BENCHMARKING OF OFF-ROAD MACHINERY OPERATIONS WITH THE USE OF GEO-REFERENCED DATA

BY

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THESIS

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ABSTRACT

Past research has revealed that farmers do not have the resources to evaluate the efficiency of their off-road machines and in order for them to do so, relevant data must be collected from those machines. The rise of modern on-board computer systems now allows researchers, farmers and off-road machinery manufacturers to collect data from off-road machines while they complete farm operations. The analysis of off-road machinery related data would allow for the benchmarking of machinery productivity, efficiency, performance and cost. Geo-referenced machinery performance data, provides an opportunity for the analysis of machinery performance in relation to unique spatial aspects of agricultural fields to determine their effects on the operation.

The goal of this study was to identify, analyze and benchmark relevant geo-referenced machinery performance data based on selected productivity, efficiency, performance and cost indicators. The methodology was applied to corn planting operations on a farm in east-central Iowa involving a 24-row planter.

The methodology was applied to two fields that were selected based on their differences in shape and slope (%). Field one featured a water way which split the field into two right triangles, while field two featured a high average slope (%). Field one, was found to be the more productive and efficient operation compared to field two. Actual field capacity, field efficiency, fuel efficiency and cost were 9.46 ha h^{-1}, 56.3%, 4.27 L ha^{-1} and \$6.54 ha^{-1} for field one, respectively, compared to field two's 7.48 ha h^{-1}, 44.5%, 5.01 L ha^{-1} and \$7.84 ha^{-1}. The key factor that contributed to the differences was that the tractor/planter was unproductive for 49% of

the time it was in field two, compared to only 11.2% of the time in field one. The large amount of unproductive time reduced the productivity and efficiency of field two and increased the cost.

A row-by-row analysis was conducted on the second operation to determine if field slope (%) was correlated with energy efficiency. The correlation analysis returned an R^2 value of 0.0511, indicating no relationship existed. Engine power was found to vary significantly between certain rows. The average power in the rows was found to be 92 kW with a standard deviation of 33 kW. The average engine speed for fourteen of the seventeen rows was 1426 r min^{-1}, compared to an average of 900 r min^{-1} for the remaining three rows. It was determined that the machine operator must have reduced the engine throttle when working in three of the rows.

The benchmarking methodology was also used to determine the effects of the water way in field one on tractor turning performance. The presence of the water way caused the tractor to make a different shaped turn at the water way edge of the field. The average time for the tractor to complete a turn at the water way edge of the field was found to be 5.8 seconds greater than the opposite side of the field where no water way was present. The extra turning time required at the water way edge of the field increased the total turning time by 13.5%. Some assumptions were made concerning this field to predict field efficiency if the water way did not exist. Field efficiency was predicted to increase from 50.2% to 69.9%, if the water way was not present.

. The benchmarking of individual machine operations conducted on a farm could be combined to benchmark the productivity, efficiency, performance and cost of all the machine operations conducted on a farm. This would empower farm managers to budget time and money more accurately for future machine operations by reviewing past benchmarking records. Farm mangers would also be able to evaluate each individual machine and operator on their farm to identify opportunities to improve their overall operation.

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CHAPTER 1: INTRODUCTION

It has been pointed out in the past that the ultimate goal of a farm business is to maximize its profit return (Hunt, 1995a). The use of agricultural machinery represents a major cost in the production of agricultural crops (Buckmaster, 2003). If farm managers are going to accurately plan and budget both time and money for the completion of farm operations, they must have access to appropriate machine performance data to determine machinery related costs (Hassan & Larson, 1978) and machine performance characteristics (Grevis-James, DeVoe, Bloome, Batchelder, & Lambert, 1983).

Many of the recent advancements in agricultural machinery related technology have been in the areas of electronics and information technologies (Schueller, 2002). These technologies have created a major shift in the agricultural equipment sector towards mechatronics and precision agriculture technologies (Srivastava, Goering, Rohrbach, & Buckmaster, 2006). In 1986, the Bosch Corporation unveiled a new serial data communication system for the automotive industry known as CAN (Controller Area Network) bus. CAN bus technology has since been integrated into off-road vehicles (Zeltwanger et al., 2001) and allows for communication among the electronic control units that operate various functions on modern off-road machines (Goering & Hansen, 2004b). CAN bus technology is also being used to collect geo-referenced performance data from agricultural machines while they are working in the field (Darr et al., 2003; Darr, 2012; Askey, Darr, Webster, Covington, & Brue, 2013).

With the use of software programs such as ArcGIS™, spatial aspects of agricultural fields such as field shape and topography, can be viewed (Buick, 1997). By entering geo-referenced data into software, machine performance can be viewed and evaluated in relation to spatial aspects of agricultural fields. Due to the large amount of data that is often collected, the analysis has the potential to be tedious. However, the integration of a program such as Microsoft Excel and its associated functions into the data analysis process, has the potential to streamline the process substantially (Crisler, Strickland, Ess, & Parsons, 2002a).

CHAPTER 2: OBJECTIVES

The goal of this research project was to develop and utilize a methodology to benchmark off-road machinery operations through the analysis of geo-referenced machine performance data from agricultural operations on farms in the American Midwest. These data were collected while the machines were completing various farm operations.

To achieve this overall goal of benchmarking off-road machinery operations, four specific objectives were outlined. The fulfillment of these objectives was necessary to determine and evaluate the productivity, efficiency, performance and economic indicators of the selected off-road machinery operations. The four objectives of this research project were:

- The identification of relevant machine performance data with the use of ArcGIS™.
- The creation of Microsoft Excel spreadsheet templates to facilitate the calculation of relevant off-road machinery productivity, efficiency, performance and economic indicators.
- Review of off-road machinery productivity, efficiency, performance and economic indicators with special emphasis on the effect, if any, of unique spatial features of agricultural fields on said indicators.
- Evaluation of machine operator performance to determine the effect, if any, of the operator's performance on machinery operations.

In this specific research project, two corn planting operations were benchmarked using the methodology described in Chapter 4. The results were analyzed to determine how the operations could be improved. A similar approach could be applied to other field operations.

CHAPTER 3: REVIEW OF LITERATURE

The objectives of this literature review are: (1) to review certain aspects of agricultural machinery management relevant to the research project undertaken, including machinery productivity, efficiency, performance and economic indicators, (2) review advancements in electronics technology and how that technology is being used to collect machinery performance data, (3) review of how performance data has been analyzed in the past, specifically, in relation to spatial aspects of agricultural fields, and (4) review of the current knowledge concerning Infinitely Variable Transmissions (IVTs) in order to lay a foundation for the research to be presented.

Agriculture has seen three major transformations since its beginning. The first transformation was the shift from human power to animal power, animals were adopted as the prime mover of agricultural operations in place of human beings (Srivastava et al., 2006). The second was the shift from animal power to mechanical power, the invention and adoption of agricultural tractors, for example (Srivastava et al., 2006; Stoss, Sobotzik, Shi, & Kreis, 2013). The third transformation, which is occurring now, is the inclusion of electronics technology into agricultural machines which is leading to “information based agriculture” (Srivastava et al., 2006). The term “information based agriculture” includes mechatronics and SSCM (Site-Specific Crop Management) which is commonly referred to as precision agriculture (Srivastava et al., 2006). It was noted in 2002, that electronics and information technologies had commanded the more recent advancements in agricultural equipment related technology (Schueller, 2002). Electronics technologies can be employed to collect data that can then be analyzed spatially to determine a range of machinery management and performance information that can be invaluable to farmers, machinery manufacturers and researchers (Darr, 2012).

3.1 Agricultural Machinery Management

Agricultural machinery productivity, efficiency, performance and economic indicators are reviewed in the following sections. The determination of these indicators was necessary to benchmark farm machinery operations. These indicators allow for the evaluation of agricultural machines and machine operators to better understand machine operations and identify opportunities for improvement.

3.1.1 Economics

The costs associated with the use of heavy machinery account for a large percentage of the cost to produce agricultural products; operating agricultural tractors, specifically, has the potential to serve as a major cost to farm operations (Buckmaster, 2003). The ultimate goal of a farm business is to achieve the highest profit return possible (Hunt, 1995a). Therefore, it is essential for farm operators to have an accurate idea of the operating costs of their machinery if they are to make informed economic decisions (Hassan & Larson, 1978).

3.1.2 Productivity and Efficiency Indicators

Being able to determine machine capacity is essential for farm managers to make sound management decisions. Machine capacity is an indicator of a machine’s capability to complete a farm operation (Grisso, Hanna, Taylor, & Vaughan, 2008). Theoretical machine capacity can be measured as: (1) field capacity, (2) material capacity and (3) throughput capacity. Field capacity is calculated using machine speed and width to determine the area worked by the machine and it is often expressed in units of ha h^{-1} or acre h^{-1}. Material capacity, is expressed in units of kg h^{-1} or lb h^{-1} and refers to the amount of harvested material collected by a machine. Throughput capacity, is often expressed as kg h^{-1} or lb h^{-1} (Hunt, 1995b). Throughput capacity, unlike material capacity, considers the fact that some of the material that enters a machine is not collected by the machine. Weeds, chaff and straw are all examples of material that will enter a machine such as a combine but be filtered out and left behind (Hunt, 1995b). Throughput capacity is variable based on crop moisture and when throughput capacity is presented, it should be accompanied by a report that describes the moisture content of the material (Hunt, 1995b).

Field efficiency is another measure of interest to farm managers. Field efficiency is defined by ASABE Standard EP496.3 as the "ratio between the productivity of a machine under field conditions and the theoretical maximum productivity" (ASABE, 2006). A field efficiency decimal will be applied to the theoretical machine capacity measure to determine the actual machine capacity. It is very difficult to operate machines without interruption or at their full width potential, hence the necessary application of the field efficiency measure to determine actual machine capacity (Hunt, 1995b). For example, a machine with a theoretical field capacity of 10 ha h^{-1} and a field efficiency of 80%, will have an actual field capacity of 8 ha h^{-1}. A great deal of research has been done in the past to understand and determine the machine capacity and field efficiency of agricultural machines in an attempt to evaluate and improve farm operations (Renoll, 1970; Renoll, 1981; Grisso, Jasa, & Rolofson, 2002; Crisler, Strickland, Ess, & Parsons, 2002b; Adamchuk, Grisso, & Kocher, 2004; Hartley, Gibson, Thomasson, & Searcy, 2011) by enabling farm managers to properly size machinery for certain tasks and budget time for certain farm operations. Of course, past research has stated and examined the factors that can affect field efficiency and therefore, the actual machine capacity of agricultural machines. The factors include: (1) machine preparation time, (2) time spent turning and navigating obstacles such as water ways, (3) in-field repair, (4) in-field maintenance, and (5) re-filling seed bins (Renoll, 1970; Renoll, 1981; Grisso et al., 2002). Field efficiency is an indicator of the impact that operator decisions such as machinery selection and operating strategy have on farm operations (Grisso et al., 2008b). A farmer may buy a 24-row planter instead of a 12-row planter because the theoretical field capacity with the 24-row planter is double that of the 12-row planter due to the longer width. However, support activities and seed re-fill time will increase with the 24-row planter due to the increased number of seed boxes and reduce the field efficiency decimal of the 24-row planter versus the 12-row planter. Therefore, field capacity does not necessarily double with the 24-row planter (Grisso et al., 2008b).

Researchers have shown in the past that field efficiency can vary from field to field based on factors such as field shape and row length (Grisso et al., 2002). Renoll (1972) created a method that takes factors such as: (1) row length, (2) turning time at the end of a row, (3) machine speed, (4) machine width, and (5) machine support activities; into account when calculating field efficiency. The method could be used to calculate the minutes-per-acre capacity of a machine. The assumption made by this method is that if the number of minutes required of a machine to work a certain area can be determined, then the amount of time needed for the machine to work a similar area of ground can be determined (Renoll, 1972). Renoll (1975) created what he called a “Field Machine Index” which attributed a certain score out of one hundred to a field indicating how well suited the field was for machine use. The higher the score a field received, the better suited the field was considered to be for machine use (Renoll, 1970; Renoll, 1975).

Larson (1977) noted that increasing the capacitive performance of cotton machinery has the potential to reduce the amount of time required to complete operations, decrease the amount of operator labor and result in a more advantageous use of expensive machinery. The machine operator has the power to determine machine speed and coordinate the operation in a way that reduces turning time. Therefore, the operator was ultimately found to be the key factor in the optimization of machine performance (Larson, 1977). When a machine operator takes control of an off-road vehicle, the operator's ability to make decisions is joined to the machine. The operators use their senses to achieve the desired machine performance (Goering, Stone, Smith, & Turnquist, 2003).

Past research indicates a strong interest in the profession to maximize in-field machine efficiency. SFC, or "Specific Fuel Consumption," is defined as "fuel consumption in relation to the amount of work that is being done by the engine" (Goering & Hansen, 2004a, p. 86). One study pointed out that if machine operators understand the performance characteristics of the engine in the machine they are operating, that they can optimize its SFC by selecting the appropriate gear ratio and engine speed combinations (Lyne, Burt, & Meiring, 1984). Lyne et al. (1984) stated that if these factors are considered and an effort is made to improve the tractive efficiency of the machine, then overall efficiency can be increased significantly. A test was conducted in this particular study to better understand how engine and tire parameters affected performance. One of the conclusions made by the authors was that overall performance could be optimized if a control system was utilized to select optimal engine and traction parameters (Lyne et al., 1984).

Due to the high cost of diesel fuel, the primary power source of farm machinery, there is a strong interest in predicting fuel consumption and energy requirement of farm machines to better understand the energy demands of farm operations. This information has a great deal of value to farmers and machinery manufacturers looking for ways to decrease fuel consumption and/or plan and budget fuel for farm operations (Koertner, Bashford, & Lane, 1977). Zoz and Grisso (2003) noted that the primary purpose of middle to high-horsepower agricultural tractors is to be a source of drawbar power and ideally, a tractor should convert all the potential chemical energy of the fuel it consumes into drawbar power. In practice, however, a large part of the potential chemical energy (a.k.a. fuel equivalent power) of diesel fuel consumed by tractors is lost out of the exhaust pipe as heat, used to overcome friction in the engine and drivetrain or lost at the soil-tire interface as wheel-slip (Zoz & Grisso, 2003). The efficient operation of farm tractors includes: (1) maximizing engine fuel efficiency and drivetrain mechanical efficiency, (2) maximizing the effectiveness of traction devices, and (3) working at optimum machine travel speed (Grisso, Kocher, & Vaughan, 2004).

New equations for predicting tractor fuel consumption were created in 2004, determined from tractor performance data acquired by the NTTL (Nebraska Tractor Test Laboratory) of Lincoln, Nebraska (Grisso et al., 2004b). The equations developed by Grisso et al. (2004b) were considered to be a general way to estimate tractor fuel consumption. More specific tractor fuel consumption models were later developed to predict tractor fuel consumption more accurately (Grisso, Vaughan, & Roberson, 2008; S.C. Kim, K.U. Kim, & D.C. Kim, 2011). Grisso et al.

