The development, validation and implementation of a data acquisition system to quantify in-field tractor performance characteristics.

by

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Abstract

In the agriculture industry, in-field efficiency of tractors is critical information for operators and producers. Properly matching tractor to implement using real-world tractor performance characteristics is the primary factor that effects in-field efficiency. Currently, tractor testing is primarily conducted in a controlled lab environment to quantify attributes such as power take-off (PTO) power and fuel consumption. However, in-field quantification of these attributes is necessary to gain a full understanding of the machine's performance. Therefore, this study was conducted with two primary objectives: 1) develop a data acquisition system to measure real-time tractor performance at varying machine states during field operations, and; 2) evaluate the performance of tractors individually and compared to each other. Studies were conducted to test multiple different sized tractors with varying implements used in a specific crop production cycle; these tractors included two smaller 71 HP machines, a 90 HP and a 100 HP machine. The primary performance comparison goals were to evaluate the performance efficiency differences between a cabin and open station machine of the same size, and to evaluate the differences in performance between two similarly sized machines.

A custom data acquisition (DAQ) system developed comprises of a torque sensor, flow meter, and GPS to acquire target performance parameters using a National Instruments cRIO system. The PTO torque sensor and fuel flow meter were tested and validated in a controlled lab using a PTO dynamometer and fuel scale. Validation field studies conducted showed that the DAQ system captured real-time performance parameters; strong correlation was observed between power, speed, and fuel consumption.

Using the real-time data allows for a better understanding of the relationship between machine and implement, as well as a more thorough understanding of the effect of terrain and crop load on fuel consumption and PTO power. The peak torque values through the implement drivetrain and their frequencies coupled with the average breakdown of power consumption by the implement gives the manufacturer and producer the opportunity to modify usage trends or design, respectively. Spatial fuel consumption data on a tractor by tractor basis allows varying machines to be compared directly based on their efficiency. Testing of the two smaller tractors took place on the same day in a uniform field. While the data did not indicate any difference between open station and cabin machines, strong correlation was observed between both operating speed and PTO mode selection and performance efficiency. The testing of the two larger tractors was done on sequential cuts of alfalfa on the same field; to account for this, bales were geotagged and weighed to produce a forage density map. Data from testing yielded two main results; the first being that the fuel consumption rate of each tractor and operation can be accurately predicted using an equation using PTO power and operating speed as variables. The equation that defines the fuel consumption for the swathing operation predicts the fuel consumption within 10% over 75% of the time in both sized machines. Data recorded by the DAQ system yields the information necessary to give the manufacturer a thorough understanding of how machines and implements interact with each other, as well as how external factors effect machine performance.

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Chapter 1 – Introduction

Agricultural machinery, specifically tractors, are primarily tested in two manners. One being through the manufacturer and the second being through a separate entity, commonly the Nebraska Tractor Test Lab. Manufacturer testing is focused on power evaluation as well as durability testing. Testing through the Nebraska Tractor Test Lab (NTTL) solely focuses on performance statistics.

The NTTL tests and publishes reports for all tractors sold in the state of Nebraska, and many tractors manufactured in the United States (Grisso, 2012). At the NTTL, testing of tractors is done primarily in accordance with OECD Code 2, a standard for tractor testing. This code describes the manner in which tests should be performed, test conditions and presentation methods. For example, OECD Code 2 states that "the shaft connecting the power take-off to the dynamometer shall not have any appreciable angularity", and "the ambient temperature shall be 23 ± 7°C". While restrictions such as these assist in creating data that can be easily compared, it does not account for the dynamic environment that is seen during agricultural operations. NTTL tests tractor performance characteristics including PTO performance, drawbar performance and hydraulic system performance. PTO testing is done using dynamometer loading to evaluate the tractor with varying parameters including rated engine speed, standard PTO speed and maximum torque. Drawbar performance testing is done on gears that provide wheel slip less than 15% and a maximum speed of 10 MPH (Grisso, 2012); "in each gear, at full throttle, the load is increased until maximum drawbar power is achieved." During each of these testing procedures, fuel consumption is also recorded. PTO power testing is done in a static lab environment, and drawbar load testing is done on a concrete track (to prevent inconsistencies between tests) (Grisso, 2012).

Kubota, a Japanese tractor manufacturer that is popular in the United States, sends their tractors to the NTTL to receive results that will allow their customers to select the appropriate tractor for their needs, for dealers to compare with competitive models, and for decision making for future development (T. Tsunemori, personal communication, November 15, 2018).

Understanding how tractors are currently tested illustrates that there is a clear gap in information for both the manufacturer and end user, or producer. Yes, tractor selection can be made based upon the power and fuel consumption data provided by the NTTL, but these values do not represent the actual performance of the machine in-field. In addition, testing tractors while operating with specific implements gives a clear picture of how the machine will perform in the field with a similar implement.

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Chapter 2 – Developing a Data Acquisition System to Quantify Necessary In-Field Tractor Performance Characteristics

Abstract

In the agriculture industry, in-field efficiency of tractors is critical information for operators and producers. Properly matching tractor to implement using real-world tractor performance characteristics is the primary factor that effects in-field efficiency. Currently, tractor testing is primarily conducted in a controlled lab environment to quantify attributes such as power take-off (PTO) power and fuel consumption. However, in-field quantification of these attributes is necessary to gain a full understanding of the machine's performance. Therefore, this study was conducted with two primary objectives: 1) develop a data acquisition system to measure real-time tractor performance at varying machine states during field operations, and; 2) Compare and contrast effect of field topography, and forage density on key performance characteristics such as PTO power, and fuel consumption. A custom data acquisition (DAQ) system developed comprises of torque sensor, flow meter, and GPS to acquire target performance parameters using a National Instruments cRIO system. The PTO torque sensor and fuel flow meter were tested and validated in a controlled lab using a PTO dynamometer and fuel scale. Field studies using a 90 HP tractor were conducted in wheat stubble and crabgrass field with varying topography and irregular shape boundaries to collect in-field tractor performance. Results showed that the DAQ system captured real-time performance parameters. Strong correlation was observed between PTO power, ground speed, and fuel consumption. Future studies will be conducted to test multiple different sized tractors with varying implements used in a specific crop production cycle. This data will provide operators with the information necessary to more efficiently pair tractors and implements.

Introduction

Testing agricultural tractors is necessary to ensure that the machines perform to their expected potential and are properly matched with implements. Pairing tractors with appropriately sized implements yields higher fuel efficiency and better power availability during dynamic work conditions. Power is transmitted from the tractor to implements via two primary systems: the hydraulic system, and the power take-off (PTO) system. The hydraulic system uses fluid power transmitted through hydraulic ports on the rear of the tractor to drive the implement, whereas the PTO system uses a gear train and output shaft on the rear of the tractor to transmit power to the implement; according to ASAE D497.7, the most efficient delivery method is the PTO shaft (ASABE Standards, 2015).

Currently, testing of agricultural machinery is primarily performed in controlled lab environments. For example, the Nebraska Tractor Test Lab conducts extensive testing and publishes data sets relating PTO power, PTO speed and fuel consumption. All of this testing is done in accordance with OECD Code 2, for the official testing of agricultural and forestry tractor performance. OECD Code 2 specifies stationary testing and precise ambient temperatures. While the testing of machinery characteristics is valuable information, there are many factors that are surpassed when the testing is completed in a lab environment. Testing machinery in real-time while performing activities in the real-field conditions allows a bigger picture to be seen. For example, testing a tractor with a baler during field conditions could provide performance data that will incorporate the effects of many external factors including forage density and terrain. However, very little research has been conducted to develop systems for real-world tractor performance and to quantify tractor performance, especially for the end users in public sphere.

The tractor when operated with matching recommended equipment during field operation can provide valuable information on key performance parameters like fuel consumption and power requirements. The tractor performance parameters knowledge can eventually help products and end user make intelligent decision on selecting tractor-implement combination which provide optimal engine power and fuel economy during diverse dynamic field conditions. Therefore, a study was designed with two goals, 1) integrate sensors and develop potable data acquisition system to record data from agricultural tractors while performing activities in the field, and 2) conduct preliminary tests to collect real-time tractor performance using a hay baler. The physical system requirements included that it be installable on any tractor, as well as not interfere with the tractor operations.

Methods and Materials

A data acquisition (DAQ) system was developed to read PTO torque and speed, fuel consumption, and Global Positioning System (GPS) data. The sensor selection and DAQ system was designed with a goal to make it portable among similar size and model of tractors. Each of sensors selected were carefully studies before including in the study and validated in the laboratory

PTO Torque and Speed Sensor

An important performance characteristic to monitor on agricultural tractors is the power take-off (PTO) power produced. The PTO shaft is the primary method used to transmit power from the tractor to the implement. When studying the performance of tractors in the field, recording the power allows analysis that can lead to the opportunity for better matching tractors with implements, thus increasing efficiency.

The PTO power can be measured directly using an in-line slip ring torque sensor that also outputs shaft speed. It is also necessary that the sensor be rugged and portable to ensure malfunction-free operation in agricultural environments.

A NCTE series 7000 sensor (Series 7000, NCTE AG, Unterhaching, Germany) was selected to measure torque and speed of the power take-off shaft (Figure 1). Roeber et al., (2016) tested two slip-ring torque sensors Datum Series 420 and NCTE Series 7000 during a study conducted at Nebraska Tractor Test Lab (NTTL) in static test conditions. The Datum sensor was found to be too prone to extreme vibration; the NCTE sensor was also noted to have excessive vibration, however, the vibration was dampened by changing the female coupler style. The torque sensor is capable of reading torques up to 3000 newton-meters as well as outputting the speed of the shaft. The sensor was configured to output an analog (0-10V) signal for the torque, and a digital pulse at a rate of one pulse per rotation for the speed of the shaft. An additional attribute necessary for this research was the ability to order the sensor with IP65 ingress protection; this allowed the sensor to be used in adverse field environments without the worry of malfunction.



Figure 1-NCTE Series 7000 Torque Sensor

The NCTE Series 7000 came supplied with two sets of flange ends for connecting to both 540 and 1000 (small) PTO shafts (Figure 2). The implement fits to the male end of the sensor in the standard way, while the female end of the sensor using a split piece to clamp to the tractor's PTO output shaft.

The two eight millimeter bolts that clamp the end also align with the round slot in the PTO shaft to prevent the sensor from sliding in the case of the bolts loosening due to vibration.

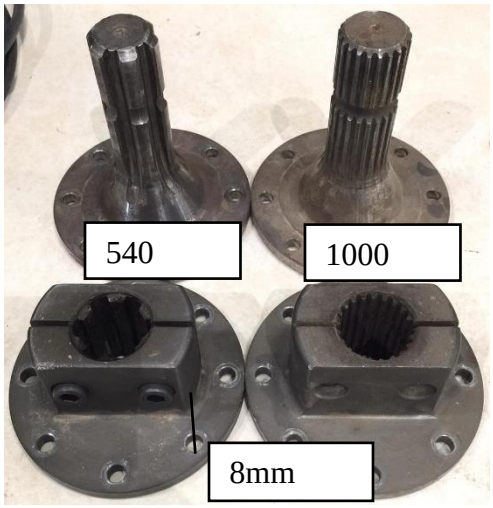


Figure 2-1000 and 540 Fittings for NCTE Sensor

Torque Sensor Implementation

For use in the data acquisition system developed in this research, the original female coupler was used, but a new method for restraining the sensor was developed to remove all vibration for safe use during field operating conditions. The manufacturer designed the sensor to be mounted using only the female coupler and a six millimeter bolt hole on the side to prevent the entire sensor from rotating, but not damping the vibrations when mounted on the PTO shaft. Therefore, a clamp style mount was developed and fabricated in the Biological and Agricultural Engineering (BAE) department at Kansas State University. The mount used steel clamps to hold the sensor to a frame, which was bolted to the drawbar mount on the tractor (Figure 3). The designed mounting method removed virtually all vibration observed during laboratory testing and also allowed the system to be used for many hours in the field without causing damage to u-joints, the sensor, or other vibration sensitive parts.



Figure 3-NCTE Clamp Mounting

In addition to the clamp mount, a three-point arm extension had to be designed and fabricated. The PTO sensor adds approximately 10.5 inches in length to the PTO shaft, so it was necessary to also extend the three-point arms by the same length to ensure that the implement's PTO shaft would compress enough to fit, and also to prevent the u-joints from undergoing unnecessary stresses. To accomplish this task, a three-point quick attach was modified. Steel was cut using a plasma cutter, and welded to the back of the quick attach to further extend its length, resulting in a total extension of 27 centimeters.



Figure 4-Three Point Extension

Torque Sensor Calibration and Verification

The PTO sensor was calibrated in a lab at Kansas State University using an AW PTO dynamometer (Nebraska 400, AW Dynamometer Inc, Illinois, USA). The Nebraska 400 dynamometer (Figure 5) is capable of measuring torque of up to 2700 N-m and 300 kW at 1000 RPM using a hydraulic brake and torque arm. The torque sensor was connected in-line with the AW dynamometer to allow both torques to be read simultaneously. For calibration, the test tractor, a Mahindra 7085 was operated at full throttle and the PTO was braked down to varying RPMs to produce varying power outputs (Table 1). Each trial was ran for 120 seconds after the desired RPM was reached and stable. The results indicate that the power indicated by the sensor is consistently lower than the actual power measured by the dynamometer.

On average, the sensor read 22.7% low, which was not an acceptable deviation. Therefore, the data collected from the dynamometer was used to fit a regression function (Figure 6) and develop the calibration equation (Equation 1). Another set of experiments were run to re-validate the torque sensor performance (Table 2) and the resulting sensor data showed that average difference between the sensor and dynamometer data was 2.30%. The sensor calibration and validation data was deemed acceptable for the purpose of this research and the calibration equation was adopted to all data.

$$CP = 1.3014 * IP \qquad (1)$$

where CP = corrected power

RP = raw power.



