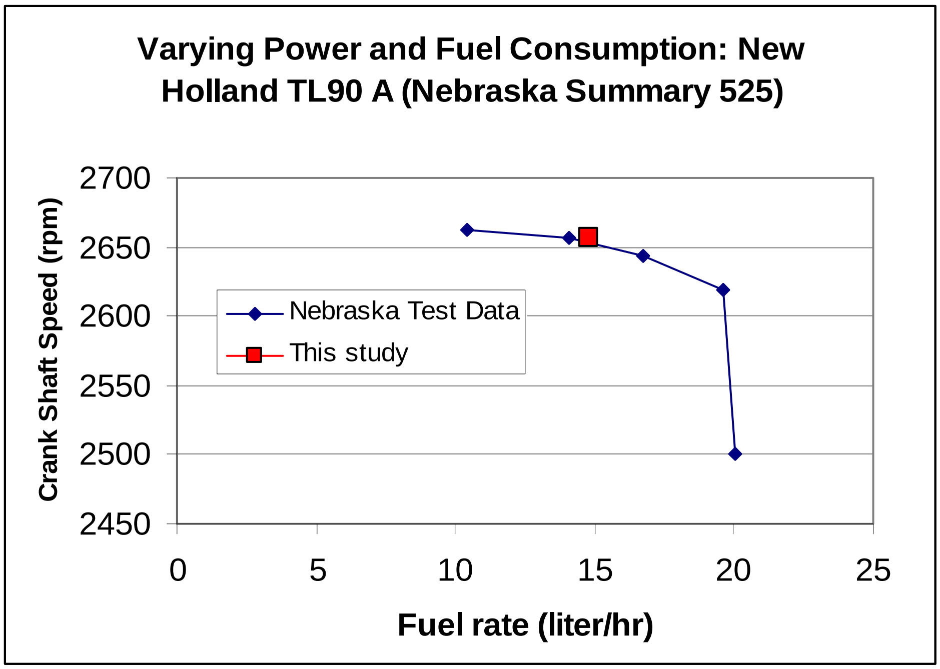

Figure A22. Validation of measured fuel rate, by comparing the engine speed and fuel rate to published testing data

The published Nebraska Tractor tests were used to give estimates of the power output of the tractor. In our study, the crank case speed and fuel consumption rate were measured, but equipment of torque or power were not able to be made with our portable emissions equipment. The Power Take-Off Performance Test conducted by the Nebraska Tractor Test laboratory, provides data on the maximum power achieved by loading the PTO using a dynamometer. The maximum engine speed and HP achieved at each PTO torque loading is provided, along with the fuel rate achieved at each setting.

During our tests, we maximized the engine speed (and PTO speed) under light loads used to power the mowing equipment. We obtained measures of engine speed and fuel rate, which can then be used to estimate power by using the Power Take-Off Performance Test by using the

Nebraska Tractor Tests. Several uncertainties are used in using the Nebraska Test Data as a Comparison exist. For example, the Nebraska Tests are performed on new vehicles selected by the manufacturer, so the actual engine performance will be different in our tested vehicles. However, it is believed to be a good approximation.

By interpolating the fuel rate curve from Nebraska Summary 525, we can determine the power output of the engine. For the PTO-engaged stationary test, the median fuel rate occurred at 14.83 l/hr (*3.92 Gal/hr*). By interpolating this value using the Nebraska Summary 525 data we determine that the power output is 32.04 kW *(43 HP)* as shown in Figure A23. The maximum power is 61.8 kW, so the stationary test was recording the tractor operating at 52% engine load.

For tractors, fuel economy is measured in units of work per unit of fuel (HP.h/gal or kW.h/l). The fuel economy for our test is calculated as 2.16 kW.h/l. At maximum load, the fuel economy is 3.90 kW.h/l (Nebraska Summary 525). Thus, the tractor during the stationary test is operating at 70% of the maximum fuel economy. In other words, at this operation level, for an equal amount of fuel, the work conducted will be 70% less than if the engine was designed to operate at maximum level.

This test (S10) was the New Holland tractor operating the Batwing mower and had a large fuel rate and percentage load. In other cases, the real-world operation would have a lower percentage load. We observed that the New Holland mowers had a low fuel economy in comparison to the other tractors. One of the reasons is that during NYSDOT mowing operations, the New Holland tractors are operating below the optimal loading capacity. Or in other words, we are using too large of an engine to conduct the work, which results in a loss of efficiency.