(2008a) developed a model to predict the fuel consumption of specific tractor models using the test data of the specific model being considered. The data were acquired from the NTTL. Grisso et al. (2008a) compared their methodology for predicting tractor fuel consumption of specific tractor models to the more general method developed in 2004 (Grisso et al., 2004b) and found that 88% of the tractors considered had an improved fuel consumption prediction using the specific prediction model compared to the more general prediction model. Kim et al. (2011) developed and verified their method by comparing the calculated fuel consumption of four tractors using their mathematical model, to the measured fuel consumption provided by the OECD (Organisation for Economic Co-operation and Development) test reports for those particular tractor models. The OECD is an international organisation that maintains a standard tractor test code that participating countries must follow in order to receive OECD approval which is designed to encourage trade among countries (OECD, 2014). Machinery energy requirements for agricultural operations, specifically tillage operations, have been determined in the past and expressed as kWh ha^{-1} (Fornstrom & Becker, 1977) and J ha^{-1} (Oyelade & Oni, 2013). Energy requirements of agricultural operations has also been expressed as MJ Mg^{-1} when studying the impact of varying the oblique blade angle of harvester cutting blades and cutting speed, on energy consumption when harvesting bioenergy crops (Maughan, Mathanker, Grift, & Hansen, 2013).

3.2 Measurement and Analysis Techniques

Past research has noted that farmers do not have the resources to evaluate the efficiency of their machines (Grevis-James et al., 1983). In order for farmers and researchers alike to understand and improve machine performance and efficiency, data acquisition techniques must be developed to collect appropriate performance data (Grevis-James et al., 1983). A number of researchers have instrumented agricultural machines to acquire machine performance data for analysis to better understand machine performance (Grevis-James et al., 1983; Green, Stout, & Searcy, 1985; Hansen, Walker, Lyne, & Meiring, 1986). Grevis-James et al. (1983) developed an inexpensive data acquisition system for tractor operations using an AIM microcomputer that measured: (1) drawbar pull, (2) wheel slip, (3) engine speed, and (4) fuel flow. Green et al. (1985) developed an instrumentation system for a John Deere 4440 to measure certain performance information including: (1) ground speed, (2) engine speed, (3) drawbar pull, and (4) fuel consumption. Hansen et al. (1986) also developed a microprocessor system to record and analyze machine performance data and noted that the groups concerned with in-field tractor performance characteristics, identified as researchers, farmers and tractor manufacturers, were "confused" concerning the extent of engine loading during the in-field operation of agricultural machines. Hansen et al. (1986) instrumented a Ford 6610 tractor with the microprocessor system mentioned previously. The tractor was then used to complete several field operations including plowing, ripping and hauling. Three people operated the tractor and the performance of the operators was evaluated as well as the machine. Performance data were represented graphically concerning power, time and engine speed. The authors note that the goal of machine operators should be to "maximize fuel efficiency and minimize total field time" (Hansen et al., 1986).

In February of 1986, the Bosch Corporation unveiled a new serial data communication system for the automotive industry known as CAN (Controller Area Network) bus. CAN bus technology has since been utilized in a number of applications including off-road vehicles (Zeltwanger et al., 2001). The CAN bus systems allow for communication among the electronic control units that operate various functions on modern off-road machines (Goering & Hansen, 2004b).

CAN Bus systems have been evaluated and employed to aid in the collection of data related to agricultural operations (Darr, Stombaugh, Ward, & Montross, 2003; Nagasaka et al., 2004; Darr, Zhao, Ehsani, Ward, & Stombaugh, 2005; Darr, 2012; Li et al., 2013).This includes the collection of machine performance data from agricultural machines while they are working in the field. Each line of data collected from the machines, in many cases, can be recorded with a corresponding GPS (Global Positioning System) coordinate location (Darr et al., 2003; Darr, 2012; Askey et al., 2013). By assigning a GPS coordinate to each line of data, researchers can observe and analyze how machine performance changes due to spatial aspects of agricultural fields (Adamchuk et al., 2004; Darr, 2012). Due to the amount of time required to complete large scale agricultural operations, these data sets can be quite large. The term “big data” has been given to large data sets that contain tremendous amounts of information (Manyika et al., 2011). The term is subjective among professions. Big data is proving to be a valuable resource to corporations seeking to learn more about their products, customers, services etc. (Manyika et al., 2011).

Precision agriculture is now a possibility thanks in part to on-board machine computer systems such as CAN Bus. Precision Agriculture can be described as prescription farm management of small areas within agricultural fields based on the needs of each particular area (Buick, 1997) There is a number of technologies that can be attributed to precision agriculture which include: GPS, digital maps, GIS (Geographic Information Systems) and on-board computers contained in off-road machines as previously mentioned (Buick, 1997). GPS or a

“Global Positioning System” was originally developed by the United States Military and is available for civilian use. Spatial data analysis would be difficult without GPS technology. There are twenty-four GPS satellites orbiting the earth; a GPS receiver will access between five and eight satellites at a time to determine its position on the planet (Srivastava et al., 2006). GPS receivers receive a signal from satellites in orbit and compare that signal to their own internal signal, the receiver calculates the phase shift between the signals and can then determine the distance between itself and the satellites because the signal is known to travel at the speed of light. Based on triangulation, the receiver can determine where it is on the earth (Srivastava et al., 2006).

Because GPS coordinates are recorded alongside every line of machine data collected, machine performance data can be input into specialized software programs and analyzed to learn the details about the specific operation that was conducted (Taylor, Schrock, & Staggenborg, 2002). A program such as ArcGIS™, can be used to view and analyze data relative to the location it was collected. ArcGIS™ and other precision agriculture technologies can be used to map fields so the field’s unique attributes such as topography (Buick, 1997) can be viewed and considered when analyzing the machine data collected in that area. ArcGIS™, has been used for numerous types of analysis in various professions including hydrologic modeling (Zhang, Haan, & Nofziger, 1990) and determining high traffic trails of logging machinery (Bettinger, Armlovich, & Kellogg, 1994). Research related to spatial analysis has been done to better understand several aspects of agricultural machine use including economics (Yang, Everitt, Murden, & Robinson, 2002) and pesticide application (Brown & Steckler, 1995). Research has been done to see how crop yield, and based on crop yield, how farm profits vary spatially in agricultural fields (Yang et al., 2002). Pesticide use has led to concern due to its impact on the environment. Research has shown that using ArcGIS™ and other precision agriculture technologies to apply pesticide spatially in a field, that is, only to the areas in a field where pesticide is needed, drastically reduces pesticide use (Brown & Steckler, 1995). One study (Brown & Steckler, 1995) calculated a reduction in pesticide use of over 40% in a certain field if spatial application was used versus conventional spraying. Spatial application is made possible with precision agriculture technologies including ArcGIS™, which can be used to create prescription spraying maps based on aerial photos of a field (Brown & Steckler, 1995).

Researchers have shown how geo-referenced data can be used to determine machinery management information (Grisso et al., 2002; Crisler et al., 2002b; Grisso, Kocher, Adamchuk, Jasa, & Schroeder, 2004; Adamchuk et al., 2004). Crisler et al. (2002b) worked to create a methodology to extract combine management information automatically from data collected during harvest. This included the machine's average, maximum and minimum speeds. A histogram was then created to display how much time the machine spent at varying speeds. Some of the factors that influence machine performance indicators, such as speed in the case of machine capacity, were extracted from Ag Leader ® advanced format .txt files using Microsoft ® Excel © and Visual Basic © macros developed by the authors. The macros help to streamline data analysis by allowing calculations to be done automatically after data is input into a spreadsheet and does not require the user to input every function every time. The macro recorded the necessary functions as they were input by the user during its creation so it could repeat the calculations on different sets of data (Crisler et al., 2002a). Grisso et al. (2002) used Microsoft Excel and a GIS system to analyze data collected by a DGPS monitor during planting operations and a yield monitor during harvesting operations to determine the field efficiency of the machines involved. Grisso et al. (2002) showed that the field efficiency of planting operations dropped by 10% comparing fields with straight rows to fields with contoured rows. Field efficiency of harvesting operations dropped by 20% comparing fields with straight rows to fields with contoured rows. Adamchuk et al. (2004) showed that performance data could be used to generate field maps that display how machine performance varies spatially within a field. A "field coverage efficiency" map was created to indicate areas in the field where the machine was maneuvering, places where overlaps occurred and places where field coverage was normal. The authors created a map to display areas of a field where the cost of harvesting was average and relative to the average, where in the field the cost was higher or lower. The authors also created a map to indicate places where machine speed was relatively high and places where machine speed was relatively low. Maps like these have the potential to be valuable to farm operators because they provide the information necessary to evaluate in-field machine performance, especially, as it relates to spatial aspects of agricultural fields (Adamchuk et al., 2004).

3.3 Infinitely Variable Transmissions

A power transmission system has the potential to be the most expensive part of an agricultural tractor (Schueller, 2002), sometimes accounting for up to 30% of the initial tractor cost (Renius & Resch, 2005). The nature of mechanized agricultural operations requires significant power transmission due to the fact that large amounts of torque are required at low speeds (Schueller, 2002). IVTs have been used in agricultural machines but adoption in tractors has been slow due to the fact that IVTs tend to be less efficient compared to fixed gear transmissions. However, these efficiencies can be improved by the adoption of "power-split" transmissions, the pairing of hydrostatic and mechanical power ways (Schueller, 2002). IVTs provide an infinite number of gearing ratios that can be manipulated on the go (Schueller, 2002) to allow a tractor engine to operate at the highest level of fuel efficiency (Coffman, Kocher, Adamchuk, Hoy, & Blankenship, 2010). The IVT allows for the implementation of a concept known as “shift up, throttle back” (Coffman et al., 2010). The “shift up, throttle back” concept can be used when an engine is not operating at a high level of load (Goering & Hansen, 2004a) and the power required for the operation can be achieved at a lower engine speed (Coffman et al., 2010). The operator can therefore reduce the engine throttle. By reducing engine throttle, friction in the engine reduces, causing the mechanical efficiency of the engine to increase, which results in greater fuel efficiency (Goering & Hansen, 2004a). Shifting the transmission up, allows for the machine to maintain the original ground speed achieved before the throttle was reduced (Goering & Hansen, 2004a). IVTs are considered to be the most technologically advanced transmissions in production and fit the needs of farm operations where large productivity and comfort are the highest priorities (Renius & Resch, 2005).

For some time there was no procedure to test the fuel efficiency of tractors with IVTs at a reduced power level under OECD Code 2. Reduced power levels are where an IVT machine has the potential to be more fuel efficient than a standard gear machine (Coffman et al., 2010). Many IVTs have a setting that will cause the IVT to act in the same manner as a standard gear transmission (Coffman et al., 2010). Coffman et al. (2010) proposed and conducted a procedure to test the fuel efficiency of an IVT tractor. A single tractor was used during the test and run in (1) manual mode, which caused the transmission to behave as a fixed gear transmission, and (2) automatic mode, which allowed the transmission to act as an IVT. Their conclusion was that the operation of the IVT allowed the tractor to be more fuel efficient compared to the manual mode if the drawbar power was at or below 78% of maximum power, the engine throttle was set at the maximum level during the test. Howard, Kocher, Hoy, & Blankenship (2011) later compared a John Deere 8295R IVT tractor to a John Deere 8295R PowerShift (fixed gear transmission) using a test protocol that could be considered as an addition to OECD Code 2. The results of the study were very similar to the findings of Coffman et al. (2010) concerning fuel efficiency of an IVT machine vs. a fixed gear transmission machine at reduced power. When both tractors were placed at full throttle, the IVT employed the shift up throttle back strategy in order to run at a more fuel efficient engine speed than the John Deere 8295R PowerShift. It was noted that when the John Deere 8295R Powershift Transmission was shifted up two gears and the engine throttle was reduced, that it was the more fuel efficient machine when the drawbar power was above 37% to 52% of the maximum drawbar power (Howard et al., 2011).

The review of literature has indicated that tractor operations have the potential to be very expensive to farm operations. Farm managers do not have the resources to evaluate the efficiency of their machine operations and in order for farmers to budget time and money accurately, they must have access to relevant data. The rise of CAN Bus systems and GPS technology, has provided researchers with an opportunity to collect geo-referenced data. These data can then be reviewed with ArcGIS™ and analyzed with the use of Microsoft Excel to determine relevant productivity, efficiency, performance and economic indicators of machine operations.

CHAPTER 4: MATERIALS AND METHODS

To benchmark corn planting operations, a methodology was created to identify the operational states of a tractor/planter and analyze the data corresponding to each operational state. The operational states were identified as: planting, turning and unproductive. Every data point that was collected from the tractor's CAN Bus system was geo-referenced. This means a set of latitude and longitude points were collected with each line of data as well as the altitude of the machine. The data were imported into ArcGIS™ (ArcGIS™ Desktop 10, Esri 2010) so the user could visualize the geographic location where each line of data was recorded. Each line of data appeared as a "point" on the ArcGIS™ generated map.

No data were collected directly from the John Deere planter itself that was used to plant the fields that were analyzed. Therefore, no data were collected regarding the planter state of operation or geographic location relative to the tractor. The operational state of the planter could be estimated for the majority of the data points by viewing the ArcGIS™ generated map. A method was developed to estimate the operational transition points in order to estimate the operational state of the planter for the remaining data points. Operational transition points were the locations where the planter transitioned from one operational state to another, specifically, the transition from planting to turning and vice versa.

To analyze the data identified as relevant in ArcGIS™, a range of equations and Microsoft Excel functions (version 15.0.4605.1003, 64-bit, Part of Microsoft Office Home and Student 2013 © 2013) were entered into two Microsoft Excel spreadsheets to automatically calculate information of interest when selected data were entered into the spreadsheets. These spreadsheets allowed for the determination of a wide range of machinery productivity, efficiency, performance and economic information. Extracting this type of information is necessary if machinery operations are to be benchmarked. The following sections describe the development of the methodology created to benchmark tractor/planter operations.

4.1 Farm and Machinery Information

The data analyzed in this project were collected from a tractor on a farm in east-central Iowa (Kennedy, 2013). The farm was 5600 hectares (14000 acres) in size and primarily grew corn. The farm utilized conventional farming techniques (Kennedy, 2013).

The tractor from which data were collected was a John Deere 8360R. The John Deere 8360R develops 240 kW of PTO power at rated engine speed (2100 r min^{-1}) according to its NTTL report (Nebraska Tractor Test Lab, 2011). The tractor's CAN Bus system was utilized to collect the data. The 8360R was used to pull a John Deere 1770NT 24-row planter (30-inch spacing between rows) to plant the farm's corn crop.

4.2 Field and Initial Data Selection

Specific data files for planting operations were selected for analysis based on the characteristics of the field that they represented. Each data file was accompanied by a "shapefile" which provided an outline of the field shape. A document was also provided by John Deere that displayed the average slope (%) of each field. Two fields were ultimately selected for analysis, one for its shape, hereafter referred to as "field one" and the other for its high average slope (%), hereafter referred to as "field two". A total of 111 columns of data were included in each data file, out of which, six data columns were selected for analysis because they contained the information of interest in this project. The data columns selected for analysis were: latitude (decimal degrees), longitude (decimal degrees), altitude (meters), machine speed (mile h^{-1}), engine speed (r min^{-1}) and actual engine percent torque at rated engine speed (%). Actual engine percent torque measurements indicate the percentage of torque the engine was producing relative to the amount of torque produced at rated engine speed.