Figure 5-Testing Dynamometer Setup

Table 1-NCTE Sensor Calibration Data

		Power (kW)			Dyno and Sensor Comparison (kW)	
		Sensor		Dyno		
PTO RPM	Trial	Average	Std. Dev	Measured	Difference	% Diff
600	1	17.3	0.600	22	4.3	20.0%
	2	19.6	1.100	25	5.8	22.8%
	3	16.5	1.100	22	5.1	23.8%
575	1	32.5	0.354	41	8.5	20.8%
	2	33.2	0.360	40	6.3	16.0%
	3	34.7	0.839	45	10.8	23.7%
550	1	39.9	1.502	51	10.8	21.2%
	2	39.2	1.387	51	12.3	23.8%
	3	41.2	0.823	54	13.3	24.4%
525	1	40.5	1.104	52	11.8	22.5%
	2	41.0	0.568	53	12. 0	22.7%
	3	41.2	0.608	55	13.9	25.3%
500	1	40.3	0.750	53	12.7	23.9%
	2	38.5	1.217	50	11.5	23.0%
	3	39.6	0.858	54	14.9	27.3%

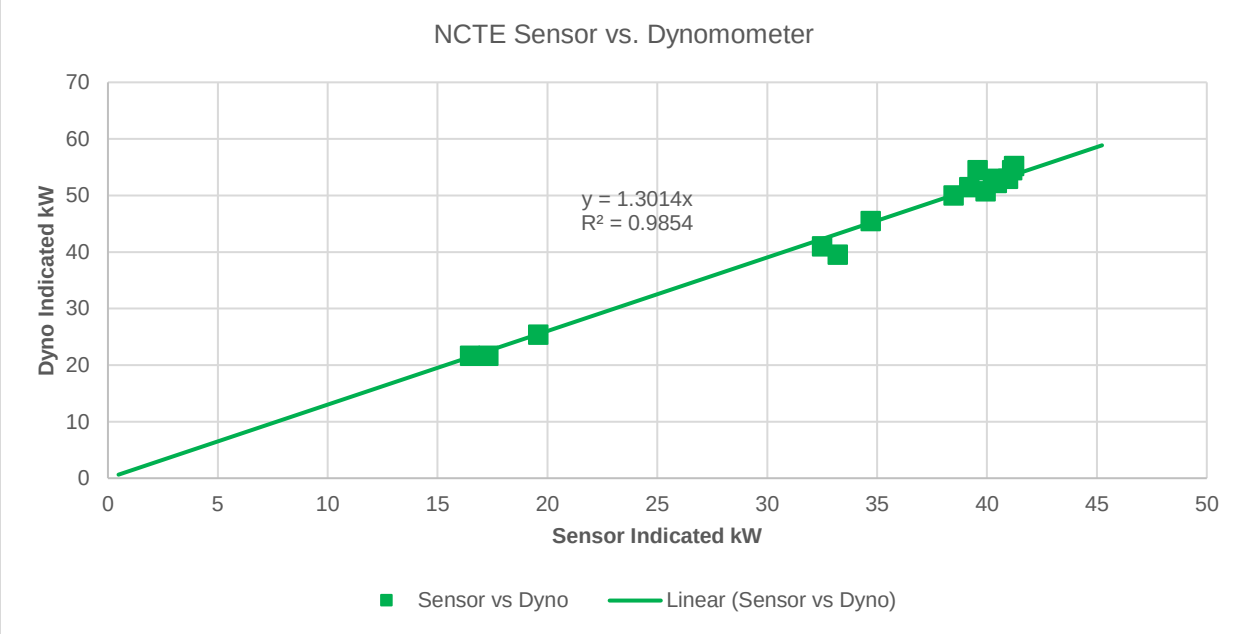


Figure 6-NCTE torque sensor Calibration Curve

Table 2-Comparison of NCTE Torque Sensor and Dynamometer Torque Data using Developed Calibration Equation

		Power (kW)		
PTO RPM	**Trial**	**Sensor Corrected**	**Dynamometer**	**% Diff**
600	1	22.52	21.6	-4.13%
	2	25.48	25.4	-0.51%
	3	21.45	21.6	0.82%
575	1	42.30	41.0	-3.13%
	2	43.21	39.5	-9.34%
	3	45.18	45.5	0.68%
550	1	51.98	50.7	-2.50%
	2	51.01	51.5	0.87%
	3	53.55	54.4	1.62%
525	1	52.64	52.2	-0.84%
	2	53.30	52.9	-0.66%
	3	53.66	55.2	2.76%
500	1	52.40	52.9	1.02%
	2	50.07	50.0	-0.22%
	3	51.50	54.4	5.40%

Data collection for the calibration testing of the torque sensor was conducted using a National Instruments cRIO-9030 FPGA chassis, NI 9205 analog input module and an NI 9403 digital input module. The analog input module uses a 16-bit analog to digital converter that results in a resolution of less than one millivolt, capable of a sampling rate of 250 kS/s. The digital input module is capable of reading 32 digital channels with an update rate of seven microseconds. Using this combined hardware, the data from the torque sensor was recorded using LabVIEW at a sample rate of 1 Hz. A counter was used to keep a running total of the digital pulses, and raw analog voltages were stored into an excel sheet. To process the data, the number of digital pulses over five seconds was converted to RPM; the average voltage from the same five second period was also averaged and converted to a torque (in N-m) using Equation 2, provided by the sensor manufacturer.

$$T = (5 - V) * 600 \qquad (2)$$

Where T = Torque in newton-meters

V = Voltage from sensor.

$$P = \frac{T*\omega}{9549.296} \qquad (3)$$

where P = Power in kilowatts

T = Torque in newton-meters

ω = Rotational speed in rotations per minute.

The calculated torque was converted to power in kilowatts using Equation 3. The dynamometer displays power on a monitor; this value was recorded and later compared to the average power for each test trial. The standard deviations of each trial were considered to ensure that there were no large variations in sensor indicated power during each testing period, shown in Table 3.

Table 3-Standard Deviation during NCTE Sensor Calibration

RPM	Trial	Standard Deviation (kW)
600	1	0.64
	2	1.15
	3	1.08
575	1	0.35
	2	0.36
	3	0.84
550	1	1.50
	2	1.39
	3	0.82
525	1	1.10
	2	0.57
	3	0.61
500	1	0.75
	2	1.22
	3	0.86

Fuel Flow Meter

In addition to the PTO power, another important aspect to consider is the fuel consumption of the tractor. Accurate measurement of fuel consumption in real-time while performing tasks in the field could provide critical information on equipment/tractor selection. The fuel consumption data can also be compared with the PTO power data to deduce the most efficient applications and power range for a given tractor. To measure fuel consumption, AIC fuel flow meter (AIC 884, Automotive Information & Control Systems AG, Switzerland) was selected. The fuel flow meter is IP67 rated and measures differential fuel flow on engines up to 220 kW (300HP) including flow rates from 1 to 80 liters per hour. The flow meter outputs a digital pulse signal at 2000 pulses per liter (ppl) with a 0.7 ms pulse length. This output can be read by a third party data acquisition system.

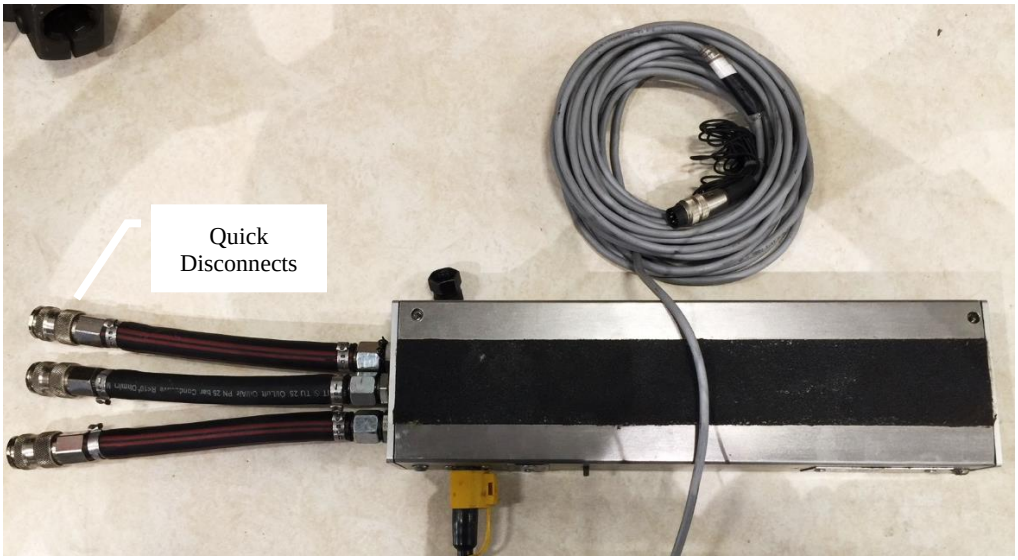


Figure 7-AIC Fuel Flow Meter with Quick Disconnects

Fuel Flow Meter Implementation

The fuel flow meter had to be directly mounted to the tractor close to the fuel filter and fuel injection pump. Using quick disconnects and proper fittings, the flow meter was installed in-line between the fuel tank and fuel filter (Figure 8). When initially connected, the tractor was ran with the return line removed for approximately two minutes to ensure that there would be no air pockets caught within the lines or flow meter. The AIC 884 comes with a filter built in, therefore it was not important that the flowmeter be installed after the fuel filter.

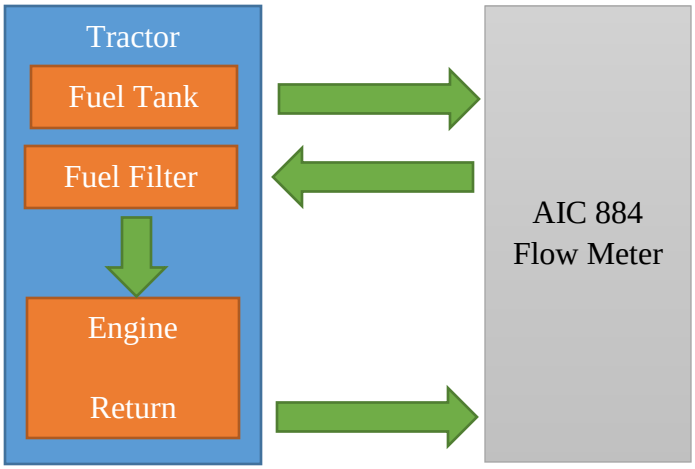


Figure 8-AIC fuel flow meter implementation diagram



Figure 9-Example views of the fuel flow meter installed on the tractor.

Fuel Flow Meter Calibration and Verification

The fuel flow meter was validated in the BAE department lab at Kansas State University using a fuel scale. The flow meter was installed on a test tractor in series with a fuel scale (Figure 9). The tractor was then operated at varying engine speed and power to simulate varying fuel consumption situations in the field. The tests ranged from idle engine speed with no load, to mid-throttle with high load, to high throttle with high load.

Data from the fuel flow meter was collected using a National Instruments (NI) cRIO-9030 FPGA chassis. The chassis was coupled with an NI 9403 digital input module capable of reading digital signals on 32 channels with a seven microsecond update rate. A simple counter was implemented using LabVIEW to keep a running total of the total digital pulses with an update frequency of 10 Hz. The data was analyzed and converted to a liter per hour value using Excel. The total number of pulses was divided by 2000 to obtain the total volume of fuel used, in liters; this value was then divided by the total elapsed time to calculate the average fuel consumption rate in liters per hour.

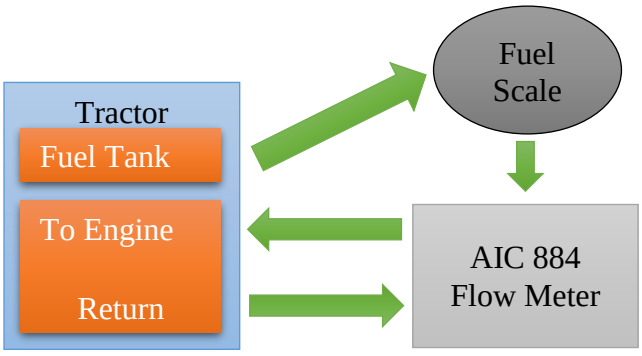


Figure 10-AIC Flow Meter Calibration Diagram



Figure 11-AIC Flow Meter Calibration Setup

To calculate the actual volume of fuel used, the mass of fuel used was found using the fuel scale. Prior to the testing process, the tractor was ran for 10 minutes at a moderate throttle to ensure that all fuel lines, including the return line, were full; this was done to eliminate the possibility for air pockets to cause errors in readings. For each test, the mass of the fuel in the scale was recorded before the engine was started; the final mass was recorded after shutting the engine off. This was done for two reasons: to ensure the readings from the flow meter and fuel scale were measuring the exact same fuel, and additionally to ensure that the vibrations from the running engine did not affect the mass reading. Results of the verification test for the AIC 884 flow meter are shown in Table 4.

Table 4-AIC Flow Meter Calibration

AIC	Fuel Scale	Compared	
L/h	L/h	L/h Diff	% Diff
0.78	1.37	0.59	75.9%
0.97	0.73	-0.24	-24.9%
1.94	2.16	0.22	11.3%
1.94	2.16	0.22	11.3%
3.99	4.21	0.22	5.5%
4.28	4.64	0.36	8.3%
6.08	6.38	0.31	5.0%
5.96	6.25	0.29	4.9%
5.60	6.18	0.58	10.3%
5.24	5.36	0.11	2.1%
6.29	6.36	0.07	1.2%
5.90	6.18	0.28	4.7%
7.67	8.25	0.59	7.6%
8.67	8.76	0.09	1.1%

As seen in the table, the AIC 884 flow meter consistently read below the true fuel consumption from the fuel scale. The data from the flow meter was plotted against the data from the fuel scale to find a trend (Figure 12) and the green line indicates a 1:1 correlation between the flow meter and fuel scale, which was the target for a calibrated sensor with zero error. The squares represent the actual data points, and the line is the line of best fit for the data. The equation for the line of best fit is shown; with an r-squared value of 0.992.

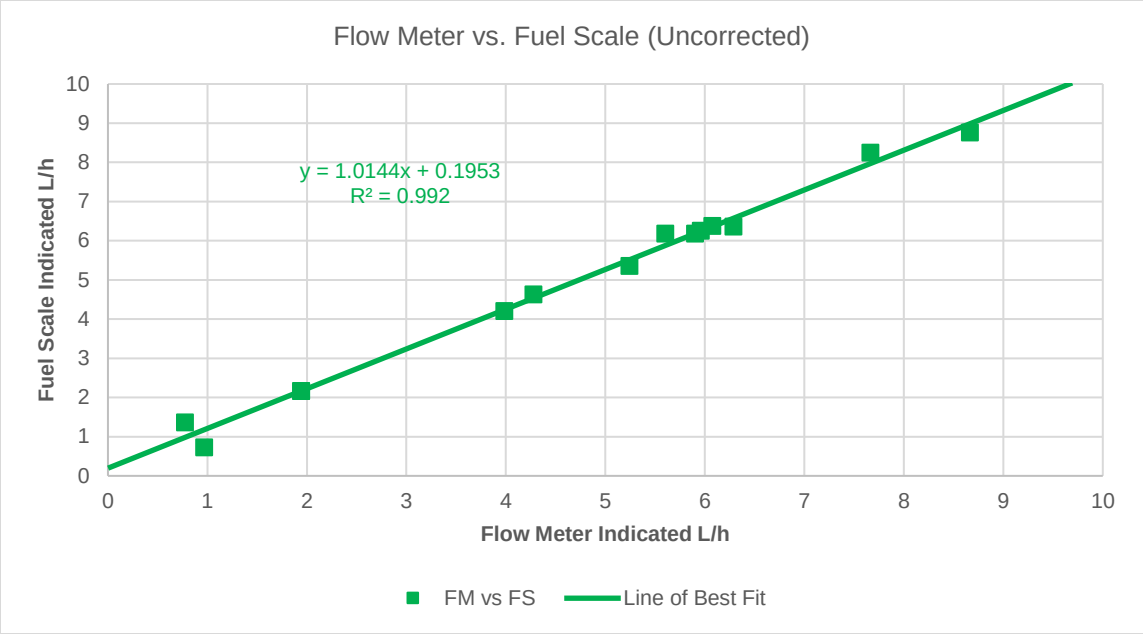


Figure 12-AIC Sensor Calibration Curve

The flow meter data from the calibration test was corrected using Equation 4:

$$CF = 1.0144IF + 0.1953 \qquad (4)$$

where CF = Corrected flow in liters per hour

IF = Indicated flow in liters per hour.

Additional tests were conducted with fuel flow meter to validate the accuracy of the regression function (Table 5). The results showed that average difference between the corrected flow meter values and the fuel scale values was 0.157 L/h, with an average percent difference of 7.11%. However, when the first two data points, or outliers, were removed, then provided an average fuel flow difference of 0.113 L/h and the two values were within 1.80%. The observations were deemed outliers due to the fact that the first two data points are at idle or low RPM with no load, a situation that will not be encountered during testing.