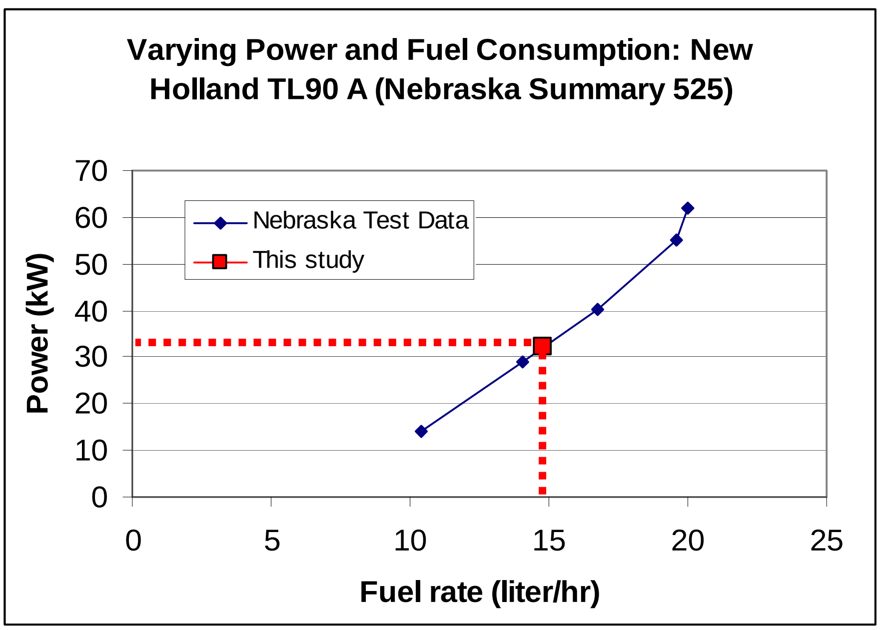

Figure A23. Power and Fuel Rate measurements that occur at a constant PTO of 1050 rpm for the New Holland TL90 A Tractor. In our Study the PTO was running at 540 rpm.

Table A24. Fuel Consumption and Power Requirements of Mowers Operated during the Stationary Mower Test.

Mower Type	Equipment ID	Make	Model	Year	Rated Engine HP	Estimated HP during test	Percentage test load	Fuel Consumption, gal/hr	Fuel Economy, Hp.h/gal
Sickle Bar	84-7107	Ford	2910	1984	40	14.6	40%	1.31	11.2
Flail	84-7153	John Deere	401B	1984	62			1.36	
	89-7074	Ford	5610	1989	72	19.1	31%	2.08	9.2
	89-7069	Ford	5610	1989	72	16.3	26%	1.96	8.3
	90-7162	Massey Ferguson	383	1990	81			1.96	
	95-7084	Case IH	4210	1995	72	13.4	22%	2.02	6.6
	95-7071	Case IH	4210	1995	72	16.4	27%	2.14	7.7
Double Flail	95-7081	Case IH	4230	1995	84	28.1	44%	2.44	11.5
Batwing	83-7091	Ford	5610	1983	72	11.0	18%	1.74	6.3
	84-7152	John Deere	401B	1984	62			1.64	
	04-7039	New Holland	TL90A	2004	90	43.0	52%	3.87	11.1
OTR	83-7110	Ford	5610	1983	72	23.5	38%	2.26	10.4
	89-7075	Ford	5610	1989	72	20.6	33%	2.14	9.6

When comparing the percentage loads, there appears to be inconsistencies in the data. For example, the New Holland TL90A appears to be running at a much higher percentage loads (52%) than the Ford 5610 (18%). The New Holland should be running at a lower percentage load since it is a much larger tractor operating a similar batwing mower as the Ford 5610. To address these concerns, correspondence was made with Dr. Roger Hoy from the Nebraska Tractor Test Laboratory and Professor Al George of Mechanical Engineering at Cornell University. It was determined that there was not a consistent method to always use our data to compute accurate percentage test loads among the different tractors. Thus, estimates of percentage loads can only be used qualitatively within an engine model (i.e. Ford 5610), but not used to compare between tractor models (i.e. Ford 5610 vs. New Holland TL90A). The comparisons between the tractors seems to be reasonable using the OTR mowers, but there are still some unresolved questions about the batwing rotary mowers as discussed in the main text. The Nebraska Tractor Test Summaries for the evaluated tractors are included in the data CD.