Each of the data categories listed above were contained in the columns of a Microsoft Excel spreadsheet hereafter referred to as the “original data spreadsheet.” To begin the initial data selection, each data column of interest in the original data spreadsheet was selected and a copy and paste operation was performed to move the data into a blank Microsoft Excel spreadsheet hereafter referred to as the “selected data spreadsheet.” The machine speed was multiplied by 1.6 to convert it from mile h^{-1} to km h^{-1} in order to remain consistent with other data contained in the original data spreadsheet that was already expressed in metric units, such as altitude. The final step of the process was to save the selected data spreadsheet in a file format that was compatible with ArcGIS™ software.

4.3 Importation of Data into ArcGIS™

To view the geographic location where data were collected in a field, the selected data spreadsheet was entered into the ArcGIS™ program ArcMap™ 10. The ArcMap™ 10 program gives the user the ability to select data based on its geographic location. This is especially valuable to determine the effects, if any, of unique spatial features of agricultural fields on machine performance. It was also essential to identify the planter state of operation and operational transition points. The process to import data into ArcMap™ 10 can be seen in Figure 1.

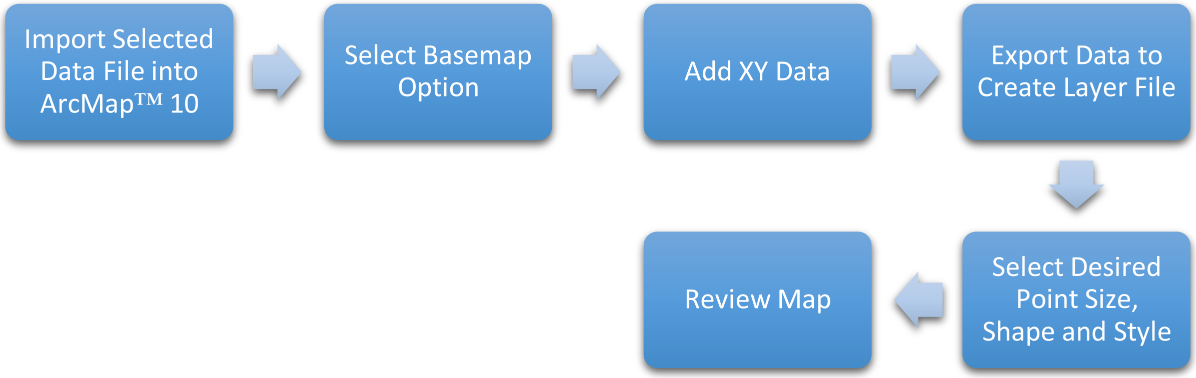


Figure 1: General process to import and view data in ArcMap™ 10.

In order for the GPS coordinates to display on the "Basemap" in the proper geographic location, the proper coordinate system had to be selected. To change the default coordinate system, the "Edit" option was selected under the "Display XY Data" menu seen in Figure 2. The "WGS 1984.prj" coordinate system was ultimately selected so the data points would display in the proper geographic location. Figures 3 and 4, display examples of the maps generated by ArcMap™ 10.

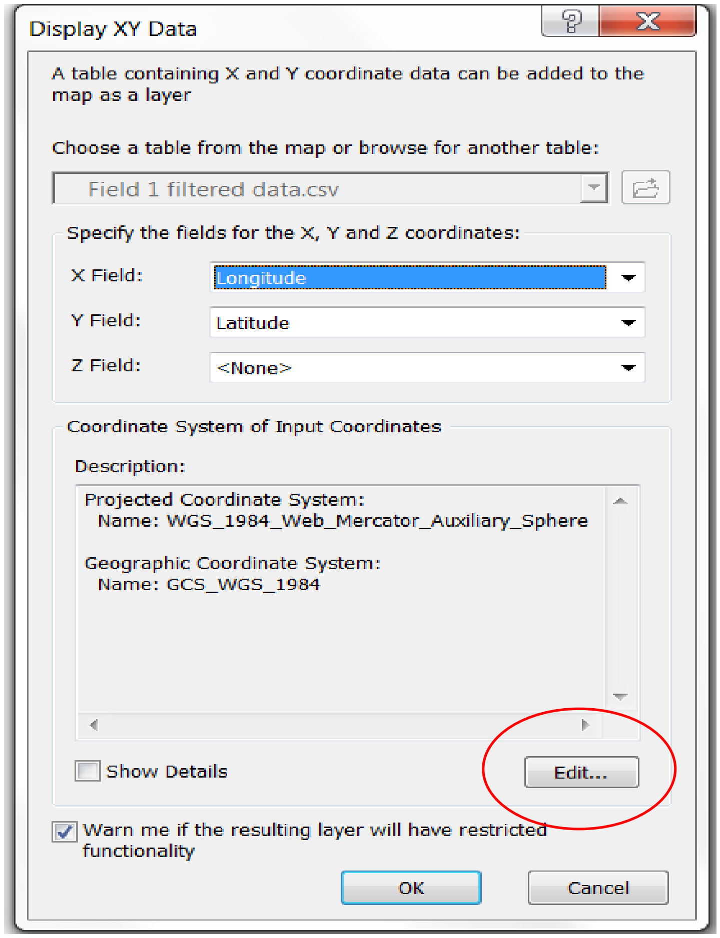


Figure 2:"Display XY Data" menu of ArcMap™ 10.

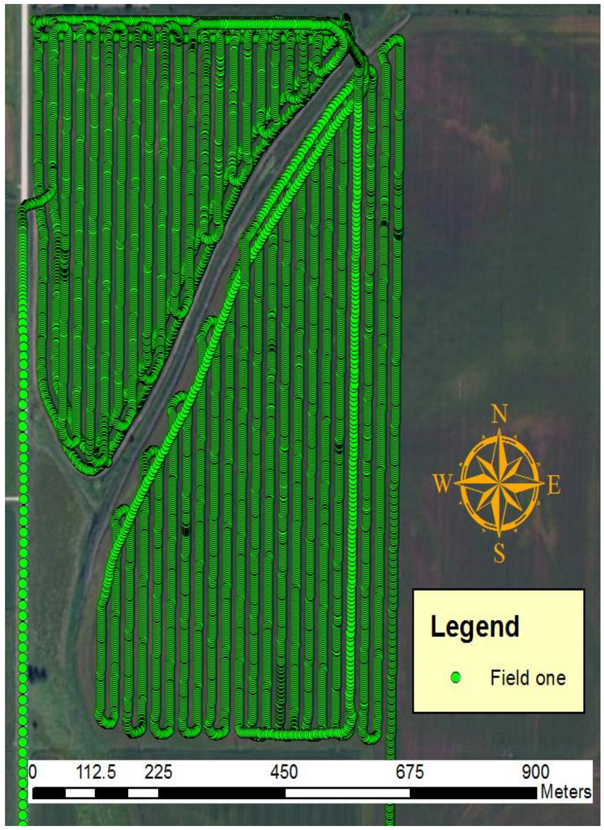


Figure 3: ArcMap™ 10 generated map.

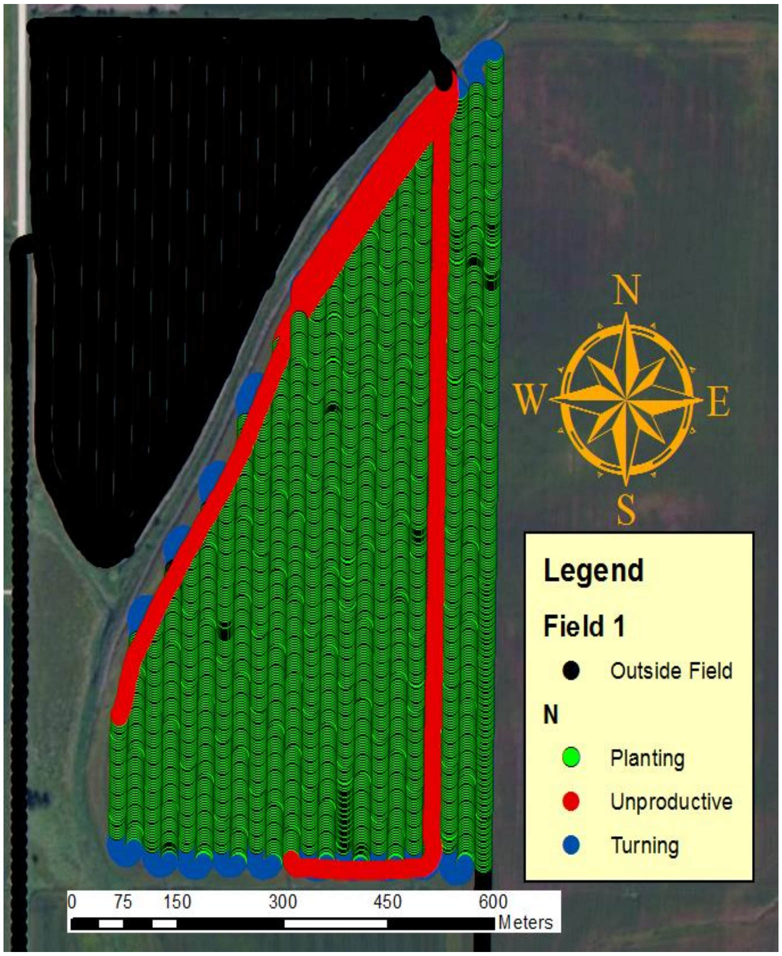


Figure 4: Map displaying operational state by point color.

4.4 Determining Planter State of Operation and Operational Transition Points

No data were collected directly from the John Deere 1770NT planter itself, which was used to complete the planting operations that were studied in the project. Therefore, there was no way to be certain what operational state the planter was in at any point in time. The operational state of the planter could be estimated with some confidence by reviewing the map generated in ArcMap™ 10. By reviewing the location of the data points and the tractor speed, the majority of the planting, turning and unproductive points could be identified. Determining the operational transition points required more consideration. A methodology was therefore developed to estimate operational transition points, specifically, points where the planter transitioned from planting to turning at the end of a row and turning to planting at the beginning of a row. The following sections discuss the various methods that were attempted to determine operational transition points. The last method presented in section 4.4.3 was considered to be the most accurate.

4.4.1 Visual Analysis to Determine Operational Transition Points

Originally, data points were viewed visually in ArcMap™ 10 by the user and the last point before the tractor appeared to turn at the end of a row was considered to be the last point where the planter was planting before transitioning into a turn. The first point where the tractor appeared to line up with subsequent data points at the opposite side of the turn was considered to be the first point of the next planted row, that is, where the planter would have transitioned from turning to planting. This method seemed reasonable but it was decided that a more specific method should be determined. The GPS receiver that was used to determine the geographic position of the tractor/planter was located on the tractor cab and not on the planter. This means the data points on the map represent the location of the tractor cab and not the location of the planter. When a tractor/planter exits a row, the tractor passes the edge of the field before the planter, this means the while the tractor has already exited the field, the planter has not and is likely still planting. The operator then turns and because the tractor leads the planter, the tractor enters the field while the planter is still in the headland. It was assumed that the operator would lift the planter right before turning to plant the next row. While this assumption seemed appropriate to determine the point where a turn began, it did not solve the issue of determining when the planter re-entered the field and was lowered in order to begin planting. Figure 5, shows a typical tractor/planter turn. The highlighted points indicate the points that would have been selected as “turning” points by simply viewing the map.

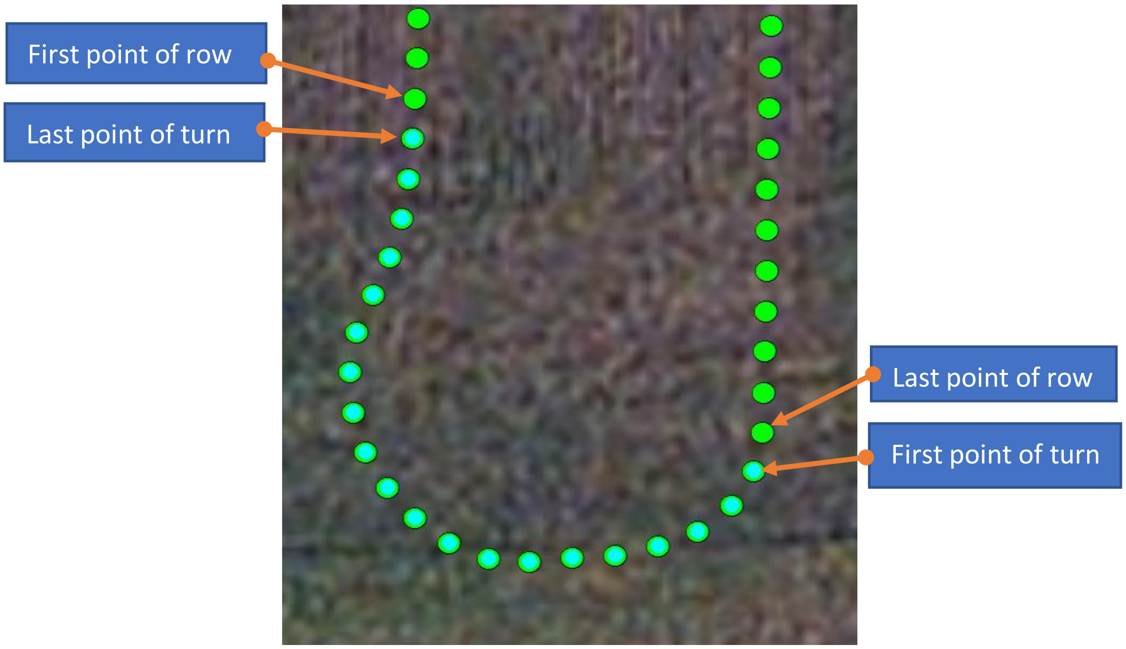


Figure 5: Highlighted points would be considered “turning” points using the visual analysis method.

4.4.2 Torque Variation Observation

Another method considered to help estimate operational transition points, was the review of tractor torque production. It was assumed that the tractor engine would produce more torque when the planter was raised due to the increased load on the engine to operate the hydraulics needed to raise the planter. It was assumed that engine torque production would then reduce when the planter was fully raised and the operator disengaged the hydraulics. It was also assumed that engine torque production would increase when the planter was lowered and contacted the ground because the load on the engine was expected to increase. A review of the data revealed that engine torque production varied more or less between turns. Figures 6 and 7, show an analysis completed on a turn to determine if changes in torque production could be used to determine the planter operational transition points. The red, green and orange circles in Figure 6, correspond to the red, green and orange circles, respectively, in Figure 7. As expected, there does appear to be an increase in torque production at the end of the right side row where the planter would have been lifted. However, there were two large torque drops that can be seen in Figure 7, shortly after the torque rise. After reviewing the photo, it was noticed that the torque drops occurred when the tractor/planter was still well inside the turn. It was decided that because engine torque production was varying in unexpected places, that using engine torque production to determine operational transitions points would be unwise. The variations in torque production during the turn could possibly be due to the operation of the power steering pump, changes in drag experienced at the soil-tire interface or by the mechanical front-wheel drive system.