Table 5-AIC Sensor Data after Correction

Corrected Data			
AIC 884 (Corrected L/h)	**Fuel Scale (L/h)**	**L/h Difference**	**% Difference**
0.98	1.37	0.39	39.8%
1.18	0.73	-0.45	-38.1%
2.17	2.16	-0.01	-0.5%
2.17	2.16	-0.01	-0.5%
4.24	4.21	-0.03	-0.7%
4.54	4.64	0.10	2.2%
6.36	6.38	0.02	0.3%
6.24	6.25	0.01	0.2%
5.88	6.18	0.30	5.1%
5.52	5.36	-0.16	-2.9%
6.57	6.36	-0.21	-3.2%
6.18	6.18	0.00	0.0%
7.97	8.25	0.28	3.5%
8.99	8.76	-0.23	-2.6%
Average		**0.157**	**7.11%**
Average (excluding first two data points)		**0.113**	**1.80%**

GPS System

An accurate and mobile GPS system is needed in this study to ensure that correct positions, elevations and speeds are recorded. The GPS coordinates will allow the in-field data sets to be mapped along with the elevation and speed. Combining this information in analysis enables conclusions to be made about the effects of speed and terrain on machine performance parameters. A Topcon GPS system (GR-5, Topcon, Tokyo, Japan) was selected to be used in this research. The GR-5 was readily available within the BAE department at Kansas State University and provided all necessary data. The Topcon GR-5 is a survey grade differential real time kinematic (RTK) system that uses a base station and rover unit to accurately measure horizontal position with sub-inch precision in dynamic conditions. This GPS unit is also capable of outputting serial NMEA strings at the necessary frequency (10 Hz) that are easily integrated into the cRIO system.



Figure 13-Topcon GR-5 GPS System

Data Acquisition System

To collect all data simultaneously during field trials, a National Instruments cRIO-9030 chassis was used and programmed with NI LabVIEW. The cRIO-9030 chassis has an RS-232 port built-in that was used for reading the GR-5 NMEA strings. The DAQ and all additional components were contained within a toolbox fitted with connectors to prevent the ingress of moisture and dust into the system. In addition to the cRIO chassis and modules, the box contained the DL-4045 (Automotive Information & Control Systems AG, Switzerland) data logger module that powers the fuel flow meter and receives the signal from the fuel flow meter, which then outputs the digital signal to the NI 9403 module. The box receives power from a 12V power supply that was split to supply power to the cRIO, torque sensor and fuel flow meter data logger module. The system connects by USB directly to a laptop that runs the data acquisition program and saves the data. The LabVIEW program runs with a sampling frequency of 10 Hz and writes the information directly to a text file. The front panel of the program displays incoming data in real time to ensure that there are no errors during recording.

Field Testing

After calibration and validation of all sensors and software, the complete system was tested in-field on a haying operation. The torque sensor, flow meter and GPS components were installed on a Mahindra 8090 90 engine horsepower MFWD tractor. The tractor was first operated using a 4.9 m (16') cutting width New Holland H7460 (New Holland, New Holland, PA) mower conditioner, and then with a 1.22x1.83 m (4'x6') New Holland BR7070 (New Holland, New Holland, PA) round baler set to produce a 1.22x1.68 m bale. The ideal field structure would be comprised of an irregular shape, as well as varying elevation areas and varying crop loads. The testing was done over an area of approximately 6 hectares of crabgrass/wheat straw crop. In addition to the PTO, fuel and GPS data, each bale produced was marked in-field and weighed using a custom apparatus. The scale is composed of a system containing four Longacre wireless scales (Boonville, IN) and two plywood platforms, one to support the bottom of the scales and one for the bale to sit on top of; the unit as a whole has a maximum capacity of 2700 kg. The bale weight was used to plot mass uniformly across the baled pass to develop a relative crop density map across the test area. An aerial satellite view of the selected field can be seen below.



Figure 14-Testing Plot Aerial Image

Data Processing

Using the data from the in-field testing, the data was first analyzed for correlations in Excel, and then using ArcMap software to plot the crop density, elevation, speed and other characteristics. The incoming data included elapsed time, latitude and longitude, elevation, torque sensor voltage and total pulses, total fuel flow meter pulses, and GPS speed. During testing with the baler, bale number was also included. An example of the incoming raw data can be seen in Figure 15. The raw data was processed using Excel; the decimal coordinates were converted to degrees, and the NCTE and AIC sensor data was converted using a method similar to how it was done in the calibration process.

```
1  0.000000,3801.926750,9753.582100,458.838000, 4.881505,  1.000000,  2.000000, 0.000000,  0.000000
2  0.014001,  0.000000,  0.000000,  0.000000, 4.881833,  1.000000,  2.000000, 0.013359,  0.000000
3  0.201012,3801.926750,9753.582100,458.837000, 4.885444,  1.000000,  2.000000, 0.000000,  0.000000
4  0.214012,  0.000000,  0.000000,  0.000000, 4.870017,  1.000000,  2.000000, 0.028956,  0.000000
5  0.402023,3801.925720,9753.581100,463.179000, 4.879536,  1.000000,  2.000000, 0.000000,  0.000000
```

Figure 15-Sample raw data strings

For use in spatial analysis, a forage density map and elevation map were produced. The process for making the forage density map involved weighing and geotagging each bale produced; the weight of the bale was then evenly distributed amongst the data points that were collected while producing this bale. This weight data was then plotted using ArcMap to yield a map that shows the relative forage density across the test plot. The elevation map was produced similarly by using the GPS elevation points collected during testing. In addition to the two maps showing the external factors, the fuel consumption and PTO power performance characteristics were plotted by their GPS coordinates to show how they vary across the plot.

Results

The data acquisition system performed well during field trials to capture the aforementioned performance characteristics. The collected data was briefly analyzed and plotted to ensure that the developed system is viable for further testing in the future.

Tractor fuel consumption distribution broken down by PTO power and by time of operation at specific fuel consumption is shown in Figures 16 and 17, respectively. Using both of these graphs clearly shows that there is correlation between fuel consumption and PTO power. Furthermore, the conclusion can be made that the 90 HP tractor may be more suited for working with the baler, and is likely underpowered for operating the swather. This conclusion is made due to the fact that the tractor consistently operated at the highest fuel consumption ranges, whereas with the baler, the tractor operated more efficiently and spent much less time in the highest consumption range.

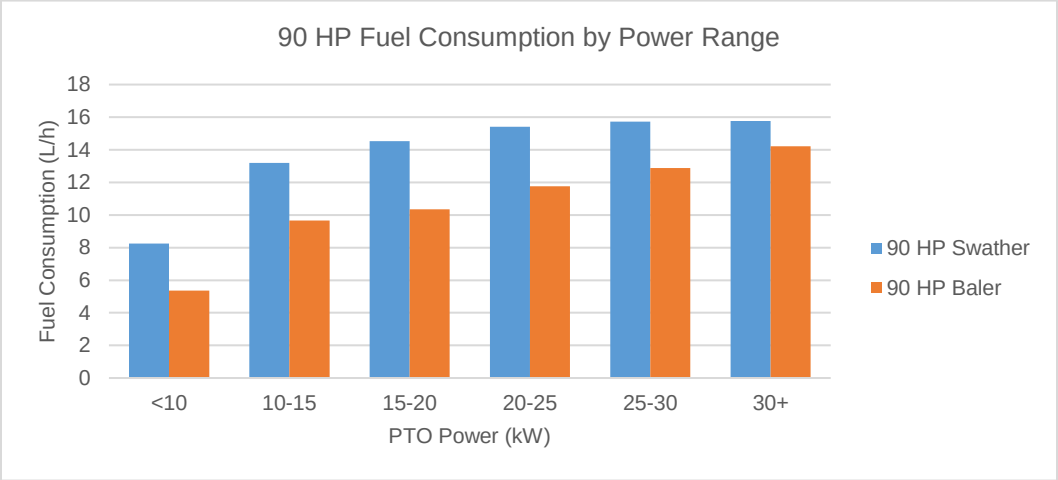


Figure 16-Test Tractor Fuel Consumption by Operating Power Range

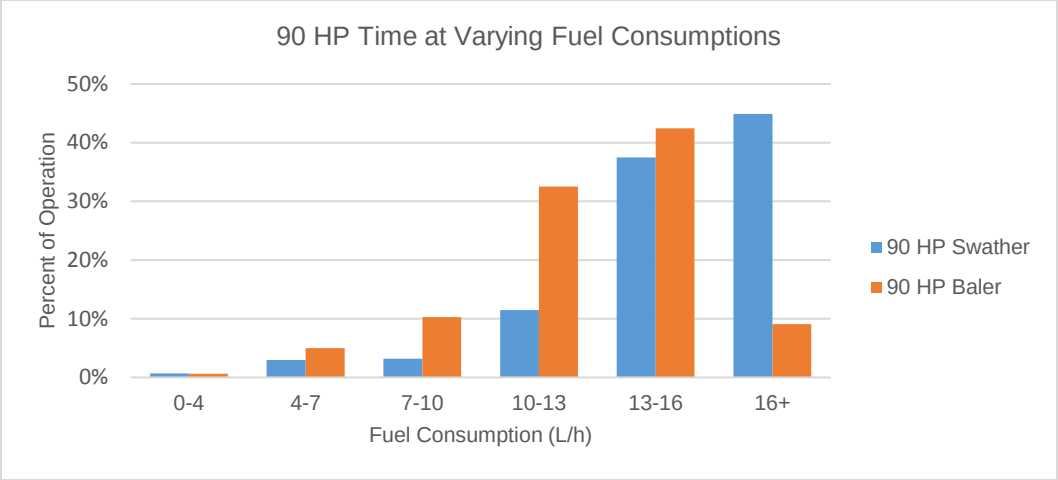


Figure 17-Test Tractor Time Spent at Varying Fuel Consumptions

Maps showing the elevation profile, relative forage density and performance characteristics of the machine in both operations are shown below in Figure 18 through Figure 22 . The maps produced for the swathing operation are missing data points due to an equipment malfunction unrelated to the DAQ system.

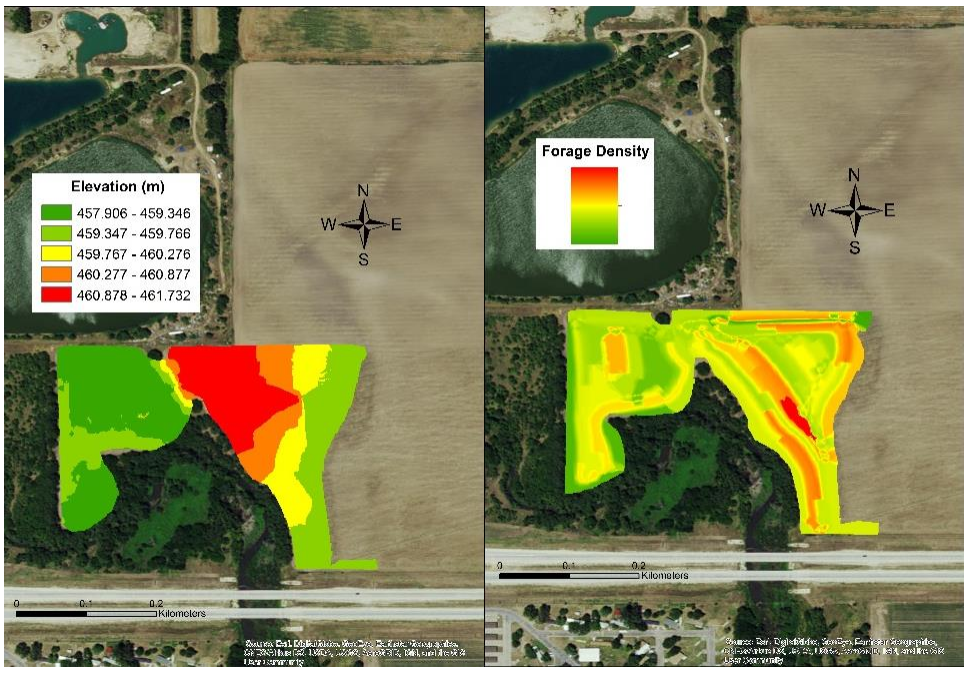


Figure 18-Test Plot Elevation and Forage Density Maps

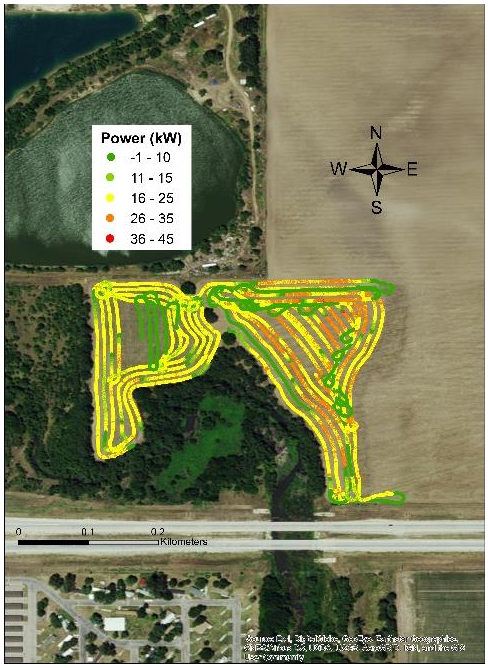


Figure 19-90 HP Baler Power Map

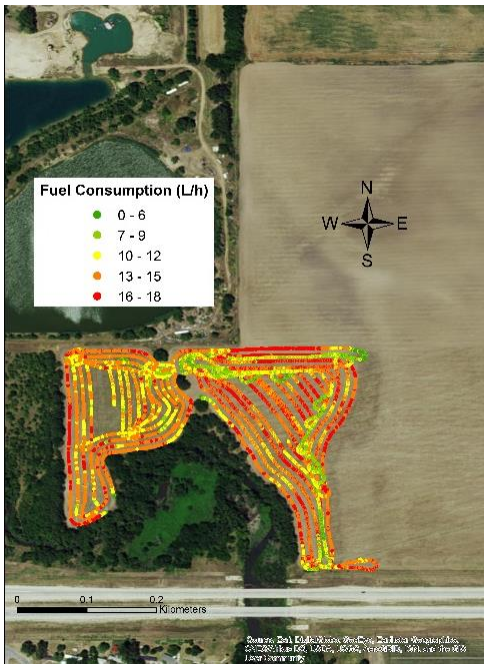


Figure 20-90 HP Baler Fuel Consumption Map

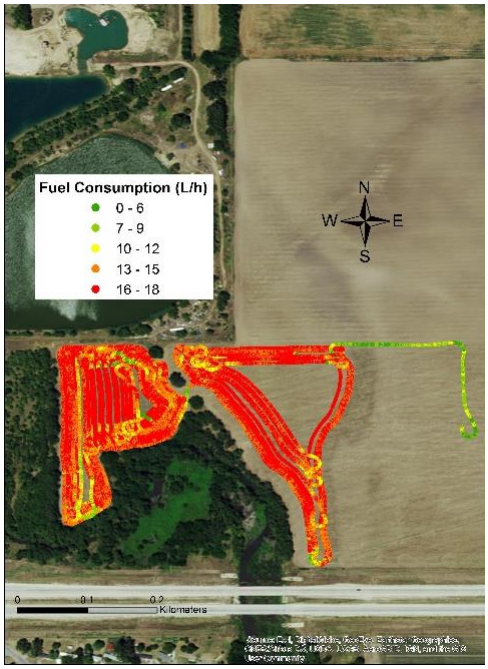


Figure 21-90 HP Swather Power Map

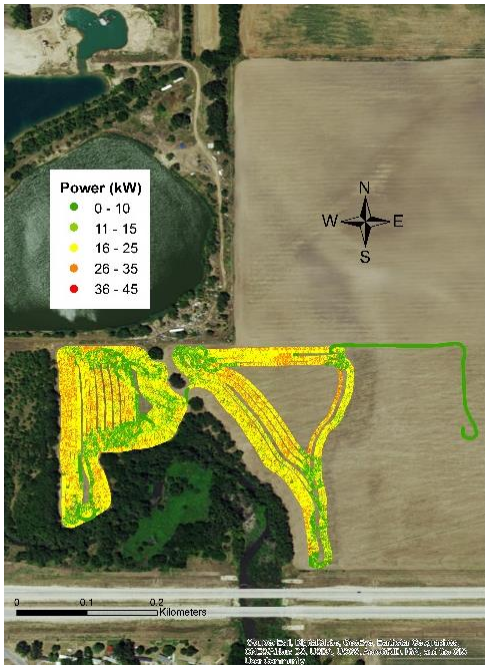


Figure 22-90 HP Swather Fuel Consumption Map

Using mapping software to display instantaneous characteristics can be valuable in assessing performance; it also provides a visual to aid in drawing conclusions about relationships between specific variables and performance. In addition, comparing the maps of performance characteristics to the terrain and forage density maps allows for assessment to be made regarding the effect of these external factors on tractor performance.