Appendix 5. Calculation of distance and acreage-based emission rates.

Table A25. 10-Minute Intervals Used to Calculate Distance and Acreage-Based Mobile Emission Rates

Equipment ID	Make	Model	Year	Mobile Test	Start time	End time
84-7107	Ford	2910	1984	M4	15:08:00	15:18:00
84-7118	Ford	2910	1984	M13 (I)	8:50:00	9:00:00
				M13 (II)	9:21:40	9:31:40
84-7153	John Deere	401B	1984	M3	11:25:00	11:35:00
89-7074	Ford	5610	1989	M7	11:28:50	11:38:50
90-7160	Massey Ferguson	383	1990	M5	9:50:00	10:00:00
90-7162	Massey Ferguson	383	1990	M8 (I)	10:29:00	10:39:00
				M8 (II)	10:39:00	10:49:00
94-7030	Case IH	695	1994	M6	14:35:00	14:45:00
95-7071	Case IH	4210	1995	M12	9:30:00	9:40:00
83-7091	Ford	5610	1983	M1	10:26:00	10:36:00
04-7039	New Holland	TL90A	2004	M11	13:36:00	13:42:00
89-7075	Ford	5610	1989	M10 (I)	11:04:00	11:14:00
				M10 (II)	11:14:00	11:24:00
89-7075	Ford	5610	1989	M14	10:50:00	11:00:00
04-7042	New Holland	TL90A	2004	M9	11:23:00	11:33:00

Table A26. Detailed information on each 10-minute "snapshot".

Mower Type	Equipment ID	Make	Model	Mobile Test	Elapsed Time (minutes)	Total Distance (miles)	Distance Traveled without mowing	Distance Mowed (miles)	Average Speed (mph)	Miles mowed per hour	Weighted Mower width (ft)	Acres Mowed per Hour	Mowing description
Sickle Bar	84-7107	Ford	2910	M4	10	0.28	0.05	0.23	1.7	1.4	8.35	1.42	roadside (partial width)
Sickle Bar	84-7118	Ford	2910	M13 (I)	10	0.47	0.00	0.47	2.8	2.8	12	4.07	roadside (full width)
Sickle Bar	84-7118	Ford	2910	M13 (II)	10	0.53	0.06	0.47	3.2	2.8	12	4.13	roadside (full width)
Flail	84-7153	John Deere	401B	M3	10	0.48	0.06	0.42	2.9	2.5	12.17	3.75	roadside (full width)
Flail	89-7074	Ford	5610	M7	10	0.57	0.03	0.54	3.40	3.2	12.17	4.75	roadside (full width)
Flail	90-7160	Massey Fe	383	M5	10	0.37	0.00	0.37	2.2	2.2	12.17	3.24	median (full width)
Flail	90-7162	Massey Fe	383	M8	10	0.18	0	0.2	1.1	1.1	6.2	0.82	roadside (partial width)
Flail	90-7162	Massey Fe	383	M8	10	0.23	0.06	0.17	1.4	1.0	8.28	1.04	roadside (full and
Flail	94-7030	Case IH	695	M6	10	0.28	0.00	0.28	1.7	1.7	12.17	2.51	roadside (full width)
Flail	95-7071	Case IH	4210	M12	10	0.45	0.00	0.45	2.7	2.7	12.17	3.98	interchange (full width)
Batwing	83-7091	Ford	5610	M1	10	0.45	0	0.45	2.7	2.7	15	4.91	interchange (full width)
Batwing	04-7039	New Hollar	TL90A	M11	6	0.30	0.00	0.30	3	3.0	15	5.45	median (full width)
OTR	89-7075	Ford	5610	M10 (I)	10	0.20	0.00	0.20	1.2	1.2	4	0.58	roadside (single pass)
OTR	89-7075	Ford	5610	M10 (II)	10	0.20	0.07	0.13	1.2	0.8	4	0.39	roadside (double-pass)
OTR	89-7075	Ford	5610	M14	10	0.28	0.09	0.19	1.7	1.1	4	0.55	roadside (double-pass)
OTR	04-7042	New Hollar	TL90A	M9	10	0.23	0.08	0.16	1.4	0.9	4	0.45	roadside (double-pass)