Figure 6: The circled points correspond to the circled points (by color) in Figure 7, to show where torque sharply increases or decreases.

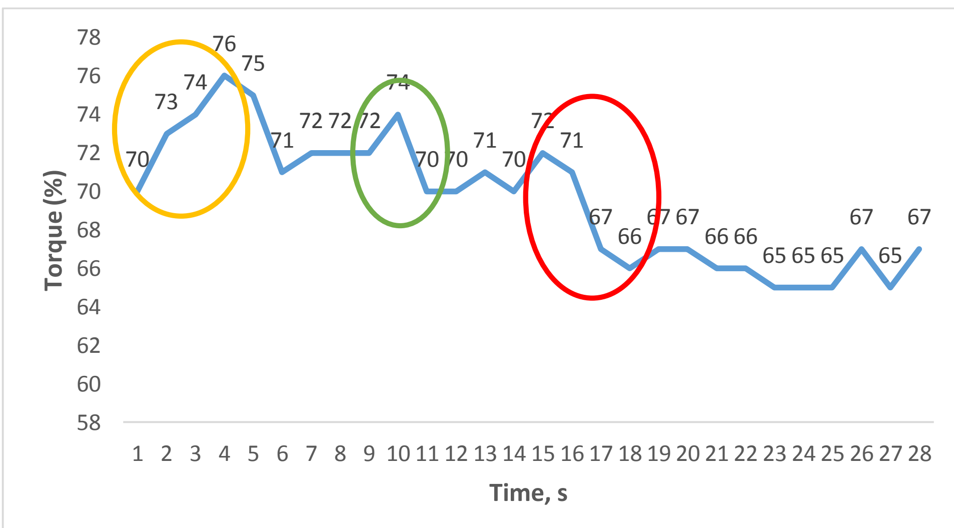


Figure 7: Sharp increases and decreases in torque inside of the turn seen in Figure 6.

4.4.3 Visual Analysis with the Aid of Measurement Information

When the previous methods were determined to be inadequate to determine the operational transition points of the 1770NT planter, a new method was created. As previously stated, it was assumed that the operator would raise the planter right before turning. However, this assumption did not solve the issue of determining when the planter would re-enter the field and be lowered after the turn was achieved. It was known that the GPS receiver on the tractor was positioned on the cab. The data points seen on the maps in Figures 5 and 6, indicate the position of the GPS receiver and not the planter. A phone call was made to a local John Deere dealership that revealed the distance between the GPS receiver on an 8360R tractor and the center of a 1770NT planter was 7.46 meters (24.5 feet). With this information, a new method was investigated.

It was assumed that the operator would lower the planter at the beginning of a row, at the place directly adjacent to where it had been raised when planting the previous row. With the use of machine speed data, distance was estimated to determine approximately how far behind the GPS receiver the planter would be located on the map. It was known that a data point was recorded for every second (1 Hertz) of operation, meaning that each point on the map represents one second of time. The last point in a row before the tractor turned, was selected and the speed at this point along with the speeds from the two points before and after this point were averaged together to determine an average machine speed for the area.

Once the travel speed in meters per second was determined, the distance between the GPS receiver and the planter, which was known to be 7.46 meters, was divided by the number of meters traveled per second to determine the number of seconds required for the tractor to travel

7.46 meters. The subsequent answer was then determined to be the number of data points between the GPS receiver and the planter. The “Points btw” categories in Tables 1 and 2, reveal the number of points between the tractor and planter. Tables 1 and 2, represent the right and left side of the turn in Figure 8, respectively. Figure 9, represents the estimated position of the tractor and planter over three rows.

Table 1: Points selected to determine the number of points between (Points btw.) the GPS receiver and the planter at the beginning of the turn in Figure 8.

Point	Speed in km h^{-1}	m s^{-1}	Planter length in m	Points btw.
1	7.92	2.2	7.46	3.39
2	8.47	2.35	7.46	3.17
3	7.92	2.2	7.46	3.39
4	7.36	2.04	7.46	3.64
5	7.18	1.99	7.46	3.73
Average	**7.77**	**2.16**	**7.46**	**3.45**

Table 2: Points selected to determine the number of points between (Points btw.) the GPS receiver and the planter at the end of the turn in Figure 8.

Point	Speed in km h^{-1}	m s^{-1}	Planter length in m	Points btw.
17	7.36	2.04	7.46	3.66
18	7.36	2.04	7.46	3.66
19	7.18	2.00	7.46	3.74
20	7.55	2.10	7.46	3.56
21	7.92	2.20	7.46	3.39
Average	**7.47**	**2.07**	**7.46**	**3.60**

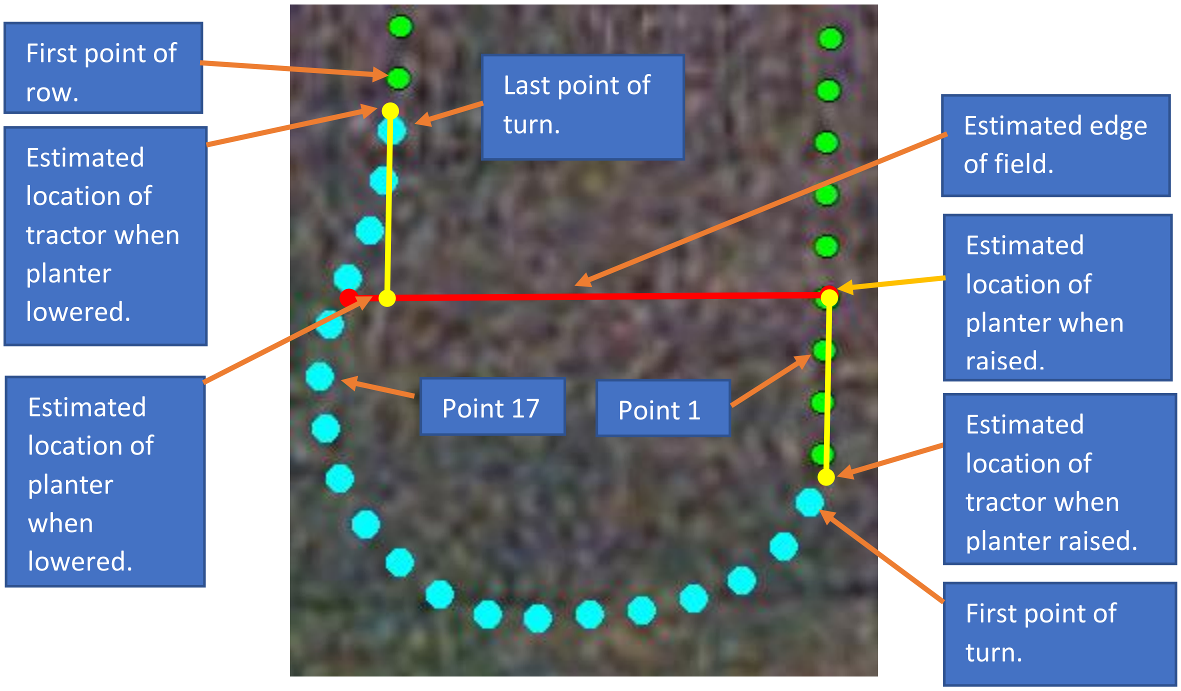


Figure 8: Estimation of tractor and planter location to determine operational transition points.

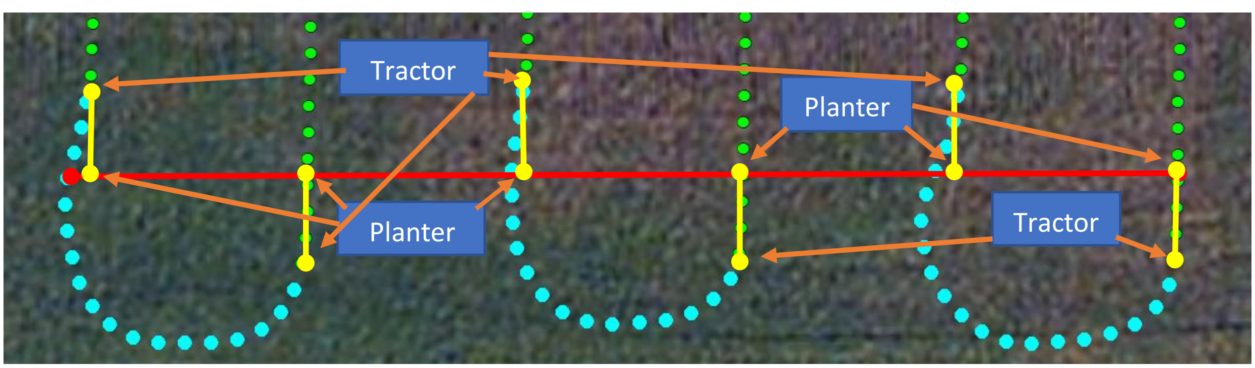


Figure 9: Estimated position of the tractor and planter across three rows.

4.4.4 Operational Transition Point Selection

Once the operational transition points were determined for each field, the “Object-ID” numbers of the planting points, turning points and unproductive points were noted and recorded. Unproductive points, were considered any points where machine speed was equal to zero, or the tractor/planter was traveling at the edge of a field and/or at a very high rate of speed. The “Object-IDs”, are simply numbers assigned to each row of data that was entered into ArcGIS™, starting with number one and continuing in numerical order up to the last row of data. Once the relevant data was identified in ArcGIS™, the identical data in the “selected data spreadsheet” was selected and analyzed.

4.5 Distance and Area Estimation

The size of each field was determined using the planter width. The working planter width was determined to be 18.7 meters from JohnDeere.com (John Deere, 2014c). ArcMap™ 10, has a drawing feature that allows the user to draw shapes on the map. Since the distance of the planter was known to be 18.7 meters and half of the planter exists on the left side of the tractor and half on the right side of the tractor, a line was drawn in ArcMap™ 10 to represent the 18.7 meter width distance of the planter. The red line in Figure 10, represents the distance of four planters, which amounts to 74.8 meters (18.7*4). ArcMap™ 10, allows for the red line that was drawn to be moved anywhere on the map. Therefore, the line was selected and used as a measuring stick to measure the length and width of each field. Figure 11, represents an example of a field measured using the technique previously described. The area of each conventionally shaped (rectangular) field was calculated using

$$A = \frac{lw}{10000} \qquad (1)$$

where: $A =$ hectares

$l =$ length, m

w = width, m

One field considered was shaped like a right angle triangle. The area of that field was calculated using

$$A = \frac{\frac{bh}{2}}{10000} \qquad (2)$$

where: A = hectares

b = base distance, m

h = height distance, m

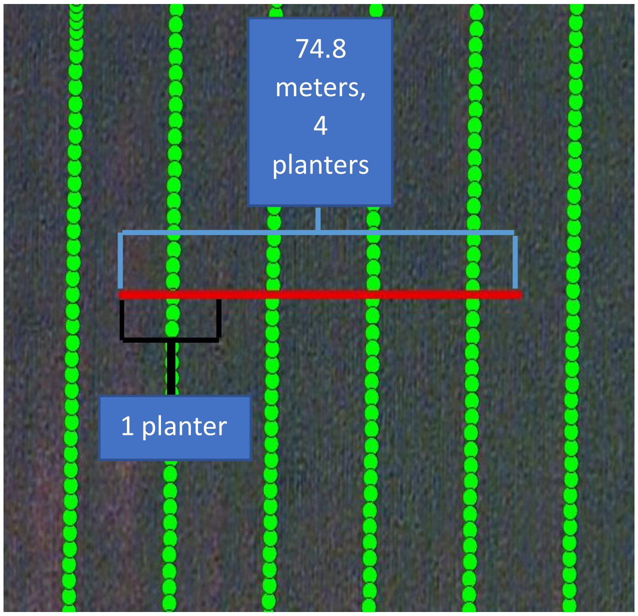


Figure 10: Technique used to measured distance using known planter width.

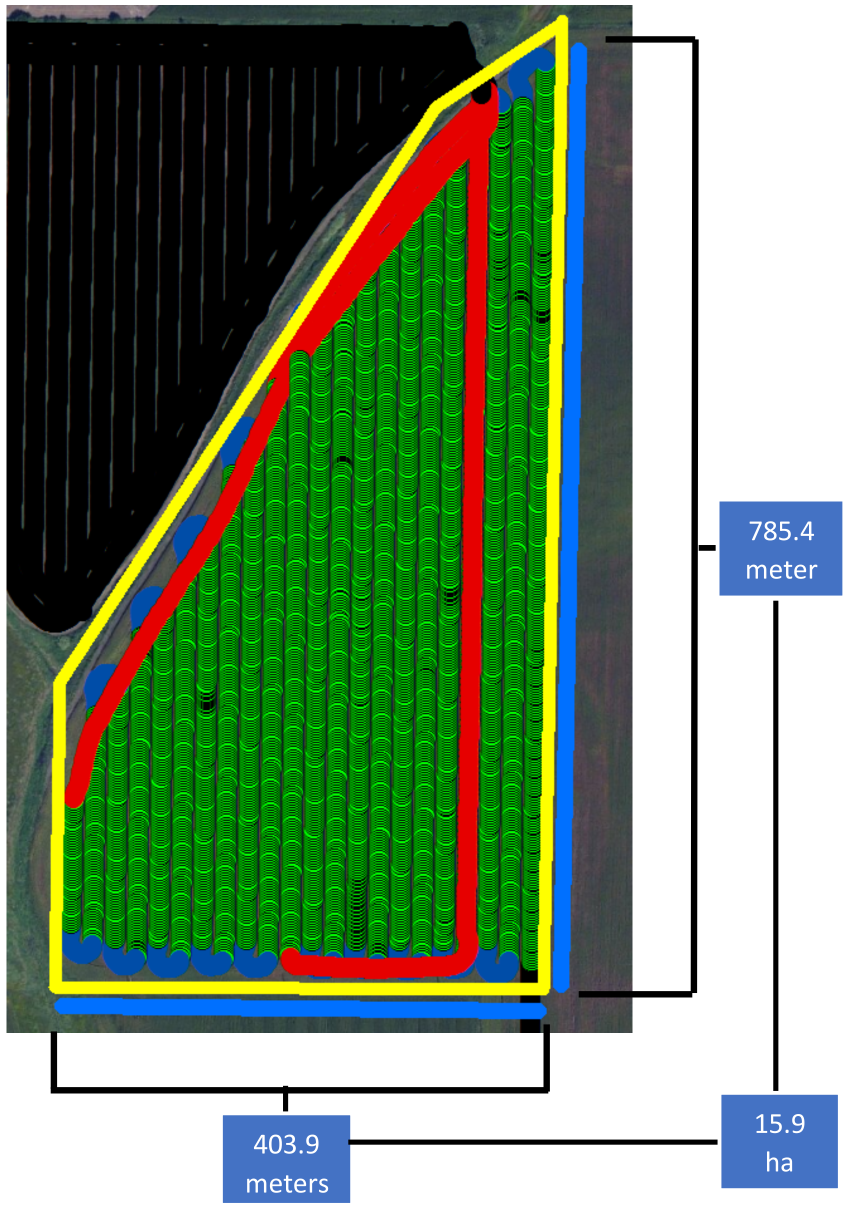


Figure 11: Outline and distance information of a selected field.