Conclusion

After calibrating and testing the separate components of the data acquisition system, as well as testing the system together, the results are satisfactory. The objective of the system was to provide meaningful and accurate data from tractors performing tasks in-field.

Future plans for modifications to the data acquisition include adding CAN parameters, tilt, drawbar force, and wheel slip. CAN parameters recorded will likely include flywheel torque, engine RPM, engine temperature and others such as oil pressure and fan speed. Real time tilt will be measured using an inclinometer to allow instantaneous grade to be recorded. Drawbar force and wheel slip will be implemented using strain gauges and encoders if testing is conducted on tillage equipment.

The next step in the testing process will be fitting this data acquisition system to different power tractors to compare their performance in similar applications. There are currently plans to test on four Mahindra tractors: 71 HP open station, 71 HP cabin, 90 HP cabin, and 100 HP cabin. These machines will be performing two primary operations in the hay and forage application: swathing and baling. Collecting data on these varying tractors will allow conclusions to be made about which power range is more suitable and efficient for different tasks.

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OECD. (2016). Code 2 OECD standard code for the official testing of agricultural and forestry tractor performance. Paris, France. Retrieved from http://oecd.org/tad/code/Code%202%20-%20Final.pdf

Roeber, J. BW., Pitla, S. K., Hoy, R. M., Luck, J. D., Kocher, M. F. (2017). Tractor Power Take-Off Torque Measurement and Data Acquisition System. *Appl. Eng. Agric.,* 33(5). https://doi.org/10.13031/aca.11994.

Chapter 3 – Evaluation of Real-Time Tractor Performance Data Collected During In-Field Operation

Abstract

Understanding and quantifying specific tractor performance characteristics while performing tasks in-field is a new and valuable asset. The performance knowledge can be used to assess potential machine efficiencies when coupled with varying implements. Implementing the data acquisition system developed in the first part of this research allowed for real time power take-off power, fuel consumption and position data to be recorded and analyzed. Adding topography and forage density features yielded information that enabled spatial analysis to be performed giving the opportunity to evaluate the effects of these factors on performance. However, there is very little information available on collection real-time performance data and value of learning for users and manufacturers. Therefore, this study was designed with two primary goals; 1) evaluate comparative performance of two similarly sized higher horsepower machines, and two similar sized lower horsepower machines; and 2) compare and contrast the performance of different machines to understand relative advantages for user adoption. Two tractors, a 90 HP and 100 HP (higher horsepower), were utilized in a swathing and baling operation on the same plot of alfalfa in sequential cuts. The two 71 tractors (lower horsepower), an open station and the other a cabin tractor, were evaluated when swathing alfalfa.

Data acquired from the higher horsepower testing proved valuable in evaluating the performance of each tractor individually. Strong correlation between power take-off (PTO) power, speed and fuel consumption was identified.

A single equation was developed that is capable of accurately quantifying over 75% of instantaneous fuel consumption values within 10% error in both higher horsepower tractors in the swathing operation using the PTO power and operation speed. The power-to-fuel consumption ratio derived during the performance evaluation exhibited the effects of under powering an implement showing that 90 HP tractor performed much less efficiently than the 100 HP. Tractor real-time data allowed for the analysis and quantification of tractor performance, proving to be a viable method to assist in machine selection for specific operations. Selecting the appropriately sized implement and tractor given a certain operation could allow for a higher field efficiency in both operating speed and fuel consumption.

Introduction

Tractor testing that involves power take-off power and fuel consumption evaluation is primarily practiced in static or controlled environments, not taking into account the effects of external factors such as terrain and forage density. Transitioning this testing to a dynamic environment could yield data sets that can be used to gain knowledge regarding the relationship between specific implements and tractors. Comparing tractors using said data would also allow conclusions to be made concerning proper implement/tractor pairing for the most efficient operation.

Prior to the start of this part of the research, a data acquisition system was developed to allow for real-time collection of instantaneous tractor performance characteristics while performing tasks in-field. The development of this system included sensor research and selection, lab calibration and field trial for validation. The specifics of the system are described in Chapter 2. Manufacturers and producers currently do not have information from this aspect; making this style of testing readily available will benefit both parties. Tractor manufacturers can identify specific markets and operations and use the data to provide a better option to the customer. Producers benefit by being able to choose a properly sized tractor that will yield the most efficient practices, thus providing a more economic option.

However, no institute or data base provides information on tractor-implement performance from field-based environments where such systems are designed to operate. Therefore, this study was designed with two primary goals; 1) evaluate comparative performance of two similarly sized higher horsepower tractors, and two similar sized lower horsepower tractors; and 2) compare and contrast the performance of different tractors to understand relative advantages for user adoption.

The primary goal of this research is to use statistical analysis of data collected by the previously developed system to evaluate two sets of tractors. First, two closely sized higher horsepower tractors are equipped with the data acquisition system and tested using identical implements. The data from this testing is used to define the relationship between power take-off power, fuel consumption and operating speed on the tractors individually with the varying implements. Analysis of the data to compare the two different tractors is then done to assess the effect of under powering or overpowering a specific implement on field efficiency, primarily fuel consumption. In addition, spatial analysis is performed to gain a visual understanding of the effects of topography and forage density on efficiency. Second, two lower horsepower tractors of the same size are equipped with the system in an effort to define the efficiency implications of three factors: cabin versus open station, operating speed and a 540 economy power-take off mode.

Methodology

The evaluation of the performance characteristics to compare the two sets of tractors involved three main parts that include external factors, data collection, and data processing. External factors detail the plot and equipment selection, data collection summarizes the system developed in prior research, and data processing highlights the post processing methods implemented to the raw data. All testing was conducted in 2018.

Tractor and Machinery for Performance Evaluation

To conduct the field studies, two pairs of tractors were tested against each other. A 67 kW (90 HP) and 75 kW (100 HP) tractor, henceforth referred as higher horsepower (HP) tractors, and two 53 kW (71 HP) tractors, one open station and one with cab, henceforth referred as lower horsepower tractors, were compared on selected performance parameters.

Higher Horsepower

The primary goal of the higher horsepower comparison was to evaluate the efficiencies of the two similarly sized tractors while using the same implements in the same field.
Tractors selected for this comparison testing included two Mahindra & Mahindra MFWD tractors; a model 8090 and a model 8100, rated at 67 kW (90 HP) and 75 kW (100 HP) respectively. Both tractors were identical in all aspects apart from the power produced.

The topographical profile of the field was an important aspect, as the effects of the varying terrain were to be considered. Therefore, a large enough plot to acquire a sufficient amount of data for thorough evaluation of performance was required. To satisfy these requirements, a 23 acre plot of alfalfa was selected in Clay County, KS; the selected plot had irregularly shaped field boundary and terraced with an elevation variation of approximately nine meters (Figure 24). The highlighted section of test plot with the elevation data shows the portion of the field that was swathed and baled.



Figure 23-Alfalfa Plot for Higher HP Testing

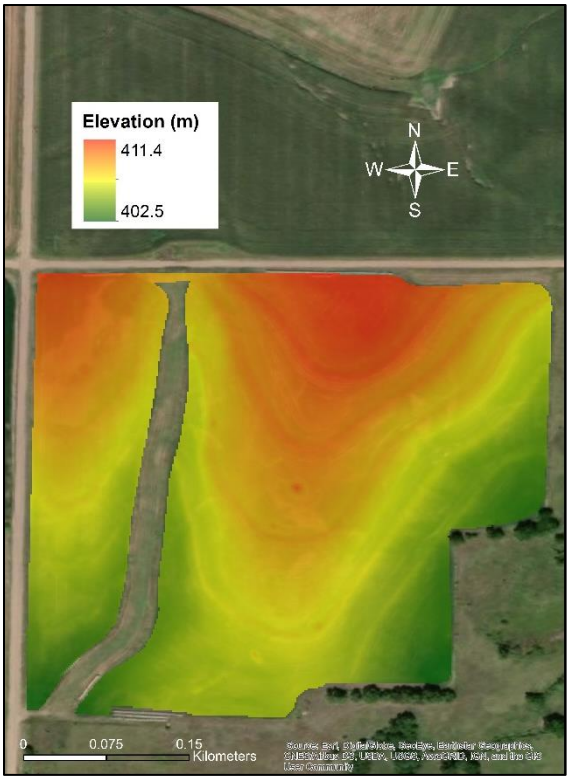


Figure 24-Elevation Plot of Higher HP Field

Tractor performance data collected on sequential cuts on the selected field higher horsepower testing was completed in July and August of 2018.

Equipment selection was done based upon the input of the producer and the availability of the equipment. For the swathing operation, a John Deere 956 MoCo hydroswing mower-conditioner was used (Figure 25); the cutting width is 4.42 m (14.5’). John Deere specifies a required power of 75 kW (100 HP) at 1000 PTO RPM; however after analyzing the performance prior to data acquisition it was decided that for the given application that the implement would perform adequately on the slightly lower powered tractors. The round baler used was a John Deere 569 Premium (Figure 26); the minimum HP requirement for this baler is 56 kW (75 HP) at 1000 RPM. For this testing, a round bale with a width and diameter of 1.52 m (5’) and 157 cm (62”), respectively, was used; the bales were net wrapped.



Figure 25-John Deere 956 Mower Conditioner



Figure 26-John Deere 569 Premium Round Baler

Lower Horsepower

The evaluation of the two lower horsepower tractors is intended to discover and define the field efficiency effects of a cab versus open station tractor, a 540E drivetrain versus a standard 540 drivetrain, and swathing speed. To accomplish these tasks, PTO power, fuel consumption and operating speed are analyzed. The two tractors evaluated in this testing were both Mahindra & Mahindra 6075 MFWD tractors; both rated at 71 HP, one was an open station and one was a cabin tractor. Given the stipulations, the lower horsepower tractors were tested in swathing alfalfa.

The focusing was more on the effects of the tractors themselves, therefore field selection played a lesser role in this evaluation. Data was collected on similar portions of the same alfalfa plot on the same day. Based on visual evaluation and the output of the field, the forage density was assumed to be consistent; thus the effect of variation on the performance of the tractors was disregarded. In addition, terrain was disregarded, as the selected plot was relatively flat. These conditions were ideal as it allowed the performance variations to be evaluated without the forage density and terrain affecting the data. Both tractors were paired with the same swather.

The swather chosen was a Vermeer TM800 trailed mower (Figure 27); the TM800 has a cutting width of 3.2 m (10.5') and a required minimum power of 48 kW (65 HP).



Figure 27-Vermeer TM800 Mower

Performance data for the two lower horsepower tractors was evaluated by cutting approximately one acre of alfalfa using two speeds and two PTO delivery selections (**Error! Reference source not found.**). There are two PTO delivery options: 540 and 540E; 540 is the standard, which used an engine RPM of 2100, whereas the 540E, or economy, mode uses a lower engine RPM of 1500 in an effort to increase efficiency.

Table 6-Lower Horsepower Testing Configurations

Tractor	Speed (MPH)	PTO Selection
71 HP Cabin	4	540
		540E
	6	540
		540E
71 HP Open Station	4	540
		540E
	6	540
		540E

Data Collection

Data collection for the evaluation of the tractors was accomplished by implementing the data acquisition (DAQ) system developed during the first part of this research in Chapter 2. e Hardware contained in the data acquisition system includes a power take-off (PTO) sensor (Series 7000, NCTE AG, Germany), fuel flow meter (884 Instructor, AIC Systems, Switzerland), and a GPS system (GR5, Topcon Positioning Systems, Japan). The PTO sensor measures both the speed and the torque delivered through the PTO shaft, the flow meter is a differential fuel flow meter that measures instantaneous fuel consumption, and the GPS is a differential RTK GPS system that yields sub-inch accuracy. The PTO sensor and fuel flow meter were both calibrated in a lab setting at Kansas State University; details regarding the procedure and results of this validation can be found in Chapter 2.

The PTO sensor was mounted to the tractor using a clamping system developed previously to eliminate vibration, described in Chapter 2; the flow meter was strapped to the frame of the tractor and measured the fuel consumption in-line between the fuel filter and fuel injection pump, and the GPS mounted using the available mount on top of the tractor. To account for the additional length in the PTO shaft due to the sensor, a drawbar and three point extension were developed. All signals were wired to a National Instruments cRIO-9030 chassis equipped with the necessary modules. The cRIO was housed in a weather-resistant box and mounted directly to the tractor. During testing, incoming data was monitored using a laptop mounted at the operator's station. The system as a whole was tested and validated in the first part of this research (Chapter 2) and yielded viable results.

Software

National Instruments LabVIEW 2017 was used to write the software to run on the cRIO to read and record the incoming data stream. The programming is broken down into two subprograms: 1) the FPGA that executes on the cRIO chassis and 2) the host VI that runs on the laptop. The FPGA VI consists of raw sensor signal read operations and runs at a high frequency; shift registers are used to keep a running total of the digital pulses output by the PTO sensor and the flow meter. The host VI was developed to process the NMEA strings from the GPS, control sampling rate, store data, and display live data. The NMEA strings from the GPS that were used include GPGGA to record latitude, longitude and elevation; and GNVTG to record travel speed. Sample NMEA strings are listed:

$GPGGA,172814.0,3723.46587704,N,12202.26957864,W,2,6,1.2,18.893,M,-25.669,M,2.0,0031*4F

$GPVTG,,T,,M,0.00,N,4.57298,K*4E

The highlighted values indicate the values of interest. The GGA string values latitude, longitude and elevation; the VTG value is speed. These four values were parsed by indexing the 0^{th} value ($GPXXX) and passing the value to a case structure to decide what further action should be taken. Within the case structure, the values of interest are parsed using the appropriate indexing value; subsequently the values are passed into an array as doubles. Additionally, within the case structure the speed (in km/h) is converted to mph. The elapsed time and raw data from the PTO sensor and fuel flow meter is sent directly to the same array as the GPS data. In addition to the data from the sensors, a control was added to allow the bale number to be saved to allow for the plotting of relative forage density (explained in the data processing section below). A summary table of the array inputs can be seen below.

Table 7-LabVIEW Array Data Description

Data Type	Description
Double	Elapsed Time (s)
16-Bit Integer	Running Total of PTO Speed Pulses
16-Bit Integer	Running Total of Flow Meter Pulses
Fixed Point	PTO Torque Analog Value (0-10 V)
Double	Latitude
Double	Longitude
Double	Altitude
Double	Speed
Double	Bale Number

The data that is combined into the array is then passed into a queue and sent to a while loop, or consumer loop. A producer/consumer style VI using a queue was selected to ensure that there would be no data loss. Within the while loop the data from the array is converted to a string; using this operation the values are formatted to hold seven decimals of precision to ensure the most precise GPS information is obtained. The string is then wrote to a .txt file and saved to the on-board laptop. A sample of the text file output by the VI is shown in Figure 28.

```
1   0.000000, 51.000000, 12.000000,  5.183478,3932.305438,9709.752830,407.879000,  0.000000,  8.000000
2   0.099812, 53.000000, 12.000000,  5.107328,  0.000000,  0.000000,  0.000000,  0.028894,  8.000000
3   0.199606, 54.000000, 13.000000,  5.133915,3932.305438,9709.752820,407.875000,  0.000000,  8.000000
4   0.299664, 56.000000, 13.000000,  5.136541,  0.000000,  0.000000,  0.000000,  0.026160,  8.000000
5   0.400408, 57.000000, 13.000000,  5.171662,3932.305438,9709.752820,407.882000,  0.000000,  8.000000
```

Figure 28-Text File Example

Timing of the data acquisition is accomplished by using a timed loop for the producer loop. The sampling rate was set at 10 Hz to ensure that there would be a sufficient amount of data to sum the digital pulse signals over a period while maintaining enough resulting data to analyze rapid changes.