Appendix 6: Herbicide Supplemental Information

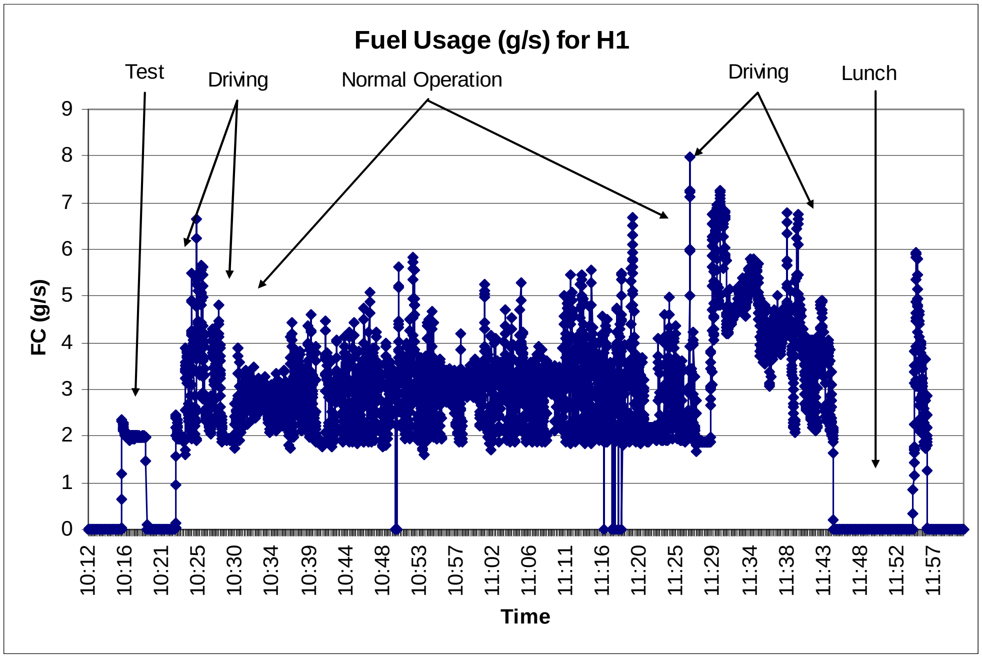

Figure A24. Axion Measurements of Fuel Consumption rates for Herbicide Test 1.

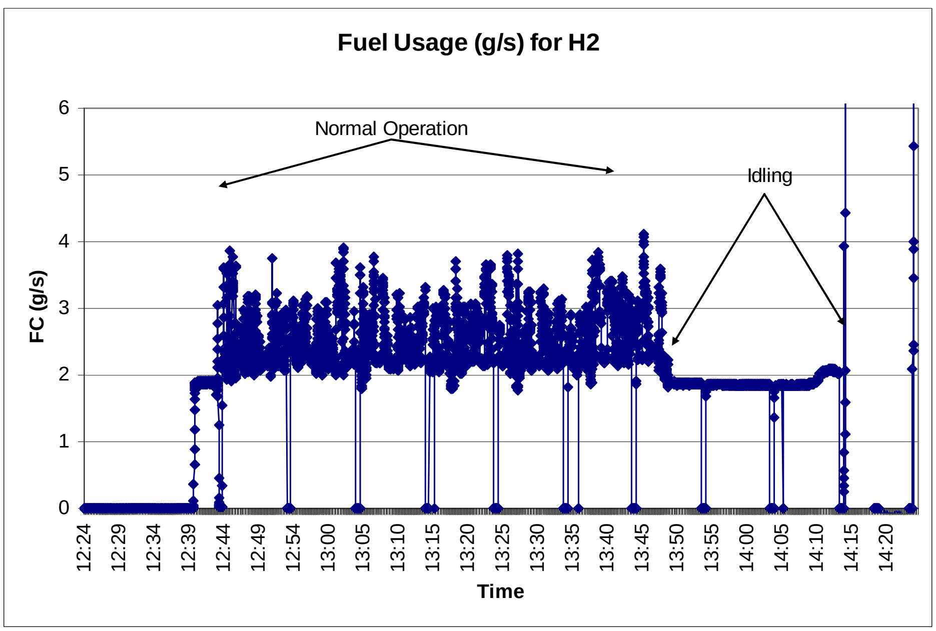

Figure A25. Axion Measurements of Fuel Consumption rates for Herbicide Test 1.