4.6 Data Analysis Templates

To expedite the data analysis process, two spreadsheets were created with the use of Microsoft Excel. The primary data analysis spreadsheet was designed to determine productivity, efficiency, performance and economic information automatically after the selected data was entered into the specified cells. To create these spreadsheets, a range of equations and Excel functions were entered into Excel spreadsheets and referenced to certain columns of cells in those spreadsheets in order for the information of interest to be determined automatically when data were entered. The following sections detail the creation of the data analysis spreadsheets.

4.7 Primary Data Analysis Spreadsheet

The primary data analysis spreadsheet included several sections including: Performance Indicators, Economic Costs and Engine Performance. The Engine Performance section included fuel predictions from both the ASABE general method and the method for specific tractor models developed by Grisso et al. (2008a). An "Input Data" section and a "Factors and Constants" section were also included in the primary data analysis spreadsheet because the equations selected to determine the desired information require certain variables to be known. The "Input Data" section included: Size of Field (ha), Labor Rate ($ h^{-1}.), Rated PTO Power (kW), Rated Engine Speed (r min^{-1}), Full Throttle Engine Speed (r min^{-1}), Price of Diesel Fuel ($ gallon^{-1}), Machine List Price ($), Number of Turns in Field and Implement Width (m). The engine related information was determined from NTTL reports. The determination of the economic information is described in section 4.7.2, "Estimated Machinery Costs." The Excel functions utilized to calculate the information of interest in this project can be seen in Table 3.

Table 3: Excel functions used to determine the desired information from data entered into the primary data analysis spreadsheet.

Function	Purpose	Example
AVERAGE	Calculates the arithmetic mean of the data in a specified cell range	=AVERAGE(N4:N400000) This function was primarily used to calculate average engine speed and torque.
AVERAGEIF	Calculates the arithmetic mean of the data in a specified cell range that meets specified criteria	=AVERAGEIF(N4:N400000,“>0”) This function was used to calculate average machine speeds. Only the average moving machine speed was of interest. Therefore, the AVERAGEIF function was utilized so machine speeds of zero would not be averaged with the moving speeds.
COUNT	Counts the number of cells in a specified range that contain numbers	=COUNT(N4:N400000) This function was utilized to determine time information. Due to that fact that data was collected at 1 Hertz, each data cell represented one second of time. Therefore, the COUNT function was used to count the number of cells containing data to determine the number of seconds the machine was planting, turning, unproductive and inside the field altogether.
COUNTIF	Counts the number of cells in a specified range that meet a specified criteria	=COUNTIF(N4:N400000,“=0”) The COUNTIF function allowed the user to specify criteria necessary for a data point to be counted. To determine when the machine was being unproductive when it was expected to be planting or turning, the COUNTIF function was used to count the number of zeros in the planting and turning speeds data columns.
COUNTIFS	Counts the number of cells in a specified range that meet multiple specified criteria	=COUNTIFS(N4:N400000,“>2.00”,N4:N400000,“<2.51”) The COUNTIFS function was utilized when data was required to meet multiple criteria to be counted. This function was utilized to count the number of seconds the machine spent inside a specified speed range. It was also used to determine the amount of time a machine spent inside a specified engine speed and torque range.

Table 3 (cont.)

MAX	Locates and returns the greatest number found in a specified range of cells	=MAX(N4:N400000) This function was used to determine the maximum value in sets of data.
MEDIAN	Returns the median value of a specified range of cells	=MEDIAN(N4:N400000) This function was used to determine the median value in sets of data.
MIN	Locates and returns the least number found in a specified range of cells	=MIN(N4:N400000) This function was used to determine the minimum value in sets of data.
STDEV.P	Determines standard deviation of a population	=STDEVP(N4:N400000) This function was used to determine the standard deviation in sets of data.

4.7.1 Performance Indicators

Machine speed is one of the two major variables concerning machine capacity. Therefore, a group of Excel functions and charts were created to determine and display machine speed information. These data can be used to benchmark tractor/planter operations concerning speed variability. Speed data was determined for two expected machinery states of operation concerning the planter: planting and turning. The ability of the machine operator to maintain the expected state of operation was evaluated. Additionally, theoretical field capacity, field efficiency and actual field capacity were determined for the operation. The Excel functions listed in the above table were utilized to determine the performance indicators listed in Table 4.

Table 4: Performance indicators determined for each selected field.

Performance Indicators
Avg. in-row speed (km h^{-1})
Avg. turn speed (km h^{-1})
Max. in-row speed (km h^{-1})
Min.in-row speed (km h^{-1})
Max. turning speed (km h^{-1})
Min. turning speed (km h^{-1})
Average Turn Time (s)
Time spent turning (min)
Time in field (h)
Unproductive time (min)
Theoretical Field Capacity (ha h^{-1})
Actual Field Capacity (ha h^{-1})
Field Efficiency (%)

To study variability in speed data, histograms were generated in Microsoft Excel (Figure 12). A total of 19 speed range categories were created. The first category included speeds of 0-1.5 km h^{-1} and the categories increased incrementally up to the 10.01 km h^{-1} and higher category.

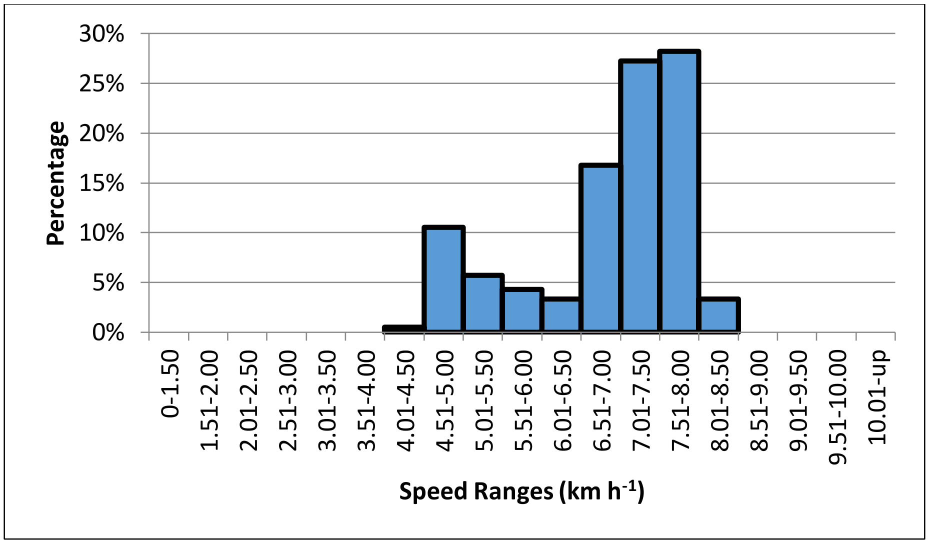


Figure 12: Speed histogram generated in Microsoft Excel.

The field capacity of each field was calculated using

$$C_a = \frac{v\, w\, \eta_f}{10} \tag{3}$$

where: C_a = field capacity, ha h^{-1}

v = travel speed, km h^{-1}

w = machine working width, m

η_f = field efficiency, decimal

The field efficiency of each field was calculated using

$$\eta_f = \frac{\tau_t}{\tau_e + \tau_h + \tau_a} \tag{4}$$

where: τ_t = theoretical time required to complete the operation per unit area, h

τ_e = effective operating time per unit area, h

τ_h = time losses not proportional to area, h

τ_a = time losses proportional to area, h

4.7.2 Estimated Machinery Costs

In order to benchmark planting operations economically, equations from ASABE standards EP493.3 (ASABE, 2006) and D497.7 (ASABE, 2011) were utilized. The equations used require certain factors and constants for calculations to be made. Therefore, a "Factors and Constants" table was included in the primary data analysis spreadsheet seen in Table 5. Past research has noted that the operation of agricultural tractors has the potential to serve as a major cost for agricultural operations (Buckmaster, 2003). Therefore, the primary data analysis spreadsheet was designed to determine economic information of interest to farmers, machinery manufacturers and researchers. The primary data analysis spreadsheet was designed to be compatible with 4WD and 2WD tractors. The John Deere 8360R tractor considered in this study was a front wheel assist model, so the 4WD repair and maintenance calculation was considered to be the repair and maintenance cost of the operations studied and the 2WD repair and maintenance calculation was ignored.

Table 5: Factors and constants section of the primary data analysis spreadsheet.

Factors and Constants
4 wheel drive and crawler tractors
RF1=
RF2=
2 wheel drive tractors
RF1=
RF2=
All machines
Rated Torque
PTO power req. for operation (P)
PTO rated (Pr)
X(P/Prated)=
partial throttle engine speed (nPT)
full throttle engine speed (nFT)
N
partial throttle multiplier (PTM)

The economic information presented in Table 6, was determined for each operation studied in this project. Fuel costs were calculated using both the ASABE general fuel consumption prediction method and the specific tractor model prediction method created by Grisso et al. (2008a). The price of diesel fuel in the Urbana-Champaign area of Illinois as of May 16, 2014 was $3.88/gallon ($1.03/liter) (AAA, 2014). To determine the cost of off-road diesel fuel, federal and state motor fuel taxes were subtracted from the price of on-highway diesel fuel as prescribed by the U.S. Energy Information Administration to estimate the cost of off-road diesel fuel (U.S. Energy Information Administration, 2014). According to the U.S. Energy Information Administration, federal and state highway taxes in the state of Illinois account for 21.5 cents of the cost of one gallon of diesel fuel (U.S. Energy Information Administration, 2012). Therefore, the estimated cost of off-road diesel fuel in the state of Illinois was considered to be $3.66 gallon^{-1}. The cost of engine oil was considered to be 10% of the total fuel costs.

According to the University of Illinois farmdoc website, \$18.7 h^{-1} is an accurate labor rate for tractor operators in Illinois as of May 16, 2014. (Ellinger et al., 5/16/2014). The \$18.7 h^{-1} labor rate was multiplied by the number of hours a machine spent in a field to determine the labor cost. The machine list price in this case was considered to be approximately \$296000 (Tractor data.2013).

Table 6: "Estimated Machinery Costs" determined for each operation.

Economic Costs
Repair & Main. (4WD) (\$)
Repair & Main. (2WD) (\$)
Fuel/Oil Cost (\$) (ASABE)
Fuel/Oil Cost (\$) (Specific)
Labor Cost (\$)

Repair and Maintenance cost was calculated using

$$C_{rm} = (RF1)\, P \, \frac{h}{1000}^{(RF2)} \quad (5)$$

where: C_{rm} = repair and maintenance cost, \$

$RF1 =$ repair and maintenance factor (0.003 for 4WD, 0.007 for 2WD)

$RF2 =$ repair and maintenance factor (2.0 for 4WD and 2WD)

$P =$ machine list price, \$

h = use of machine, h

4.7.3 Engine Performance

Determining and evaluating engine performance information was a major area of interest in this project. Average engine power was determined for each planting operation using the average engine torque (Nm) and engine speed (r min^{-1}) for each operation as a whole. Engine fuel consumption and fuel efficiency were also of strong interest in this project. As mentioned previously, two methods were used to determine fuel consumption and efficiency. The general method outlined in ASABE D497.7 section 3.3.3 (ASABE, 2011) was utilized and the results compared with the method to predict fuel consumption of specific tractor models developed by Grisso et al. (2008a). The method for specific tractor models has been found to be very accurate in past research at predicting fuel consumption when compared to measured fuel consumption data obtained by the NTTL for a specific tractor model (Grisso et al., 2008a). The engine performance information determined for each operation can be seen in Table 7. Engine power was determined using

$$Pb = \frac{2\pi NT}{60000} \tag{6}$$

where: $Pb =$ brake power, kW

N = engine speed, r min^{-1}

T= engine torque, Nm

Table 7: "Engine Performance" measures determined for each field.

Engine Performance
Average engine speed (r min^{-1})
Average torque (Nm)
Average Power (kW)
Fuel consumption (L h^{-1}) (ASABE method)
Fuel consumption (L h^{-1}) (specific method)
Fuel efficiency (L kWh^{-1}) (ASABE method)
Fuel efficiency (L kWh^{-1}) (specific method)
Fuel efficiency (L ha^{-1}) (ASABE method)
Fuel efficiency (L ha^{-1}) (specific method)
Total volume of fuel consumed (L) (ASABE)
Total volume of fuel consumed (L) (specific)
Total energy required (MJ ha^{-1})

The total energy required to complete the operation, was calculated by multiplying the average power in kW by the number of hours in the field to determine the kWh of energy required. The resulting answer was multiplied by 3.6 and divided by the total number of hectares constituting the field to determine MJ ha^{-1}.

A large amount of input information is required to use the prediction method for specific tractor models created by Grisso et al. (2008a). The input information was obtained from the 8360R NTTL report (Nebraska Tractor Test Lab, 2011). The input data required is not reviewed here but can be seen in Appendix A. The equation to predict fuel consumption of specific tractor models can be seen below.

Fuel consumption in L h^{-1} was calculated using

$$Q = (a\,X + b)[1 + (c\,X\,N_{Red} - d\,N_{Red})]\,P_{pto} \quad (7)$$

where: Q = fuel consumption, L h^{-1}

a, b, c, d = coefficients as described by Grisso et al. (2008a)

X = the ratio of equivalent PTO power to rated PTO power, decimal

N_{Red} = equation outlined by Grisso et al. (2008a), see below

P_{pto} = the rated PTO power of the tractor, kW

N_{Red} was calculated using

$$N_{Red} = \frac{(RPM_F - RPM_R)}{RPM_F}\,100 \quad (8)$$

where: N_{Red} = percentage of engine speed reduction during drawbar 50 and 75% load tests

RPM_F = Full throttle engine speed, r min^{-1}

RPM_R = Reduced throttle engine speed, r min^{-1}

The fuel consumption in L h^{-1} was used to determine fuel efficiency and the total amount of fuel consumed for each operation. To verify the accuracy of the fuel prediction method for specific tractor models, operating parameters from the John Deere 8360R NTTL report (Nebraska Tractor Test Lab, 2011) were input into the primary data analysis spreadsheet. The predicted fuel consumption determined by the model was compared to the measured fuel consumption data provided in the "Varying Power and Fuel Consumption" section of the NTTL report. The power ratings in this section of the NTTL report were taken from the PTO. The PTO power was divided by 0.90 to determine engine power as per ASABE D497.7. The accuracy of the model was considered sufficient to benchmark fuel consumption. The results can be seen below (Table 8).

Table 8: Measured vs. predicted fuel consumption.