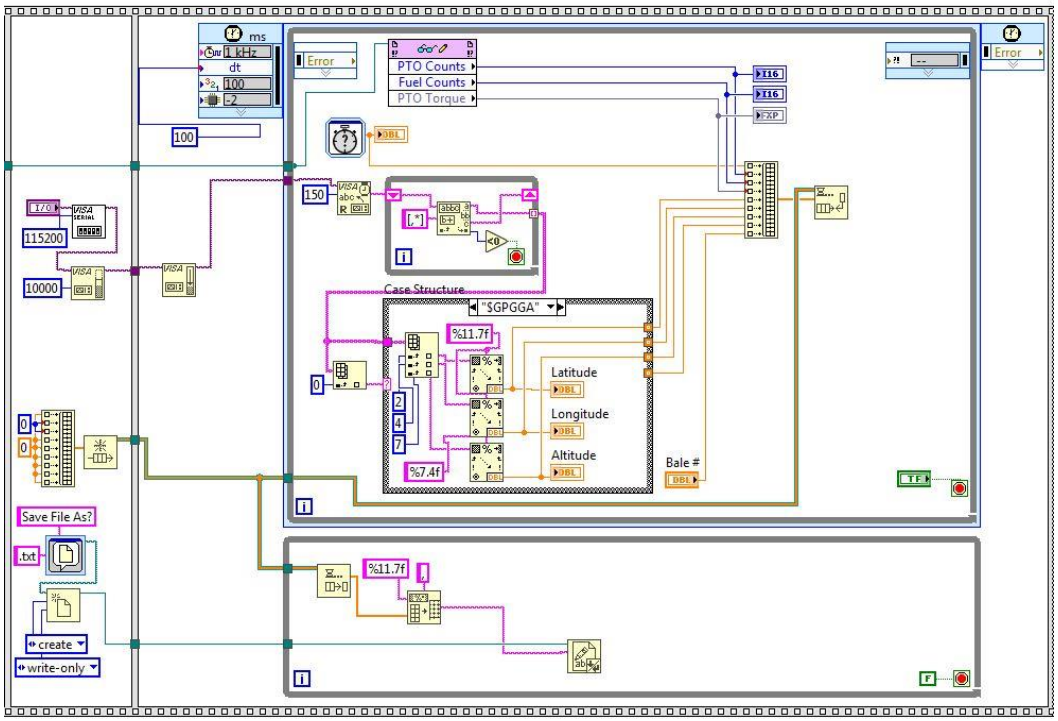


Figure 29-Host VI

Data Processing

The four parts of the data to be processed included the data from the PTO sensor, flow meter, GPS and the bale weight distribution. The text files were imported into Excel for processing. PTO sensor data contains the speed signal that was saved a summation of the pulses, and the the analog voltage that indicates the torque passing through the sensor. To convert the summation of pulses to a speed (RPM), the change in the number of pulses was divided by the change in elapsed time, and then multiplied by 60; this is shown in Equation 5. A Δt of approximately one second was used.

$$RPM = \frac{P_{t_f} - P_{t_i}}{t_f - t_i} \qquad (5)$$

where $RPM = PTO\ RPM$

$P = Total\ Pulses$

$t_f = Final\ Time$

$t_i = Initial\ Time$

Converting the analog voltage from the sensor to a torque value was based on an equation derived from the voltage and torque range of the sensor (Equation 2). Power was derived from the torque and speed using Equation 3, and then corrected using the correction factor developed during the calibration of the sensor in Chapter 2 (Equation 1).

$$T = (5 - V) * 600 \qquad (2)$$

where T = Torque in newton-meters

V = Voltage from sensor.

$$P = \frac{T * \omega}{9549.296} \qquad (3)$$

where P = Power in kilowatts

T = Torque in newton-meters

ω = Rotational speed in rotations per minute.

$$CP = 1.3014 * IP \qquad (1)$$

where CP = Corrected power in kW

RP = Raw power in kW.

The fuel flow meter data is recorded identically to the PTO pulses: a running summation of the pulses. Given the information that the sensor outputs 2000 pulses per liter, the following equation was derived to convert the raw data to a flow rate in liters per hour (L/h) (Equation 6).

A Δt of approximately one second was used. Similarly to the PTO sensor, a correction factor was developed through calibration outlined in Chapter 2. Equation 4 corrects the indicated flow.

$$F = \frac{P_{t_f} - P_{t_i}}{t_f - t_i} x \frac{3600}{2000} \qquad (6)$$

where $F = Flow\ (^{L}/_{h})$

$P = Total\ Pulses$

$t_f = Final\ Time$

$t_i = Initial\ Time$

$$CF = 1.0144IF + 0.1953 \qquad (4)$$

where CF = Corrected flow in liters per hour

IF = Indicated flow in liters per hour.

When recording the GPS data using the method described in the previous section, the GGA and VTG strings alternate with every loop; due to this, every other time stamp contains no data for one of the two datasets (latitude/longitude/altitude or speed). To correct this, a simple formula was implemented that averages the two values on either side of the blank row; the high sampling rate and relatively low operation speeds allows this to be done without compromising the data. The GPS strings recorded directly from the GR5 unit are in a DMS format; these values were converted to decimal format using a premade Excel spreadsheet.

Forage Density Mapping

For evaluating the higher horsepower tractors, a relative forage density map is necessary to identify the effect of variations across a plot on the performance of the machine. To accomplish this, each bale produced was geotagged and weighed. Using Excel, the mass of each bale was distributed evenly to each data point that was recorded during the making of the bale.

For example, if bale #5 data contains 5,000 data points and the bale weighed 1,500 lbs., each of the 5,000 points was assigned 0.3 lbs. This column of weights was used to produce a forage density map using ArcMap, explained below.

ArcMap GIS software was used to plot performance characteristics from the higher horsepower testing to allow for spatial analysis. For both the swathing and baling applications, three maps were produce: power, fuel consumption and speed. The XY coordinates for each of these maps was plotted using the latitude and longitude. The symbology feature provided a method to color code each point by a third value. The scales that define the color of the point were chosen to ensure that changes in the selected parameter could easily be seen on the map. However, maps of the same parameter and operation are identical; different scales would not allow for direct comparison.

In addition to the maps plotted with performance characteristics, an elevation and forage density map were produced to compare with the performance characteristics. The elevation map was produced using the built-in tool in ArcMap and elevation data from multiple cuts to ensure an accurate result. The forage density map used the IDW interpolation method and the weight distribution points described in the previous section. With the maps produced using ArcMap, spikes or valleys in performance characteristics can be evaluated to allow for a better understanding of the effects of terrain and forage density on tractor performance.

Results and Data Analysis

Higher horsepower and lower horsepower analysis was performed separately, as the intended goals for each of the two are different.

Higher Horsepower

First, each tractor's performance will be gauged and then the two will be compared. For all further analysis, only data that was recorded with a PTO speed of greater than 700 RPM will be considered. Eliminating PTO speeds of less than 700 RPM ensures that performance during implement operation is not skewed by idle time or no load situations.

Performance

The percent of time that the tractor operated in the given PTO power range for the 100 HP tractor in both swathing and baling applications is shown in (**Error! Reference source not found.**). The performance data showed that both swather and baler utilized an average of 22.7 and 16.72 kW of PTO power; and average of 16.33 L/h and 11.99 L/h fuel consumption respectively. The data also indicated that in both operations and both operational characteristics, the tractor operated for at least 57% of the time in ± 25% of the mean PTO power utilized (Figure 30) and fuel consumption (Figure 31). Much stronger but similar results were observed for fuel consumption for both baler (Figure 31) and swather. Looking at the PTO power values, in both operations the power utilization in the 25% of the peak value was less than one percent of the time. These results suggested that although the peak power requirement was very high compared to average but peak power utilization was for a negligible amount of time. Overall, it could be concluded that assumption might be made around mean power to characterize the necessary power. The top 50%, 25% and 10% values are based upon the maximum PTO power/fuel consumption seen during that specific operation.

Table 8-100 HP Data Summary

Characteristic	Statistic	Swather		Baler	
		Value	% of Operation	Value	% of Operation
PTO Power (kW)	Mean	22.68	N/A	16.72	N/A
	Peak	93.89	N/A	41.20	N/A
	Top 50%	46.95	0.09%	20.60	29.84%
	Top 25 %	70.42	0.002%	30.90	0.37%
	Top 10%	84.50	0.001%	37.08	0.01%
	+/- 25% Mean	17.01/28.35	57.26%	12.54/20.90	58.74%
Fuel Consumption (L/h)	Mean	16.33	N/A	11.99	N/A
	Peak	23.68	N/A	19.80	N/A
	Top 50%	11.84	98.43%	9.90	75.33%
	Top 25 %	17.76	10.18%	14.85	12.51%
	Top 10%	21.32	0.08%	17.82	0.11%
	+/- 25% Mean	12.25/20.42	97.9%	8.99/14.98	67.62%

The PTO power and fuel consumption points for the 100 HP baling operation are plotted below in Figure 30 and Figure 31; the black lines represent the mean and the 25% range on either side of the mean.

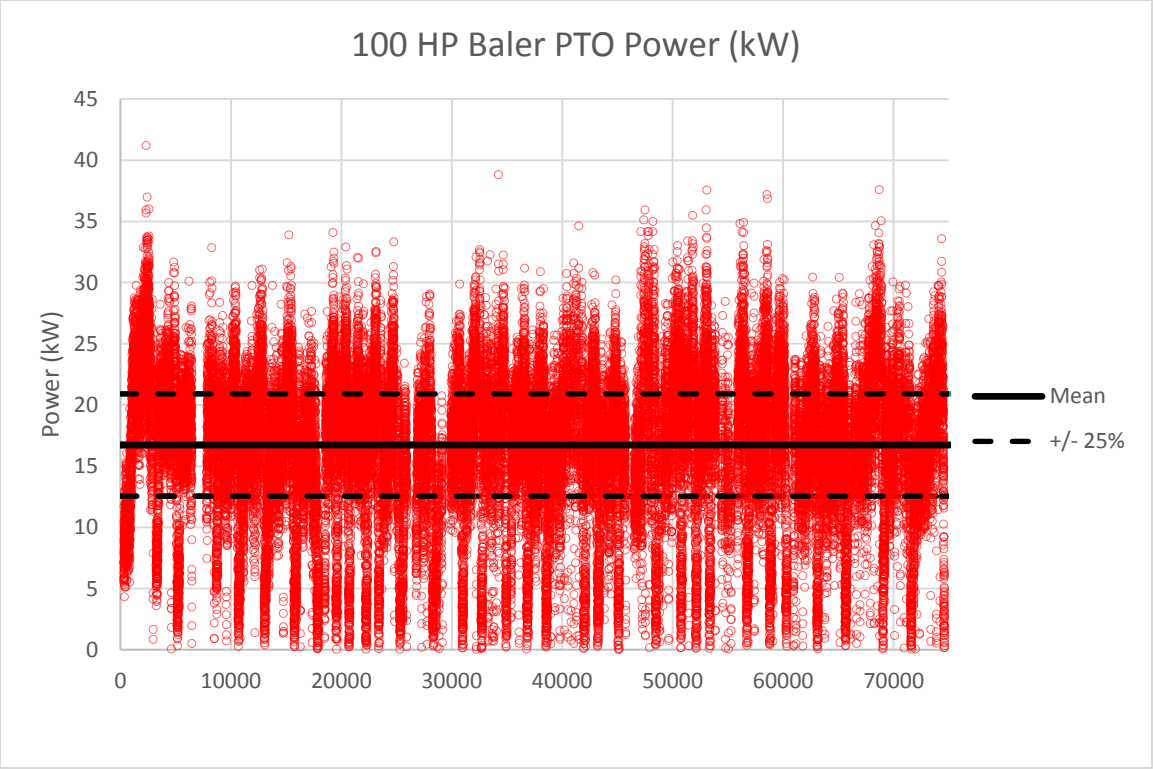


Figure 30-100 HP Baler Power Plot

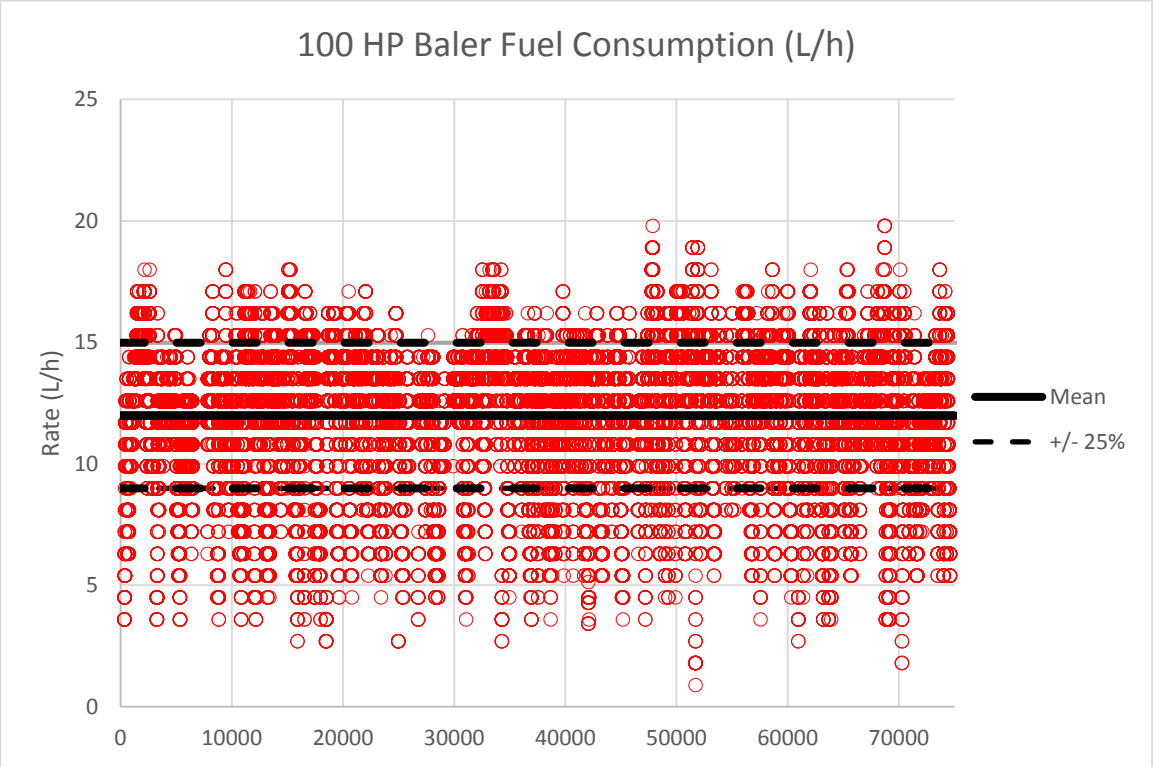


Figure 31-100 HP Baler Fuel Consumption Plot

A visual inspection of the plots of the PTO power and fuel consumption shows a definitive correlation between the peaks and valleys of the data. However, a linear regression model of the fuel consumption vs. PTO power yielded an R-squared value of 0.357 which was insufficient. Understanding that speed would have an effect on the fuel consumption, further statistical processing was done using R. A multiplicative linear regression model was tested and yielded an equation that defines the relationship between speed, PTO power and fuel consumption. The resulting equation predicted the fuel consumption of the tractor 54.2% of the time with less than 10% error, and 71.5% of the time with less than 25% error. Equation 7 defines the relationship and yielded an R-squared value of 0.5783.