PTO Power (kW)	Measured fuel consumption ($L\ h^{-1}$)	Predicted fuel consumption ($L\ h^{-1}$)	Difference (%)
240	66.8	67.7	1.3
210	59.4	60	1
158	47.2	48.4	2.5
106	35.7	37.5	5
53.1	24.4	26.1	6.9
2.81	16.4	15.5	-5.8

The SFC (general prediction method) for each operation was calculated using

$$SFC_v = \left(0.22 + \frac{0.096}{X}\right) PTM \tag{9}$$

where: SFC_v = specific fuel consumption volume, L kWh^{-1}

$X =$ equivalent PTO power required, kW

$PTM =$ partial throttle multiplier

The partial throttle multiplier was calculated using

$$PTM = 1 - (N - 1)(0.45\,X - 0.877) \tag{10}$$

where: PTM = partial throttle multiplier

$$N = \frac{partial\ throttle\ engine\ speed,\ r\ min^{-1}}{full\ throttle\ engine\ speed,\ \ r\ min^{-1}}$$

$$X = \frac{equivalent\ PTO\ power\ required\ by\ current\ operation,\ \ kW}{rated\ PTO\ power\ available,\ \ kW}$$

4.8 Secondary Data Analysis Spreadsheet

A second spreadsheet was developed to determine how much time the tractor's engine spent in the specified speed and torque ranges seen in Figure 13. Microsoft Excel's COUNTIFS function was utilized to determine the distribution of engine speed and torque data. These spreadsheets provided an excellent idea concerning the extent of engine loading during the planting operations. Based on the histogram seen in Figure 13, bar-type histograms were generated and can be seen in Figures 14 and 15.

4.9 Engine Performance Histograms

Mid-point of engine speed range

Torque %

	870	1010	1150	1290	1430	1570	1710	1850	1990	2130	
125	0	0	0	0	0	0	0	0	0	0	0
115	0	0	0	0	0	0	0	0	0	0	0
105	0	0	0	0	0	0	0	0	0	0	1
95	0	0	0	0	0	0	0	0	0	0	1
85	0	0	0	0	1	0	0	0	0	0	2
75	0	0	0	0	12	1	0	0	0	0	14
65	0	0	0	0	29	3	0	0	0	0	33
55	0	0	0	0	22	2	0	0	0	0	25
45	0	0	1	1	7	1	0	0	0	0	9
35	0	0	1	1	2	1	0	0	0	0	5
25	0	1	3	1	1	0	0	0	0	0	6
15	0	2	1	0	0	0	0	0	0	0	4
5	0	0	0	0	0	0	0	0	0	0	1
%	0	3	7	3	75	9	2	1	0	0	100
800	940	1080	1220	1360	1500	1640	1780	1920	2060	2200	

Percentage of points in range.

Speed range, 1500-1640

Percentage of points in range.

Figure 13: Percentage of time in speed and torque range.

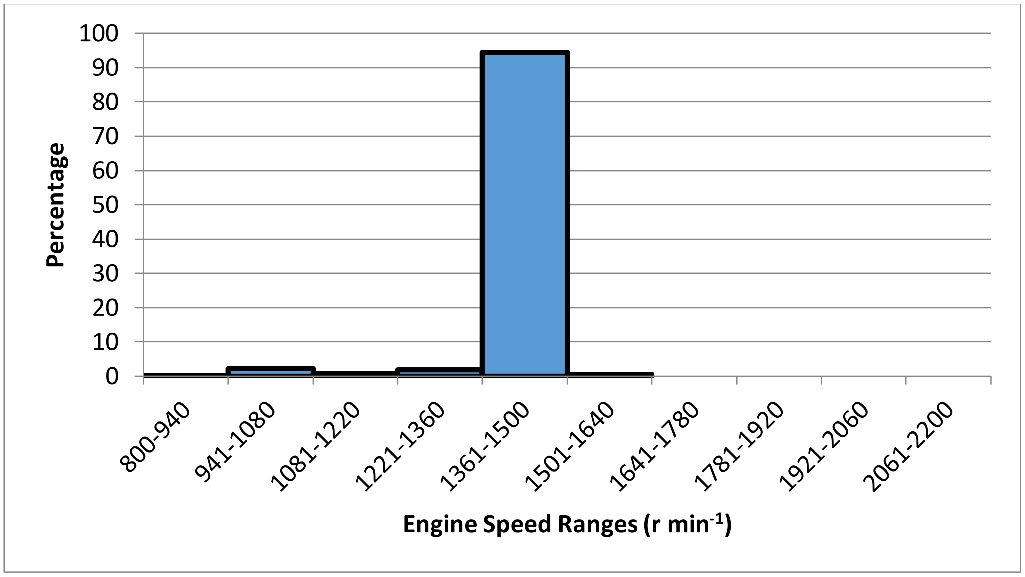


Figure 14: Engine speed histogram.

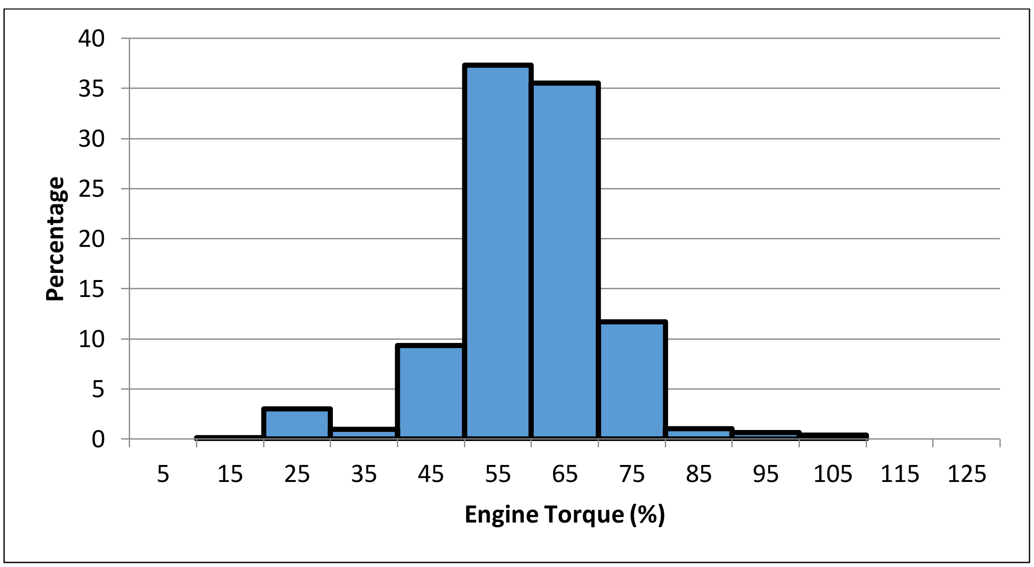


Figure 15: Engine torque histogram.

CHAPTER 5: RESULTS AND DISCUSSION

The methodology presented in the previous chapter was utilized to benchmark two corn planting operations located on a farm in east-central Iowa. The fields were designated field one and field two and can be seen as Figures 16a and 16b. A complete record of the general benchmarking information for field one and field two can be found in Appendix A. The benchmarking methodology was used to explore the effects of a water way running through field one on machine performance and is presented in section 5.1. A row by row analysis of field two was conducted to determine the effect of field slope (%) on engine performance and can be found in section 5.2. Finally, a comparison of the benchmarking analysis of field one and field two is presented in section 5.3.

(a) **(b)**

Figure 16a and 16b: Images of field one (a) and field two (b) showing the path taken by the tractor during planting.

5.1 Field Shape and Machine Performance

Field one was selected for analysis to determine the effect of the field's shape on the tractor/planter's performance. As shown in Figure 16a, a water way runs through field one and splits the field approximately 60/40, the southern section accounting for 60% of field one's area and the northern section accounting for 40% of field one's area. The southern section of the field was 15.9 hectares in size and the northern section 10.3 hectares. The methodology presented in the previous chapter was used to benchmark only the southern section of this field. The row spacing in the southern section of the field made it relatively easy to determine where planting took place, but the spacing of two specific rows in the northern section of the field made it difficult to determine the planter state of operation in those two rows. Due to the fact that no data were collected from the planter, the state of planter operation could not be determined with any certainty in the northern section of the field. A photo displaying the two rows in the northern section of field one that made it difficult to determine the planter state of operation can be seen in Appendix B. The input data and calculated performance indicators for the southern section of field one can be seen in Table 9.

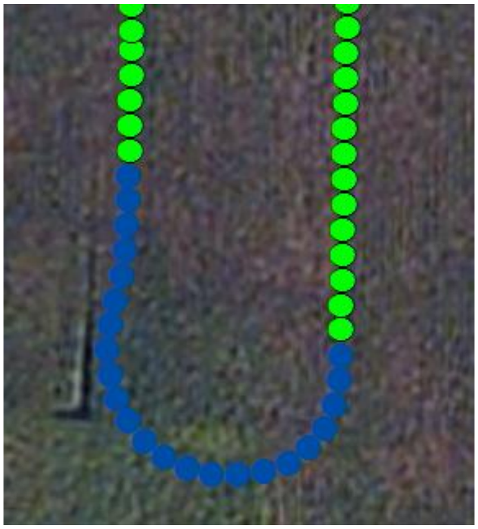
Table 9: Input and performance indicator information for the southern section of field one.

Input Data	Info.
Size of field (ha)	15.9
Labor rate ($ h^{-1})	18.7
Rated PTO power (kW)	240
Rated engine speed (r min^{-1})	2100
Full throttle engine speed (r min^{-1})	2225
Price of diesel fuel ($ gal^{-1})	3.66
Machine price ($)	296,000
Number of turns in field	20
Implement width (m)	18.7

Performance Indicators	Info.
Avg. row speed (km h^{-1})	7.66
Avg. turn speed (km h^{-1})	7.27
Max. row speed (km h^{-1})	8.47
Min. row speed (km h^{-1})	0
Max. turn speed (km h^{-1})	9.21
Min. turn speed (km h^{-1})	0
Average turn time (s)	23.7
Total time spent turning (min)	7.9
Unproductive time (min)	11.3
Total time in field (h)	1.68
Theoretical field capacity (ha h^{-1})	16.8
Actual field capacity (ha h^{-1})	9.46
Field efficiency (%)	56.3

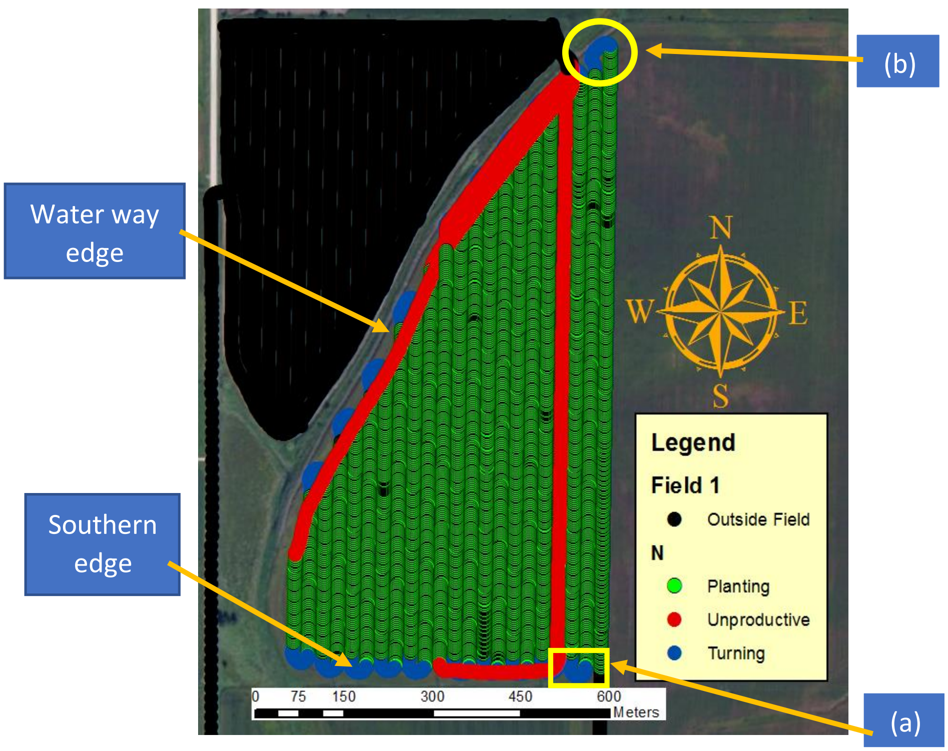
5.1.1 Machine Turning Performance

A consequence of the water way being present in field one was that the tractor/planter operator was required to make a different shaped turn every time the tractor/planter reached the water way edge of the field. The southern edge of field one was relatively straight and the operator was able to make a conventionally shaped turn at that edge of the field. Figure 17, displays an example of each type of turn. The data points in Figure 17 have been color coordinated to show planting points in green, turning points in blue and unproductive points in red. The benchmarking methodology outlined in Chapter 4, was utilized to study the effects of the water way on the turning performance of the tractor/planter. The average turning time at the water way edge of the field was 26.7 seconds as opposed to 20.9 seconds at the southern edge of the field. As a result, the operator spent 4.45 total minutes turning at the water way edge of the field as compared to 3.48 minutes at the southern edge of the field. The turns at the water way edge of the field therefore contributed an extra 58.2 seconds to the total turning time. This accounts for 12.3% of the total turning time of 7.9 minutes. The greater the turning time, the longer the machine is in the field. In this case, total turning time was increased by 13.5% due to the presence of the water way. It can be seen in Table 10, that the tractor/planter stopped at one point at the water way edge of the field. It can also be seen in Figure 19, that the tractor planter spent some time in the 0-1.50 speed range at the water way edge of the field. The tractor/planter spent more time at higher travel speeds when turning at the water edge of the field versus the southern edge of the field. The turning speed histogram for the southern edge of the field can be seen in Figure 18. The tractor/planter was able to turn faster at the water way edge of the field compared to the southern edge but not fast enough to overcome the increased distance of the different shaped turn and match the turning time at the southern edge of the field.



(a)

(b)



(c)

Figure 17a, 17b and 17c: (a) is the turn pattern from the southern edge of field one (c), (b) is the turn pattern from the water way edge of field one (c).

Table 10: Basic analysis of turning data at the southern and water way edge of field one.

Variable	Water way edge	Southern edge
Maximum (km h^{-1})	9.21	8.29
Minimum (km h^{-1})	0	4.23
Range (km h^{-1})	9.21	4.05
Average turn speed (km h^{-1})	7.57	6.88
Median (km h^{-1})	7.92	7.18
Std. Dev. (km h^{-1})	0.99	1.00
Average Turn Time (s)	26.7	20.9
Overall Turn Time (min)	4.45	3.48

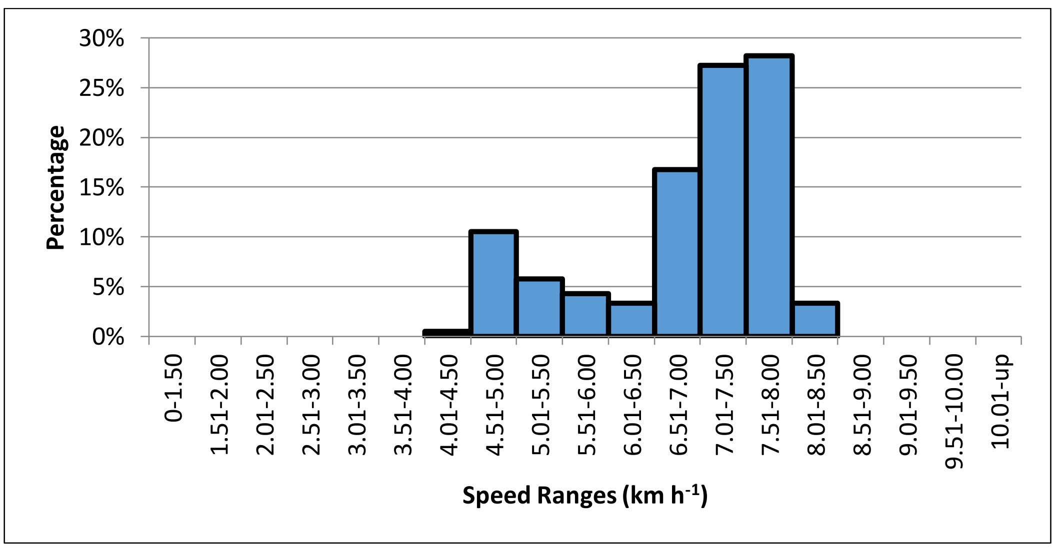


Figure 18: Distribution of turning speed data from the southern edge of field one.