$$FC = 0.2183217P + 0.5417799S - 0.0071553PS + 5.5466554 \quad (7)$$

where $FC = Fuel\ Consumption\ (L/h)$

$P = PTO\ Power\ (kW)$

$S = Speed\ (MPH)$

Looking at the plots (Figure 32 & Figure 33) it is clear that the relationship between power and fuel consumption applies in the swathing operation as well. Attempting to use the same equation on the data from the 100 HP baling operation yielded subpar results. This is likely due to the fact that the swathing operation produces a much higher drawbar load, thus the speed of the machine and terrain have a greater effects on the fuel consumption. Processing the swathing data in R returned a new equation that predicted the fuel consumption within 10% 77.1% of the time and within 25% 98.2% of the time (Equation 8). The results highlighted that although the considered factors provided a model to estimate fuel consumption fairly accurately, other data points such as drawbar load and engine RPM must be considered to increase robustness and accuracy.

$$FC = 0.1926780P + 1.1181157S - 0.0281747PS + 9.6065559 \quad (8)$$

where $FC = Fuel\ Consumption\ (L/h)$

$P = PTO\ Power\ (kW)$

$S = Speed\ (MPH)$

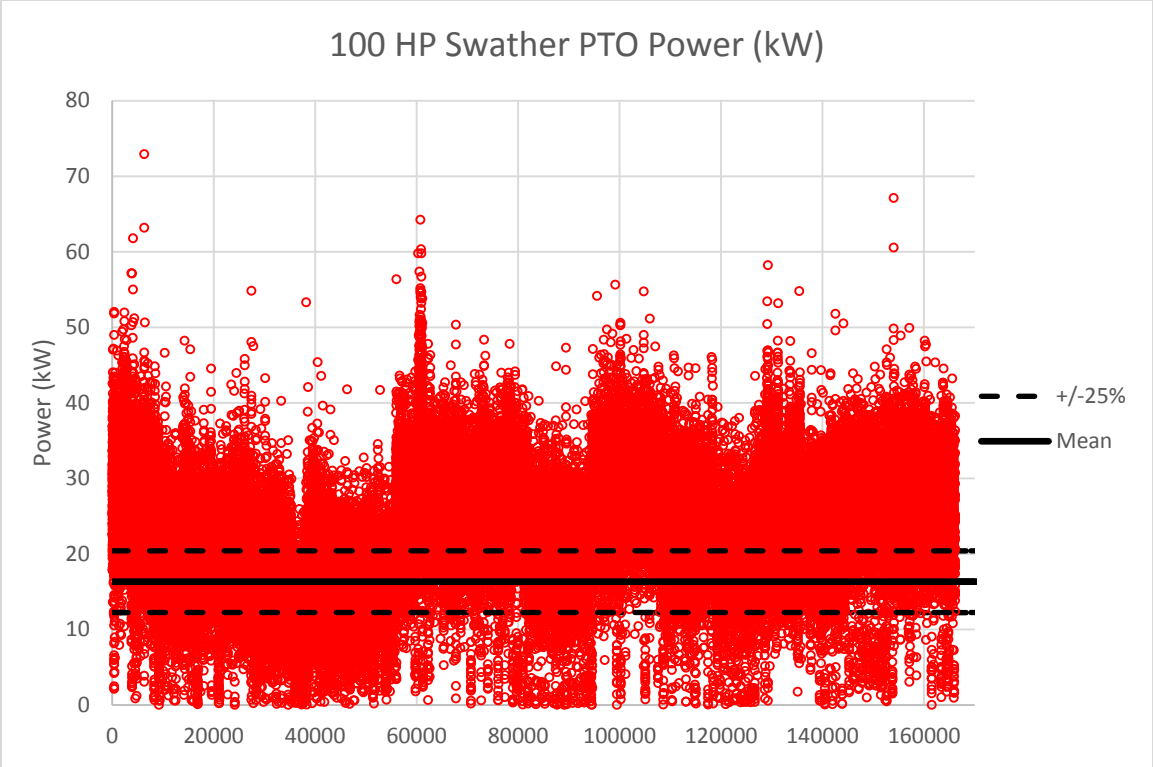


Figure 32-100 HP Swather Power Plot

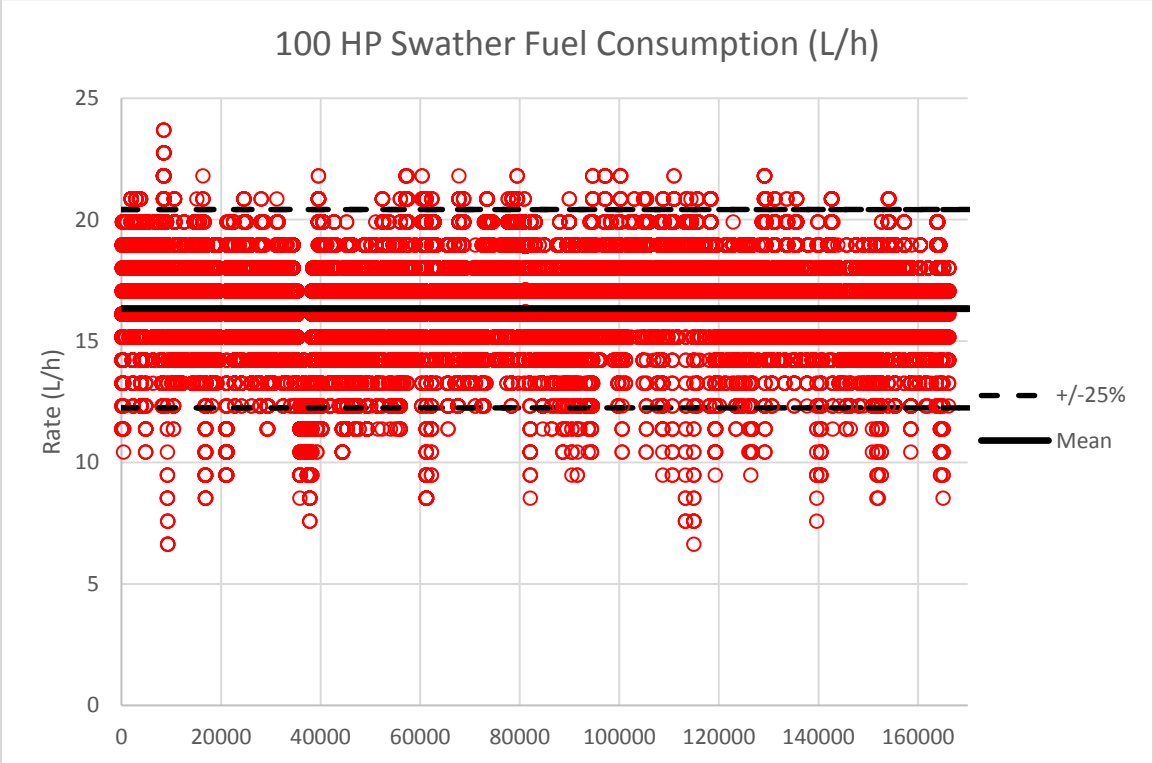


Figure 33-100 HP Swather Fuel Consumption Plot

Analysis of the same performance characteristics from the 90 HP testing was performed. Similarly to the 100 HP, the 90 HP machine operated within the ±25% of the mean values for PTO power and fuel consumption for at least 50% of the time (Table 9). Again, in both operations, the PTO power and fuel consumption values fall within this range over 50% of the time. Power and fuel consumption fall within the top 10% of values less than one-half percent of the time, and less than one percent of power values fall in the top 50%.

Table 9-90 HP Data Summary

Characteristic	Statistic	Swather		Baler	
		Value	% of Operation	Value	% of Operation
PTO Power (kW)	Mean	19.42	N/A	18.39	N/A
	Peak	70.17	N/A	71.66	N/A
	+/- 25% Mean	14.56/24.27	50.62%	13.79/22.99	58.74%
Fuel Consumption (L/h)	Mean	15.96	N/A	14.44	N/A
	Peak	34.25	N/A	21.62	N/A
	+/- 25% Mean	11.97/19.95	98.12%	10.83/18.06	67.62%

Based on the plots below of the power and fuel consumption of the baling and swathing operations tested on the 90 HP, the same conclusions can be drawn regarding a potential relationship between power and fuel consumption. Applying Equation 7 to the 90 HP baling data shows that 12.2% and 44.1% of fuel consumption data can be predicted within 10% and 25%, respectively. However, when a new linear regression is performed on the 90 HP baler data, Equation 9 is developed that predicts 62.9% and 92.8% of the fuel consumption rates within 10% and 25% respectively.

$$FC = 0.2380333P + 1.1061125S - 0.0299112PS + 7.6956555 \quad (9)$$

where $FC = Fuel\ Consumption\ (L/h)$

$P = PTO\ Power\ (kW)$

$S = Speed\ (MPH)$

Similarly to the 90 HP baling data, the equation previously developed from the 100 HP swathing data (Equation 8) was applied to the swathing data from the testing of this tractor. The results show that 77.6% and 98.2% of the fuel consumption points are predicted within 10% and 25%, respectively.