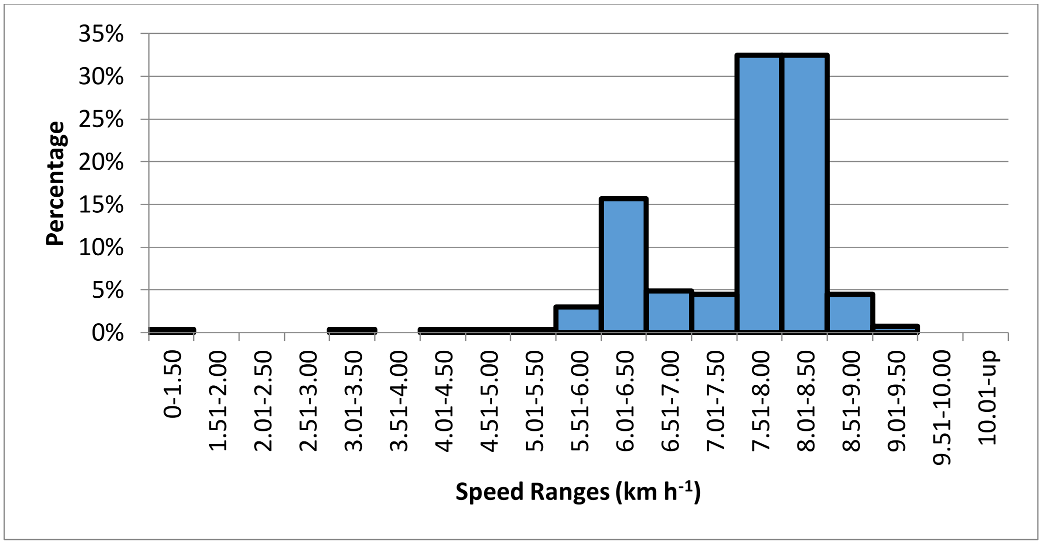


Figure 19: Distribution of turning speed data from the water way edge of field one.

5.1.2 Time Usage and Field Efficiency

Grisso et al. (2002) noted that field shape and row length can affect field efficiency. Field one is roughly shaped like two right angle triangles due to the presence of the water way. Field one was therefore evaluated to determine the effect of the field's shape on field efficiency.

The total amount of time required for the tractor/planter to plant the northern section of field one was determined to be 85.8 minutes. The total amount of time required to plant the southern section of field one was found to be 101 minutes (1.68 hours) when the initial benchmarking information was calculated and can be seen in Table 9. Therefore, the total time required to plant the northern and southern sections of field one separately was 186.8 minutes (85.8+101) or 7.13 min ha^{-1}. The northern and southern sections of field one put together constitute 26.2 ha. The theoretical field capacity of the tractor/planter was determined to be 16.8 ha h^{-1}. Therefore, the theoretical time required to complete the two operations would be 93.6

minutes. This means the field efficiency of the two operations is approximately 50% (93.6/186.8).

To estimate the field efficiency of field one if the water way did not exist, some assumptions were made. It can be seen in Figure 20, that row 22 spans the entire length of field one. The number of points in row 22 was therefore multiplied by 24, because it was assumed there would be 24 rows of similar length to row 22 in field one if the water way did not exist. The number of rows was expected to increase because an area of the field that was not available for planting due to the water way, would become available for planting if the water way did not exist and can be seen in Figure 20. There are a total of 20 turns in the southern section of field one, so it was assumed that if two extra rows were added, that the number of turns would increase by one at each end of the field. Therefore, there would be 22 turns in the field as a whole. The average turn time for the turns at the southern edge of field one was determined to be 20.9 seconds in section 5.1.1 and was multiplied by 22 to estimate the total turning time for the field as a whole if the water way did not exist. The total amount of unproductive time was found to be 0.71 min ha^{-1} for the southern section of field one when the initial benchmarking information was determined. It was therefore assumed that the operator would spend 0.71 min ha^{-1} being unproductive in the field if the water way did not exist.

The total area of field one was measured using the technique described in section 4.5 and was found to be 34.7 ha. It was assumed that the water way area would become open for planting if the water way did not exist, so the area to be planted would increase if the water way was not present. Field efficiency was estimated to increase by 39.2% if the water way did not exist. Table 11, contains the results of the analysis.

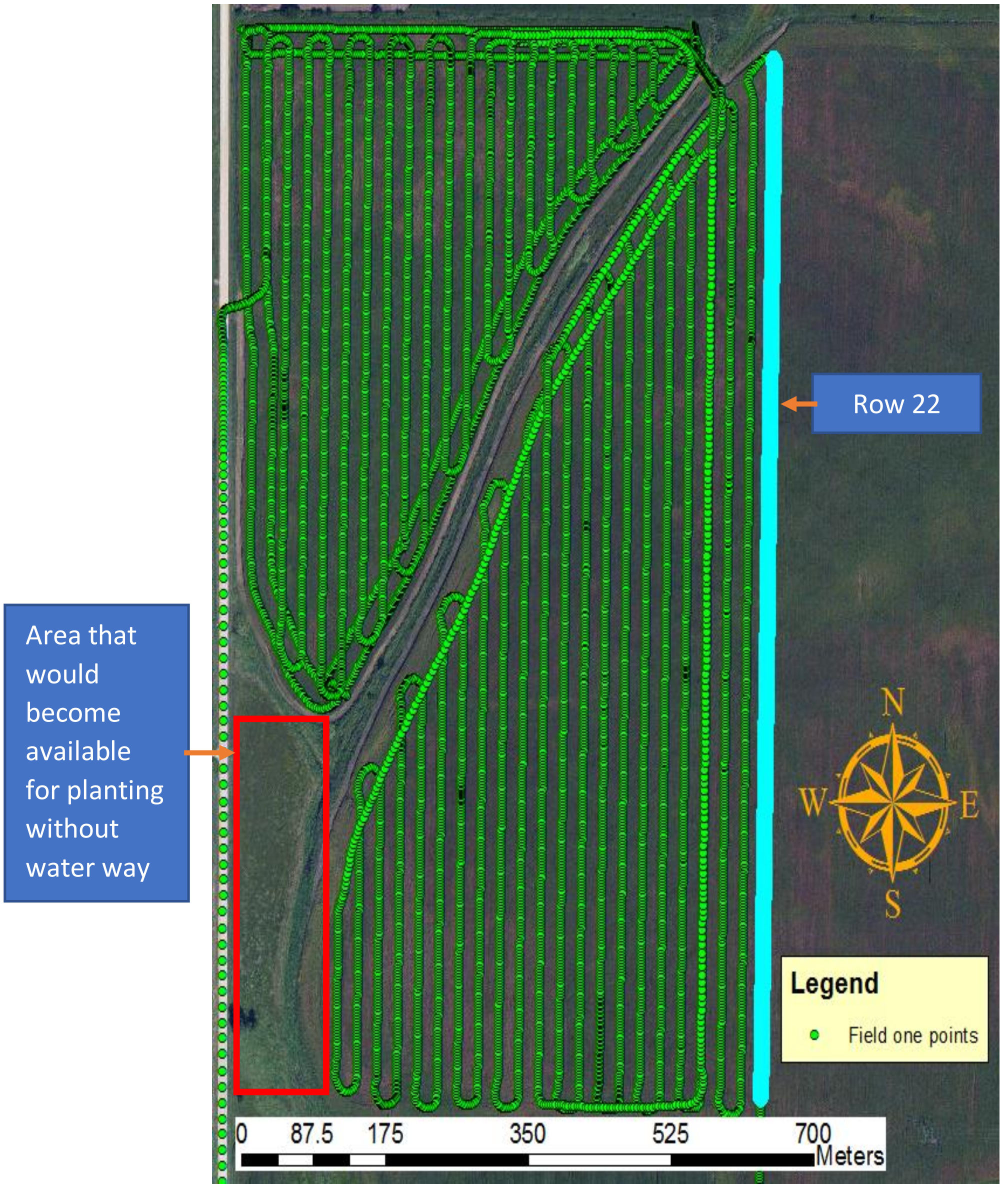


Figure 20: Field one with red rectangle indicating the area that would become available for planting if the water way did not exist, row 22 is highlighted.

Table 11: Results of field efficiency analysis of field one.

Field one	Theoretical time (h)	Actual time (h)	Field efficiency (%)
Northern Section	0.61	1.43	42.7
Southern Section	0.946	1.68	56.3
Water Way	1.56	3.11	50.2
No Water Way	2.07	2.96	69.9

5.2 Fuel Consumption and Use Efficiency

Field two, was selected for analysis due to the high average slope (%) of the field. To evaluate engine performance, a wide range of engine performance measures were determined for each of the seventeen rows in field two. Figure 21, represents field two with selected rows numbered. The calculated information can be seen in Table 12 and is accompanied by Table 13, which contains a statistical analysis of the data. The information determined includes: fuel efficiency (FE) in L ha^{-1}, energy efficiency (EE) in MJ ha^{-1}, fuel consumption (FC) in liters, engine speed (ES) in r min^{-1}, engine torque (ET) in Nm, engine power (EP) in kW, cost of fuel in dollars ($), area of each row in hectares (ha) and slope of each row in (%).

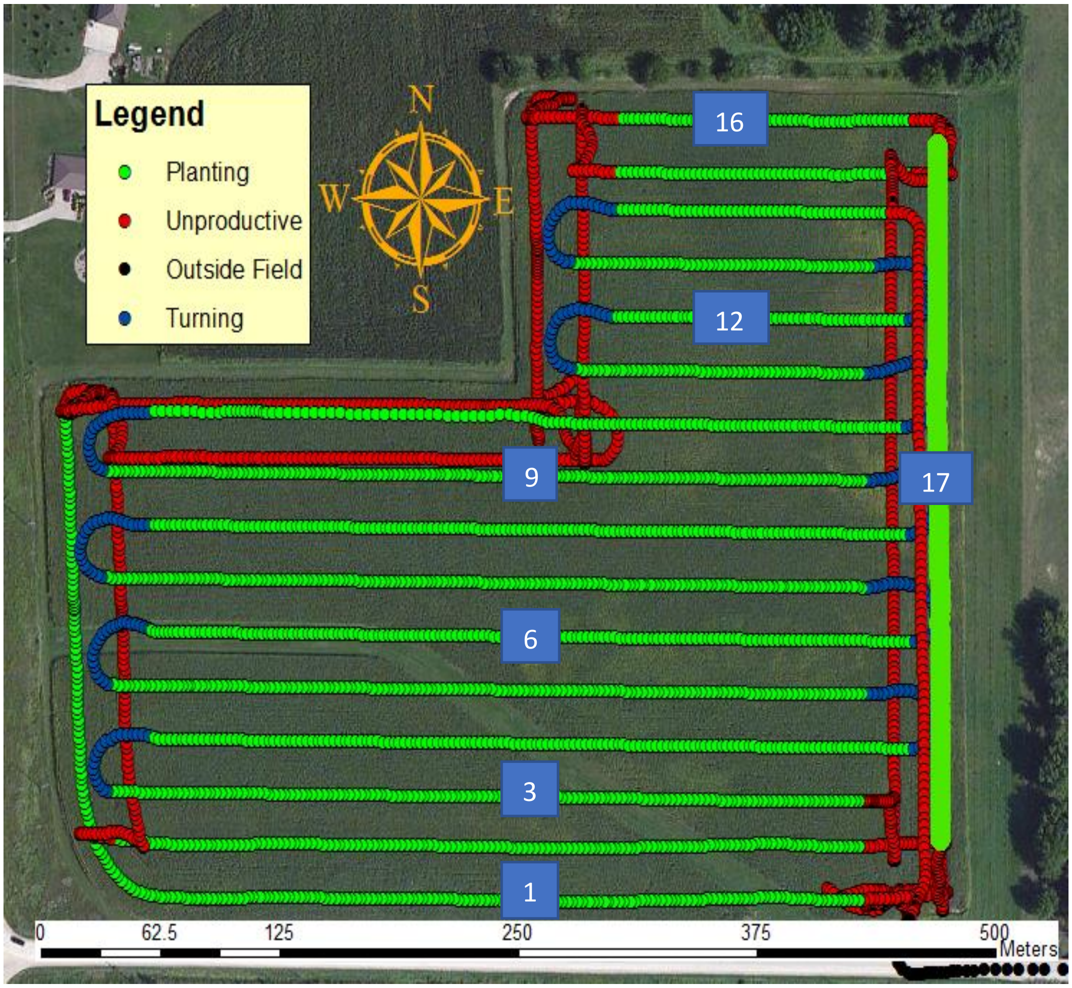


Figure 21: Field two, with rows numbered and points color coordinated to show planting points in green, turning points in blue and unproductive points in red.

Table 12: Calculated engine performance information for each row.

Row	FE (L kWh^{-1})	FE (L ha^{-1})	EE (MJ ha^{-1})	FC (L)	ES (r min^{-1})	ET (Nm)	EP (kW)	Cost ($)	Area (ha)	Slope (%)
1	0.372	3.14	30.2	2.54	1448	711	108	2.70	0.81	2.9
2	0.372	2.84	27.1	1.53	1449	708	107	1.63	0.54	3.4
3	0.360	4.84	48.8	2.61	1450	775	118	2.78	0.54	3
4	0.378	2.79	26.8	1.51	1450	681	103	1.60	0.54	-2.69
5	0.359	3.09	30.9	1.67	1451	783	119	1.78	0.54	2.48
6	0.377	2.9	27.7	1.57	1450	686	104	1.67	0.54	-2.39
7	0.354	3.31	33.9	1.78	1451	814	124	1.90	0.54	2.18
8	0.357	3.19	32.3	1.72	1448	795	121	1.83	0.54	-2.7
9	0.368	3.09	30.3	1.66	1449	732	111	1.77	0.54	2.4
10	0.446	1.95	16.1	1.05	1358	513	73	1.12	0.54	-2.7
11	0.759	1.85	8.9	0.37	900	346	33	0.39	0.2	1.8
12	0.765	1.81	8.6	0.36	900	342	32	0.38	0.2	-6
13	0.748	1.9	8.9	0.38	899	353	33	0.40	0.2	6
14	0.380	2.78	26.2	0.55	1205	888	112	0.59	0.2	-5.2
15	0.577	1.83	11.3	0.36	1450	296	45	0.39	0.2	-5.3
16	0.374	3.02	28.6	0.60	1452	696	106	0.64	0.2	-5
17	0.369	2.95	29.3	1.33	1447	732	111	1.41	0.45	-1.7

Table 13: Statistical analysis of engine performance data for rows 1-17 of field two.