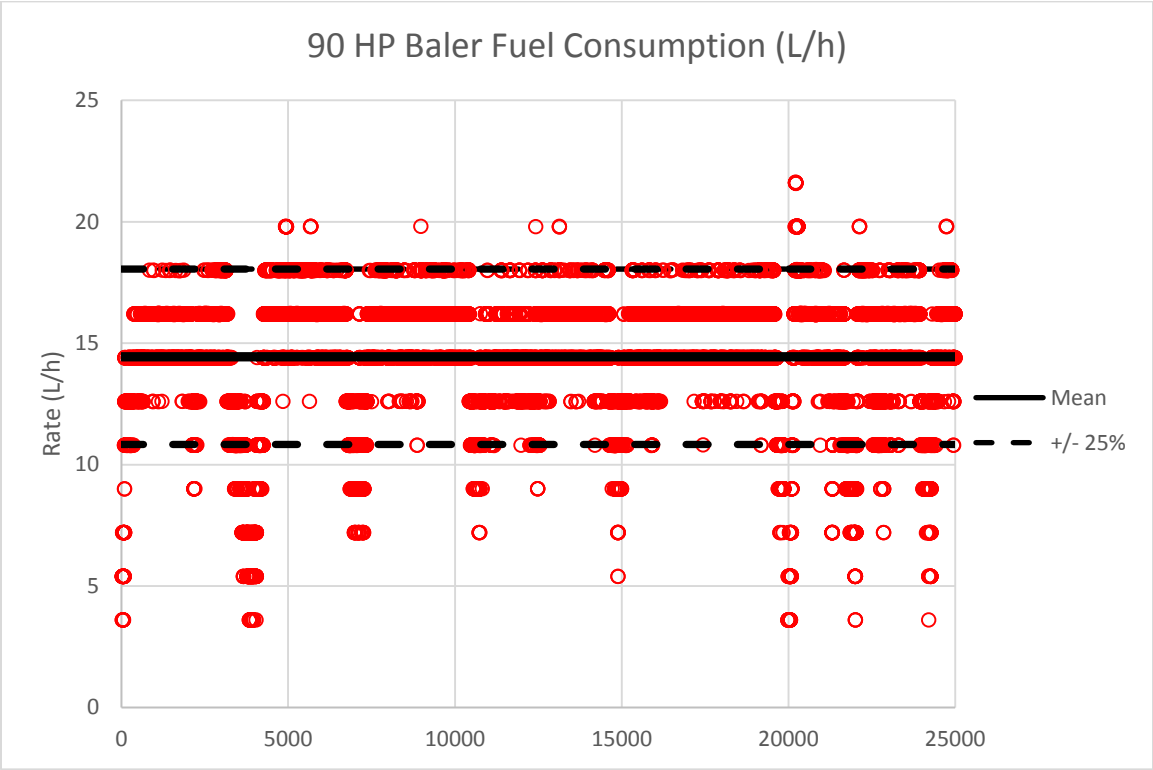


Figure 34-90 HP Baler Fuel Cons Plot

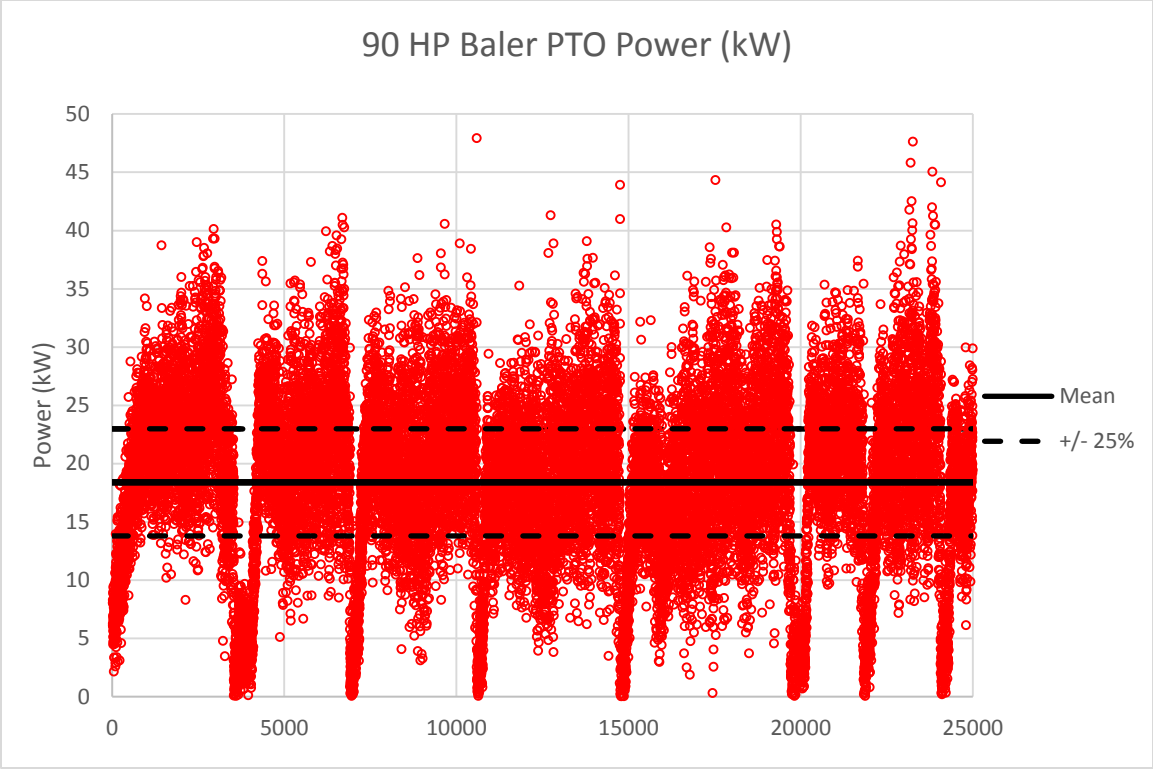


Figure 35-90 HP Baler Power Plot

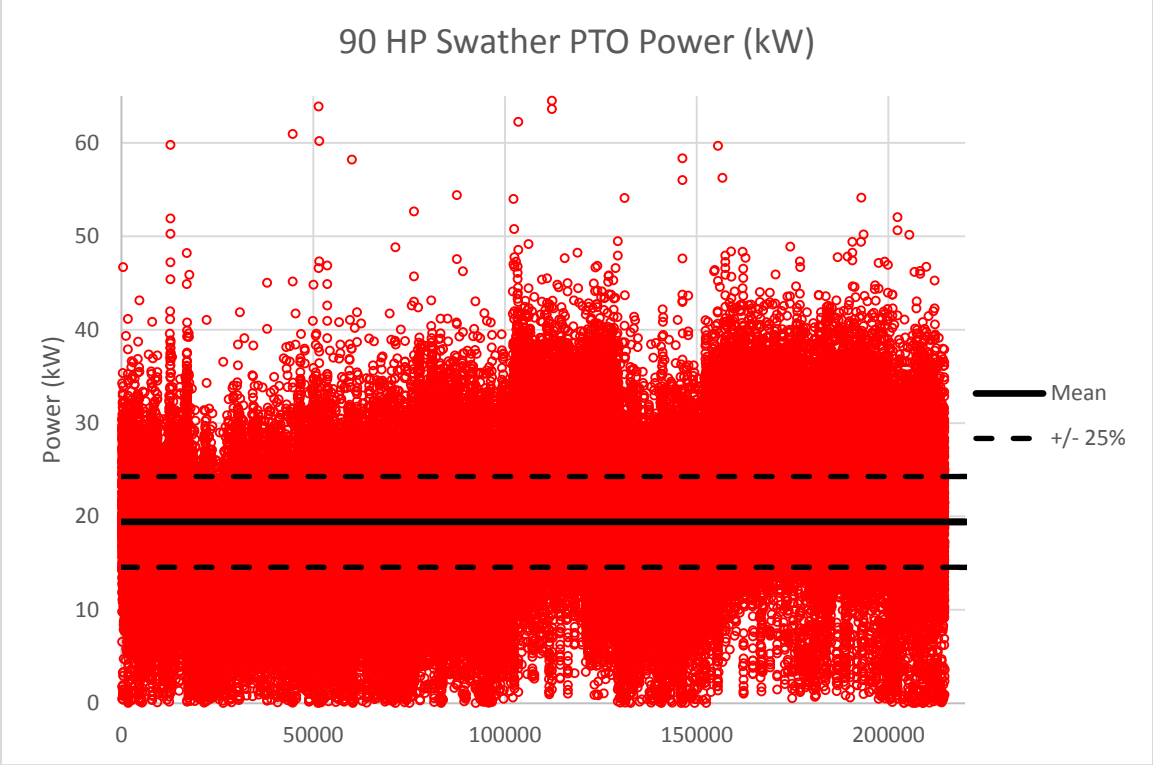


Figure 36-90 HP Swather Power Plot

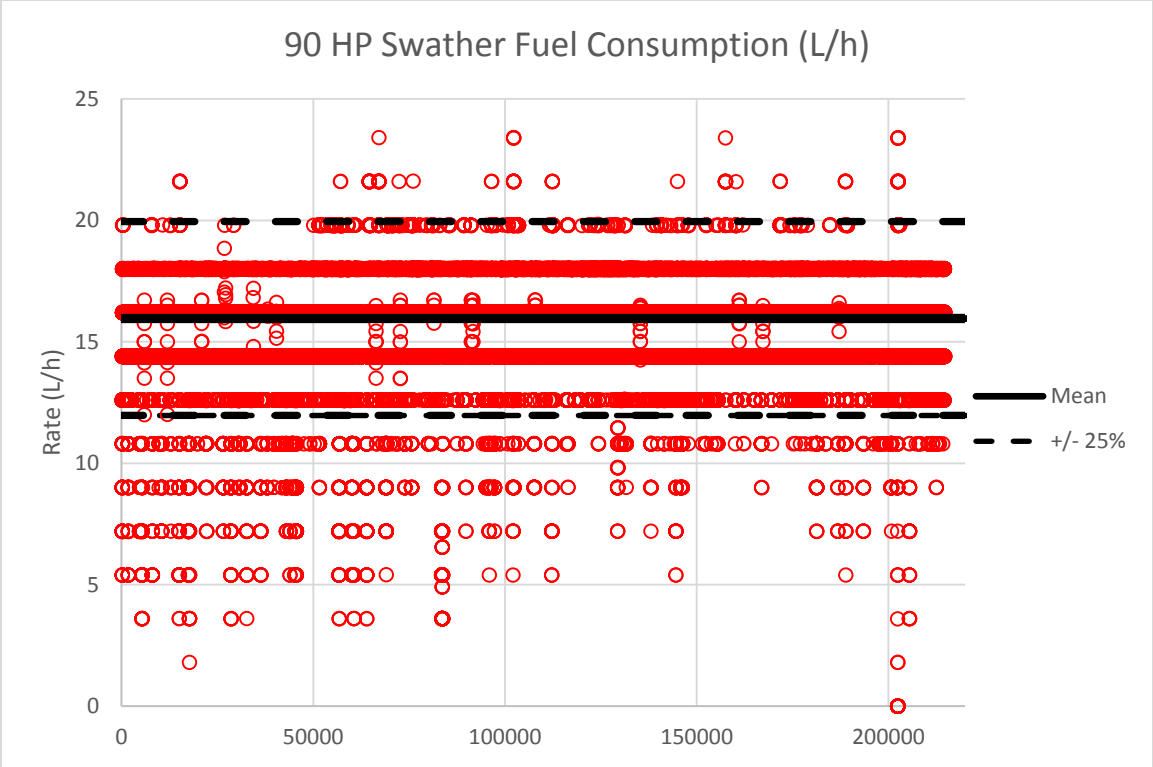


Figure 37-90 HP Swather Fuel Cons Plot

Spatial

Maps of PTO power, fuel consumption and speed were plotted by their GPS coordinates for each operation. Figure 38 shows the forage density distribution of the testing plot that was derived from bale weights and production path; Figure 24 is shown again below to reiterate the elevation of the plot.

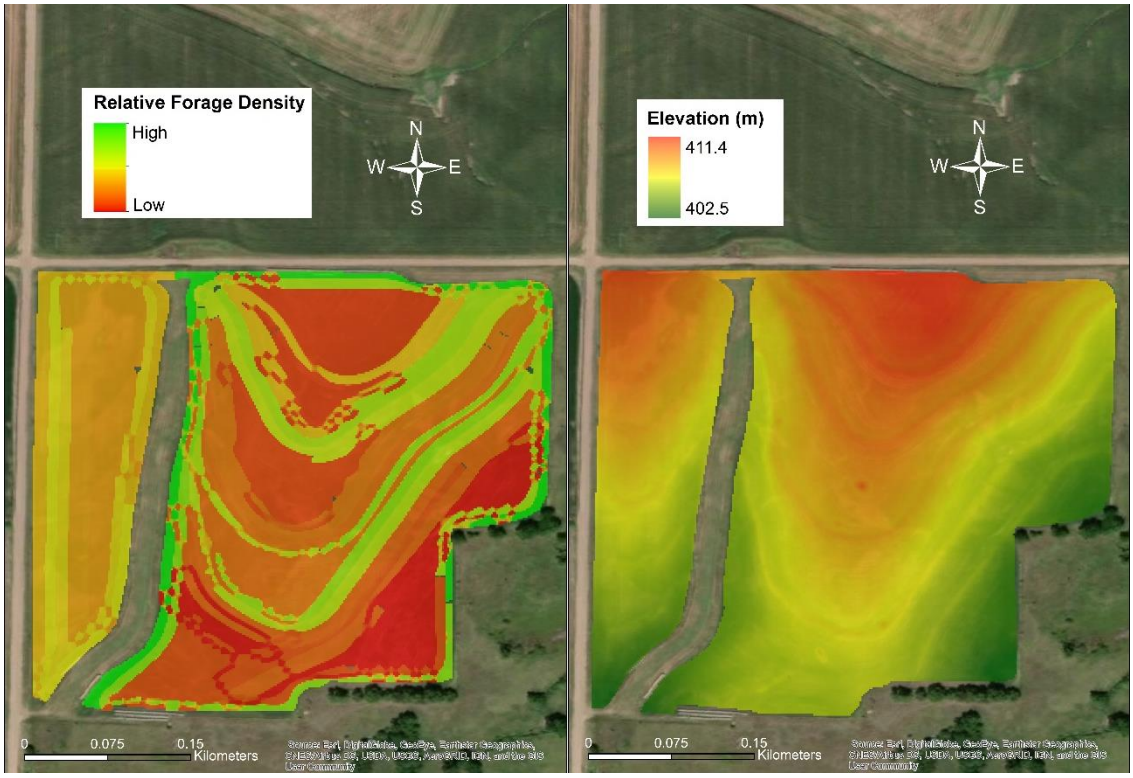


Figure 38-Forage Density Map

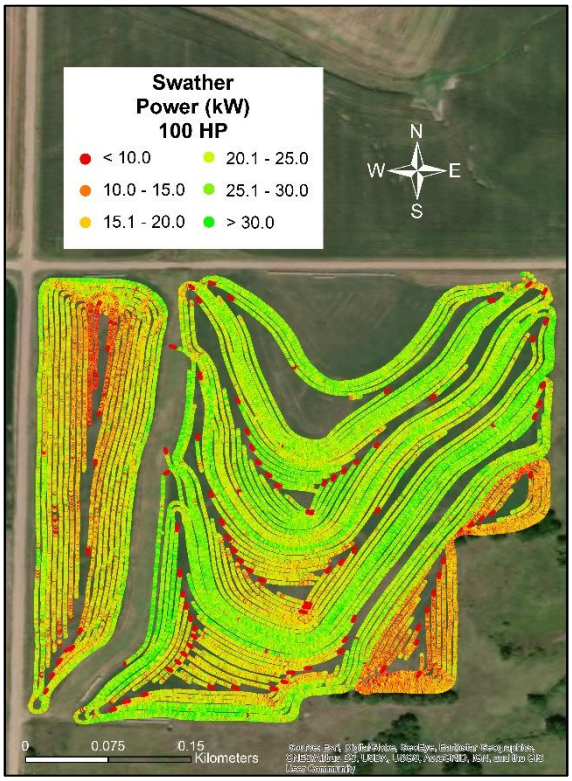


Figure 39-100 HP Swather Power Map

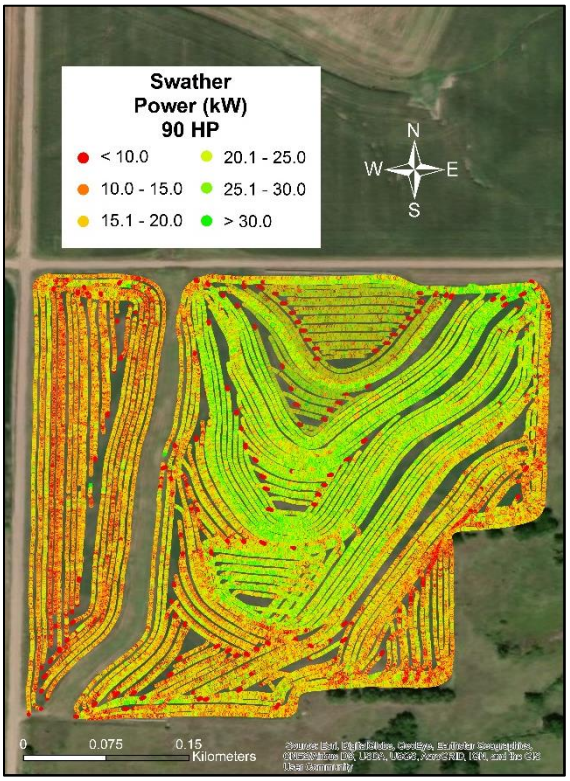


Figure 40-90 HP Swather Power Map

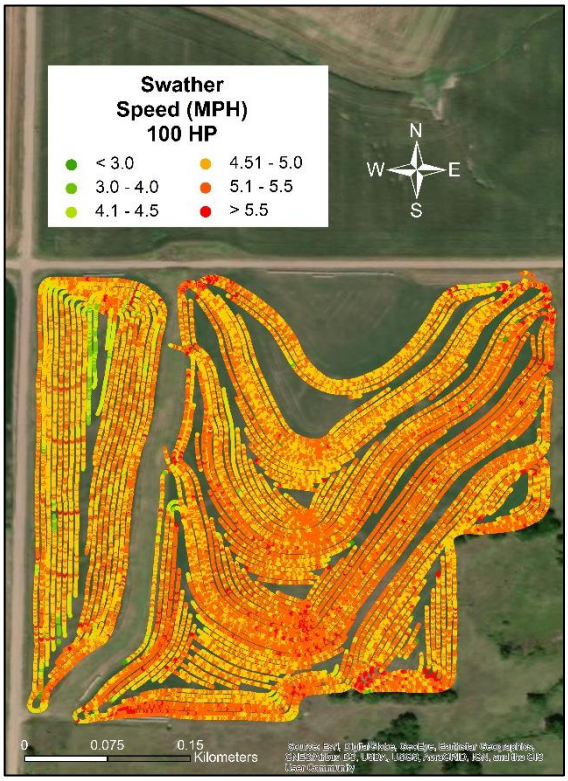


Figure 41-100 HP Swather Speed Map

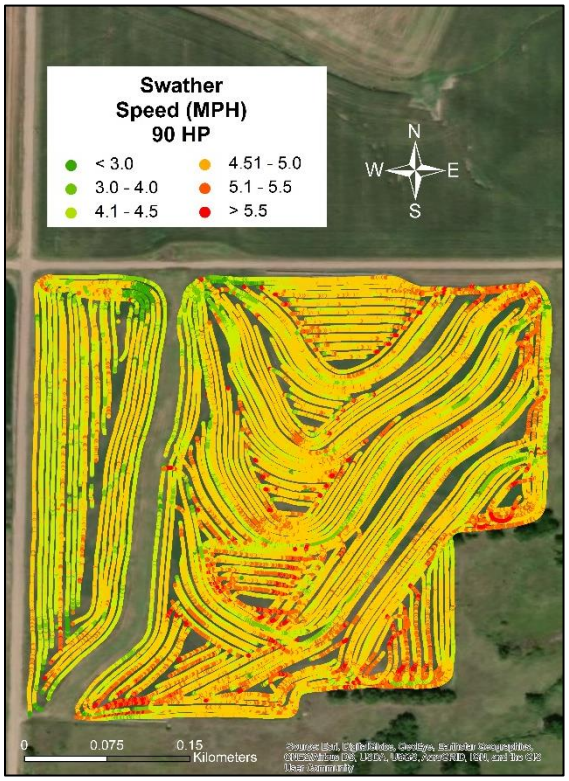


Figure 42-90 HP Swather Speed Map

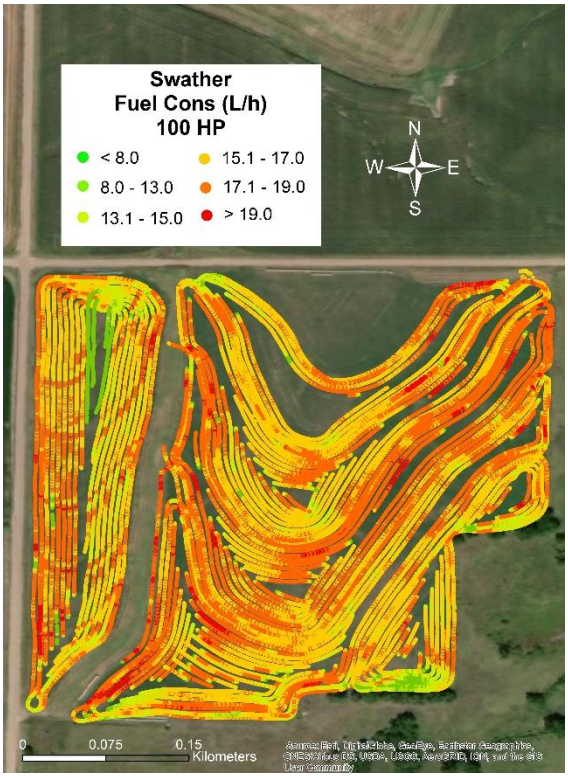


Figure 43-100 HP Swather Fuel Cons Map

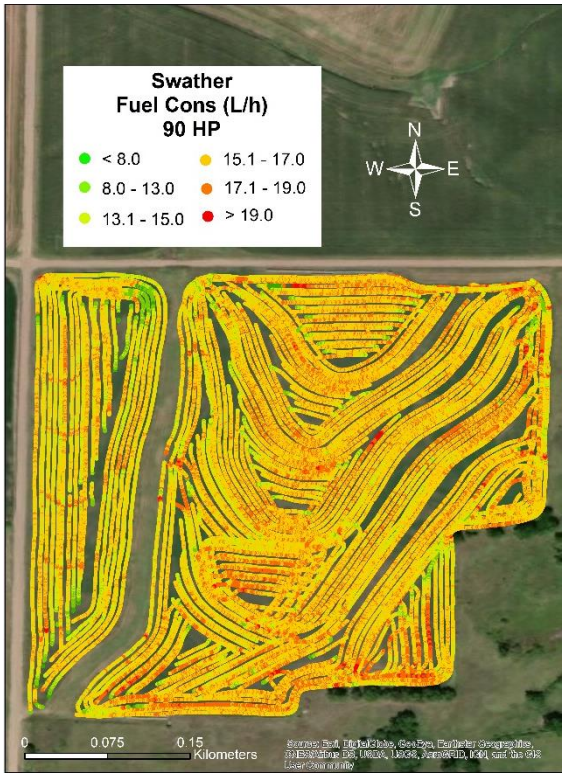


Figure 44-90 HP Swather Fuel Cons Map

Analyzing the above maps shows the direct correlation between power, fuel consumption, speed, terrain, and forage density. Focusing on the west section of the plot in both the 90 HP and 100 HP maps, it can be seen that the forage density was higher than the majority of the entire plot but the fuel consumption and PTO power were lower in this region. However, the speed plot indicated that the lower working speed was responsible for the lower fuel consumption and power values. Additionally, when comparing the 100 HP fuel consumption map with the elevation map, the higher regions of fuel consumption correlate directly with the regions of the field that have increasing elevations. The left section of the field was cut in a clockwise pattern, resulting in a gain of elevation on the west half and a loss in elevation on the east; given the relatively consistent forage density, power and speed indicates that the change in elevation was the primary contributor to the change in fuel consumption.

Comparison

The comparison of the two higher horsepower tractors aims to evaluate the differences in performance and efficiency based solely on the horsepower difference. As stated previously, the tests were performed on the same plot; additionally the total crop output during the 100 HP was 22.8 tons compared to the 21.7 tons during the 90 HP testing. This difference spread over 23-acres was considered to be negligible. The speeds during testing were made as close as possible, as the 90 HP testing slowed the tractor more than testing with the 100 HP.

Table 10-Higher Horsepower Comparison

Tractor	Operation	Avg. Power (kW)	Avg. Fuel Cons (L/h)
90 HP	Swathing	19.4	16.0
	Baling	18.3	14.4
100 HP	Swathing	22.7	16.3
	Baling	16.7	12.0

Average power and fuel consumption of the two machines are shown in Table 10. The average fuel consumption, in liters per hour, was similar when comparing the two tractors in the swathing operation, however when the total fuel consumption is taken into account, the 100 HP used only 74 liters compared to the 93 liters consumed by the 90 HP machine. Figure 45 shows the difference in speeds between the two tractors.

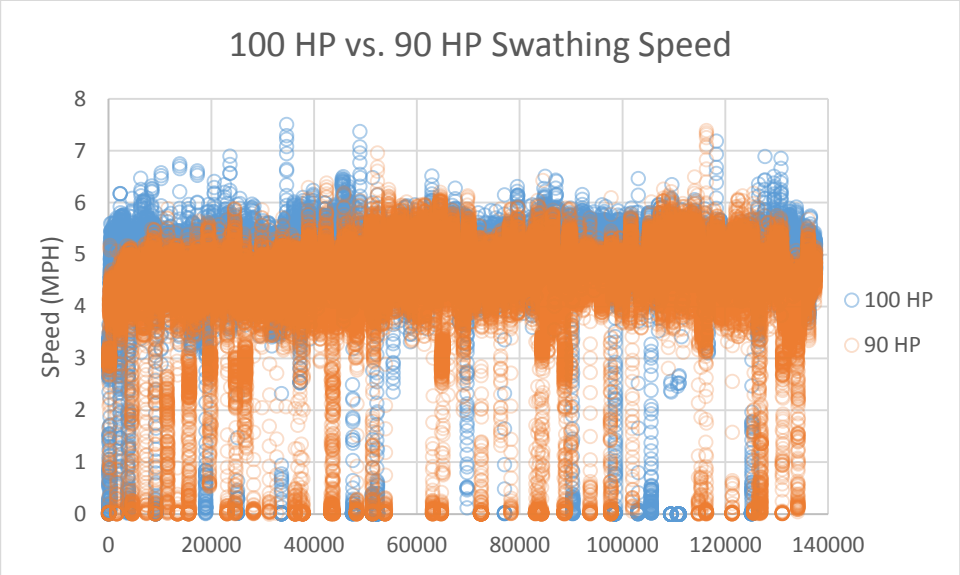


Figure 45-100 HP vs. 90 HP Swathing Speed

Analyzing the breakdown of the power usage and fuel consumption of the two tractors allowed further conclusions to be drawn about their efficiencies. The percentage of the operation period that each machine spent in varying ranges of power and fuel consumption is shown in Figure 46 and Figure 47 below. The power breakdown indicates that the 100 HP tractor delivered greater than 21 kW of power approximately 62% of the time, whereas the 90 HP tractor spent 40% of its operational period in this zone. In the baling operation, the 100 HP spent 23% of the operation period in this zone, compared to 37% with the 90 HP. From this information the conclusion can be drawn that due to the lack of available power from the smaller tractor combined with the heavier drawbar load of the swather resulted in a lack of available power to the PTO. In turn, the machine had to be operated a slower speed and higher throttle resulting in a lower efficiency. When evaluating the tractors based upon the fuel consumption breakdown, the aforementioned conclusion is reiterated. During the baling operation, the 100 HP spent just 26% of the time using greater than 14 L/h; the 90 HP operated in this range 76% of the time.

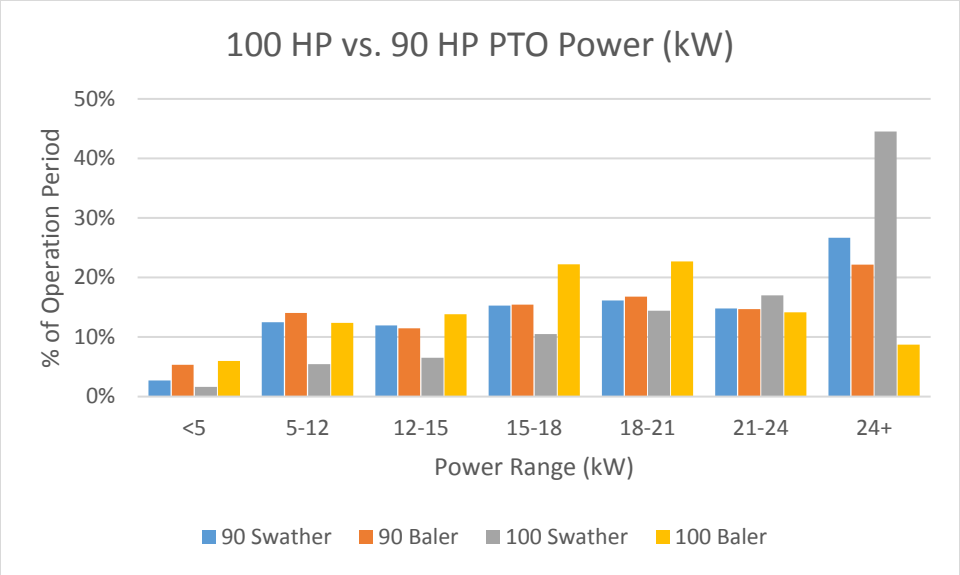


Figure 46-100 HP vs. 90 HP Power Breakdown

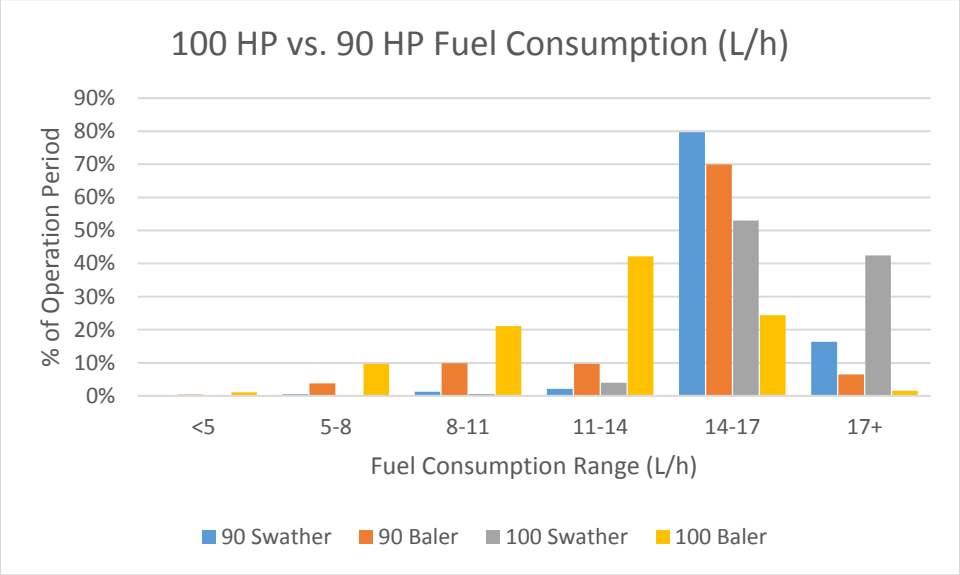


Figure 47-100 HP vs. 90 HP Fuel Cons Breakdown

As an additional measure of the efficiency of the tractors in the varying operations, a ratio of PTO power to fuel consumption rate was calculated and averaged across the entire dataset. As expected and previously shown through the data, the tractors in the baling operation have a higher ratio of power to fuel consumption; this was likely caused by the higher drawbar load of the swather. Table 11 shows these ratios.

Furthermore, the 100 HP showed a higher ratio of power to fuel consumption in both operations which aligns with the previous conclusion that the larger of the two tractors performed more efficiently. The 100 HP also showed much less difference in this ratio when comparing the two operations, signifying that the 90 HP is underpowered in the swathing operation.

Table 11-Higher Horsepower Power to Fuel Consumption Ratio

Tractor	Operation	$kW/L/h$
90 HP	Swather	1.1982
	Baler	1.2708
100 HP	Swather	1.3893
	Baler	1.4007

Summary

Through the first half of the higher horsepower analysis it was shown that PTO power and operating speed can be used to predict the instantaneous fuel consumption, however including variables such as drawbar load and engine RPM could further improve the confidence level of the estimation. Although the equations that define this relationship vary by operation as expected, testing of machines equipped with the data acquisition system described in Chapter 1 can be used to develop these equations. Additionally, spatial analysis made possible through mapping performance characteristics could be a very practical approach to make conclusions regarding the effects of forage density and terrain on performance.

Cabin vs. Open Station

Similarly to the higher horsepower testing, only data points with a PTO RPM of greater than 400 will be considered. Table 12 summarizes the recorded performance characteristics and the derived power-to-fuel consumption ratio. The data collected during the lower horsepower testing showed relatively weak correlation between field efficiency and a cab versus open station machine.

However, when defining the effect of the PTO drivetrain mode, strong correlation exists. The mean PTO power was slightly lower in both tractors when operating in the 540E mode, likely due to the lower RPM of the engine and a higher percentage of the output power being delivered to the ground to pull the implement. Disregarding the slight loss of PTO power, at similar speeds the economy PTO mode provided better fuel efficiency and a higher power-to-fuel consumption ratio than the standard 540 mode in each of the tested scenarios.

Table 12-Lower Horsepower Summary

Tractor	PTO Mode	Average Speed (MPH)	Mean PTO Power (kW)	Mean Fuel Cons (L/h)	Power-to-FC Ratio
71 HP Open Station	540	3.89	7.36	13.81	0.5332
		5.77	7.03	8.27	0.8501
	540E	4.91	6.23	5.57	1.1183
		6.16	6.39	6.24	1.0226
71 HP Cabin	540	4.52	8.84	9.18	0.9632
		6.36	8.75	10.18	0.8595
	540E	4.84	7.95	7.01	1.1329
		5.90	7.56	7.66	0.9867

In three of the four scenarios tested, higher swathing speeds resulted in lower mean PTO power values; additionally in three of the four scenarios the mean fuel consumption was disproportionately higher, resulting in a lower power-to-fuel consumption ratio, thus performing less efficiently. Given the results of the analysis above regarding the lower horsepower tractor testing, three main conclusions are made. 1) There is no evidence to support a relationship between the field efficiency of the tractor and the cabin or open station machine; this is unexpected and could be due to unaccounted for external factors during the testing and data acquisition phase. 2) The 540E option offers a more efficient operating option in low power requirement operations; the slight decrease in PTO power when switching to this mode leads to the conclusion that with a higher power requirement operation, not enough power would be available through the PTO to support the implement.

3) Higher operating speeds in this swathing operation results in a lower field efficiency proven by lower PTO power and higher fuel consumption.

Conclusion

Quantifying the highlighted tractor performance characteristics, fuel consumption, PTO power and operating speed, allows for analysis, yielding a better understanding of how these machines' performance and efficiencies vary in changing environments. Implementation of a system as done in this research fills a gap in available information regarding performance that will allow manufacturers and producers to better match implements with machines leading to higher field and fuel efficiency.

Testing and analysis of the higher horsepower tractors gave conclusions regarding individual tractor performance and the comparison of the two tractors when used in the same operation. Individual analysis provided results that showed excellent correlation between PTO power, operating speed and fuel consumption; an equation relating these three parameters developed using the data from the 100 HP swathing operation also fit the 90 HP swathing operation data almost identically. The analysis of these two machines also proved valuable for assisting in sizing the machine properly to the implement that produces the most performance efficient coupling. The data and derived ratio of PTO power-to-fuel consumption clearly showed that the 100 HP machine is better suited to be operated with the selected implement.

Overall, the results from this part of the research indicate that the system and analysis of in-field performance data is valuable for evaluating machines individually, as well as using it to compare multiple machines and make the selection that will yield the highest performance efficiency.

Testing of a wider range of machines would provide the opportunity for producers to make a better selection when deciding on a machine, as well as allow manufacturers to advertise specific machines based upon the primary operations of their target markets.

References

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Chapter 4 – Conclusion

Overall Summary

The development of the data acquisition system in the first part of this research provided a viable option for capturing real-time performance characteristics from tractors performing tasks in the field. Implementation of this system on tractors to be evaluated allowed detailed performance analyses to be made concerning the efficiencies of varying machines. In addition to the development and implementation of the DAQ system, a new and simple method to map relative forage density across a plot was developed. Combining all of the collected data yields results that assist in identifying operating options that are the most efficient.

Practical Implications

The research outlined in this paper contains many practical implications. A new testing methodology was developed to provide additional information to producers and manufacturers. This information allows producers to pair tractors and implements to provide the best in-field efficiency possible. Additionally, manufacturers are provided with the information necessary to make data-based decisions regarding marketing, product validation and product development.

Future Potential

A continuation of the testing outlined by testing a wider range of machines would provide opportunity for producers to make a better tractor selection that would yield the highest performance efficiency for the given operation. Building a database that describes the interaction between certain sized tractors and implements will help characterize the differences in efficiencies of paired implements and tractors.

Further development of this data acquisition system should include CAN data, drawbar load and instantaneous inclination. Adding CAN could create the potential for identifying the percentage of engine power that is going to the ground, rather than to the implement, thus allowing for a more accurate fuel consumption approximation. CAN data also contains other valuable pieces of information such as coolant temperature, transmission temperature, oil pressure, etc. that could help identify the cause of low performance efficiency. As shown in the data analysis section, drawbar load and inclination both have significant effects on performance efficiency; adding sensors to quantify these parameters would provide the data to allow for a more thorough evaluation of the machines.

In addition to the additional testing and parameters to be added in the future, collected data has the potential to be used as simulation data. Development of a testing lab that contains a chassis dynamometer and PTO dynamometer could implement the aforementioned data to simulate actual tested field conditions. Being able to simulate field environments in a lab would allow for dynamic testing in a controlled area, thus providing a much faster turnaround period for this style of tractor testing.