Field 2	FE (L kWh^{-1})	FE (L ha^{-1})	EE (MJ ha^{-1})	FC (L)	ES (r min^{-1})	ET (Nm)	EP (kW)	Cost ($)	Slope (%)
Maximum	0.765	4.84	48.8	2.61	1452	888	124	2.78	6
Minimum	0.354	1.81	8.6	0.36	899	296	32	0.38	-6
Range	0.411	3.03	40.2	2.25	553	592	92	2.4	12
Median	0.374	2.84	27.7	1.51	1449	708	107	1.6	-1.7
Average	0.454	2.72	25.1	1.27	1333	638	92	1.35	-0.56
Std. Dev.	0.150	0.75	10.5	0.71	209	185	33	0.76	3.65

The total amount of fuel consumed while the tractor was being productive in field two was determined by adding the fuel consumption of each individual row and was found to be 21.6 liters. The total amount of fuel consumed for the entire field was predicted to be 44.6 liters when the general benchmarking analysis was conducted. A complete record of the benchmarking information can be found in Appendix A. It can be determined that only 48.4% (21.6/44.6) of the fuel required to plant the field was actually used productively.

After all the information was reviewed, rows three and twelve were found to be the minimum and maximum rows concerning fuel efficiency, respectively and were selected for further analysis to determine why they were the least and greatest row concerning fuel efficiency. After reviewing row three, it was noted that the operator had spent 78 seconds at a machine speed of "0", indicating the machine was being unproductive. As a result, the machine consumed 0.364 liters of fuel, worth approximately $0.35, while planting zero hectares of land. Row three, was also the row where the engine developed an average power rating of 118 kW, the fourth highest power rating achieved in any of the rows. The extra 78 seconds the engine spent at the average power of 118 kW, caused row three to be the least fuel efficient row. The soil type of row three was determined to be a Clyde-Floyd-Schley complex and was classified as "somewhat poorly drained" by the USDA soil survey (Soil Survey Staff, National Resources Conservation Service, United States Department of Agriculture.Web Soil Survey). It is possible that the tractor lost traction and became stuck at the beginning of row three due to wet soil conditions, causing the 78 seconds of unproductivity.

When the tractor was operating in row twelve, it only developed an average power of 32 kW and consumed only 0.36 liters of fuel. The small amount of power required to plant the row is what made row twelve the most fuel efficient row at only 1.81 L ha^{-1}. Rows three and twelve are compared to field two in Table 14. Row twelve, had the largest negative slope (%) of any row in the field at -6%. To determine if slope (%) was correlated with energy efficiency, a correlation analysis was conducted (Figure 22).

Table 14: Comparison of rows three and twelve with the average of field two.

Field/Row	FC (L)	FE (L ha^{-1})	Power (kW)	Torque (Nm)	Cost ($)	Slope (%)
Field 2 Average	1.27	2.72	92	638	1.35	-0.56
Row 3	2.61	4.84	118	775	2.78	3
Row 12	0.36	1.81	32	342	0.38	-6

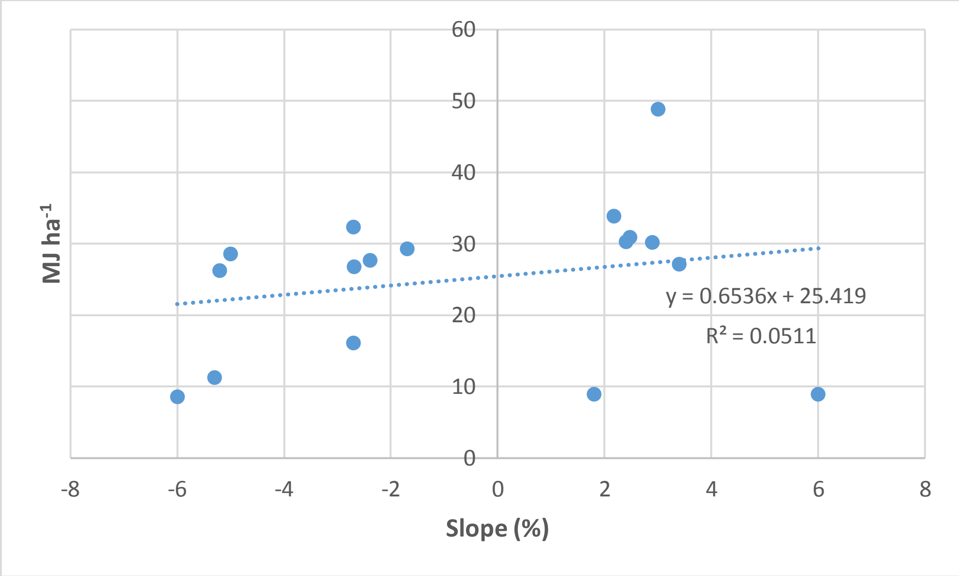


Figure 22: Correlation analysis to determine if any relationship exists between energy efficiency and slope (%).

The correlation analysis only returned an R^2 value of 0.0511, indicating that there was no correlation between slope (%) and energy efficiency. The variation in energy consumption between each row and lack of relationship between slope (%) and energy efficiency was believed to be partially caused by the operator. The average engine speed of rows eleven through thirteen was only 900 r min^{-1} compared to an average of 1426 r min^{-1} for the remaining rows. It was evident that the operator reduced the engine speed when planting rows eleven through thirteen.

When looking at the average engine power of rows eleven through thirteen, it was noted that the engine never achieved a power rating above 33 kW. The range in power between rows eleven through thirteen was only 1 kW. Rows eleven and thirteen, were rows in which the tractor was ascending up slopes of 1.8% and 6% respectively, and their average power ratings are identical. The 8360R did not produce more power to climb the steeper slope of row thirteen. Row twelve, however, was a row where the tractor was descending on a slope of -6% and the tractor maintained almost the exact same power rating at 32 kW as row thirteen at 33 kW. The slope (%) of the rows was verified using Google Earth (Google Earth, version 7.1.2.2041, Google 2013). The specific engine performance information for rows eleven, twelve and thirteen can be seen below (Table 15).

Table 15: Engine performance information for rows eleven through thirteen of field two.

Row	FE (L kWh^{-1})	FE (L ha^{-1})	EE (MJ ha^{-1})	FC (L)	ES (r min^{-1})	ET (Nm)	EP (kW)	Cost ($)	Area (ha)	Slope (%)
11	0.759	1.85	0.67	0.37	900	346	33	0.39	0.2	1.8
12	0.765	1.81	0.65	0.36	900	342	32	0.38	0.2	-6
13	0.748	1.9	0.7	0.38	899	353	33	0.4	0.2	6
Avg.	0.757	1.85	0.67	0.37	900	347	33	0.39	0.2	0.6

Considering the average engine speed between rows eleven through thirteen was 900 r min^{-1}, the machine travel speeds were reviewed to see if the machine was moving too slowly to be planting. The average speed for the three rows was 7.45 km h^{-1}, which was higher than the average row speed for field two as a whole (7.36 km h^{-1}). It was apparent that the tractor was not just slowly traveling through the field when the engine speed was low. Unfortunately, there is no way to know why the tractor performance was so variable in field two. It is believed that the operator changed their operating style when planting rows eleven through thirteen based on the low engine speeds relative to the rest of the field.

5.3 Benchmarking of Machine and Operator Performance

One of benefits of benchmarking farm operations, is it provides an opportunity for farm managers and researchers to compare different fields to evaluate machine and operator performance between fields. The following section contains a comparison of field one and field two to evaluate machine and operator performance between the two fields. Field one and field two are compared in Table 16.

Table 16: Benchmarking information for fields one and two.

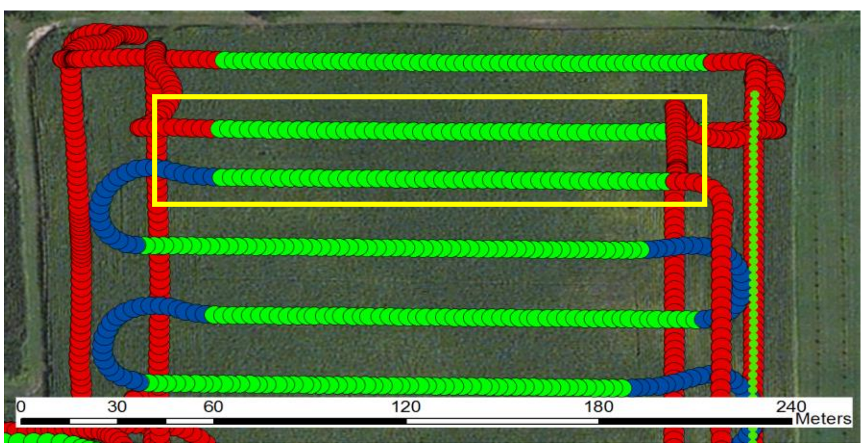
Variable	Field one	Field two
Avg. row speed (km h^{-1})	7.66	7.36
Avg. turn speed (km h^{-1})	7.27	7.17
Max. row speed (km h^{-1})	8.47	12.9
Min. row speed (km h^{-1})	0	0
Max. turn speed (km h^{-1})	9.21	8.47
Min. turn speed (km h^{-1})	0	5.16
Average turn time (s)	23.7	24.9
Total time spent turning (min)	7.9	4.57
Unproductive time (min)	11.3	35
Total time in field (h)	1.68	1.19
Theoretical field capacity (ha h^{-1})	16.8	16.8
Actual field capacity (ha h^{-1})	9.46	7.48
Field Efficiency (%)	56.3	44.5
Size of field (ha)	15.9	8.9

5.3.1 Field Efficiency

The operator in the southern section of field one achieved a field efficiency of 56.3% vs. the operator in field two who only achieved a field efficiency of 44.5%. Both field efficiency numbers are well below 65%, the average set forth in ASABE standard D497.7 for planting operations. The operators in field one and two only maintained average planting speeds of 7.66 and 7.36 km h^{-1}, respectively. The operators in both fields are well below the 9 km h^{-1} speed that ASABE standard D497.7 considers to be the typical field speed for planting operations, but are relatively close to the 8 km h^{-1} target typically determined by the exit angle of the seed at the bottom of the seed tube to achieve net zero horizontal velocity for the seed as it is deposited in the furrow. The average turning time for field one was 23.7 seconds, compared to 24.9 seconds for field two. As mentioned in section 5.1.1, the tractor/planter operator in field one was forced to make a different shaped turn at the water way edge of field one which increased the average turning time at the water way edge of the field by an average of 5.8 seconds per turn vs. the southern edge of the field. Field two, is shaped like a rectangle, allowing the operator to make a conventional turn every time at the end of a row. Regardless, the operator in the southern section of field one negotiated each turn with an average of 1.2 seconds quicker than the operator in field two. It can be seen that field two has a very large percentage of unproductive time compared to field one. The tractor/planter was unproductive 49% of the time it was in field two. This greatly contributed to lowering field two's field efficiency. The tractor/planter was unproductive only 11.2% of the time when in field one. If field two had the same percentage of unproductive time as field one, the amount of unproductive time would only be 8 minutes and the operation would have been completed 27 minutes sooner. The total time in field two would then be 44.4 minutes, raising the field efficiency to 71.6%. A field efficiency of 71.6%, is well above the ASABE D497.7 typical field efficiency of 65% for planting operations.

When the map for field two was reviewed, an anomaly was noted. The row spacing between rows fourteen and fifteen is short relative to the spacing of the other rows. The fact that the row spacing was too short, means that the planter must have planted the same area twice. The overlap between the rows was determined to be approximately six meters. Out of the seventeen rows in field two, row fourteen was actually the sixteenth row planted while row fifteen was the fourth row planted. It is possible the operator did not notice that he had already planted in that area and ended up planting the same area twice. The anomaly can be seen in Figure 23a and 23b.

(a)



(b)

Figure 23(a) and 23(b): Field two with row spacing anomaly boxed.

5.3.2 Engine Performance

Engine performance was compared between field one and field two with special attention paid to fuel efficiency and average engine power. Although fuel consumption predictions were made with both the ASABE general prediction method and the method developed by Grisso et al. (2008a), only the predictions made by the Grisso et al. (2008a) method were used to calculate fuel cost. Based on the conclusions reached by Grisso et al. (2008a), the method to determine fuel consumption of specific tractor models was considered more accurate than the ASABE general prediction method. The ASABE general prediction method was included in Table 17 to determine the difference in prediction values between the two methods.

Table 17: Engine performance information for fields one and two.

Variable	Field one	Field two
Average engine speed ($r\ min^{-1}$)	1433	1362
Average torque (Nm)	725	658
Average Power (kW)	109	94
Fuel consumption ($L\ h^{-1}$) (ASABE method)	43.4	40
Fuel consumption ($L\ h^{-1}$) (specific method)	40.5	37.4
Fuel efficiency ($L\ kWh^{-1}$) (ASABE method)	0.397	0.417
Fuel efficiency ($L\ kWh^{-1}$) (specific method)	0.371	0.398
Fuel efficiency ($L\ ha^{-1}$) (ASABE method)	4.57	5.23
Fuel efficiency ($L\ ha^{-1}$) (specific method)	4.27	5.01
Total volume of fuel consumed (L) (ASABE method)	72.7	46.6
Total volume of fuel consumed (L) (specific)	67.9	44.6
Total energy required ($MJ\ ha^{-1}$)	41.5	45.2

Field one was the more fuel efficient operation at 4.27 $L\ ha^{-1}$ compared to 5.01 $L\ ha^{-1}$ for field two. If the tractor/planter had achieved the same level of fuel efficiency in field two as field one, the total fuel consumption would have been 38 liters, 6.6 liters less than the predicted. This comes out to $7.03 worth of diesel fuel and engine oil that would not have been required if the planting operation in field two had been as fuel efficient as field one.

The general prediction method is far easier to set up relative to the specific method. However, based on the conclusions reached by Grisso et al. (2008a) it is recommended that the time be taken for the equations required to use the specific prediction model be entered into an Excel spreadsheet and used to predict fuel consumption of farm operations. It can be seen in the analysis of field one and two, that the farm manager would likely over budget money to purchase the fuel required to complete the operations if using the ASABE general prediction method.

It should be noted that engine speed and torque was more variable in field two than field one. The standard deviation of engine speed and torque for field one was 81 r min^{-1} and 152 Nm respectively, compared to 176 r min^{-1} and 227 Nm for field two. This further confirms the conclusion from the previous section that the engine performance in field two was peculiar; possibly caused by the operator. It is possible the operator set a specified engine speed in field one and part of field two but disengaged the feature in the upper part of field two. Figures 24-29 and Tables 18 and 19 display the engine speed and torque information.

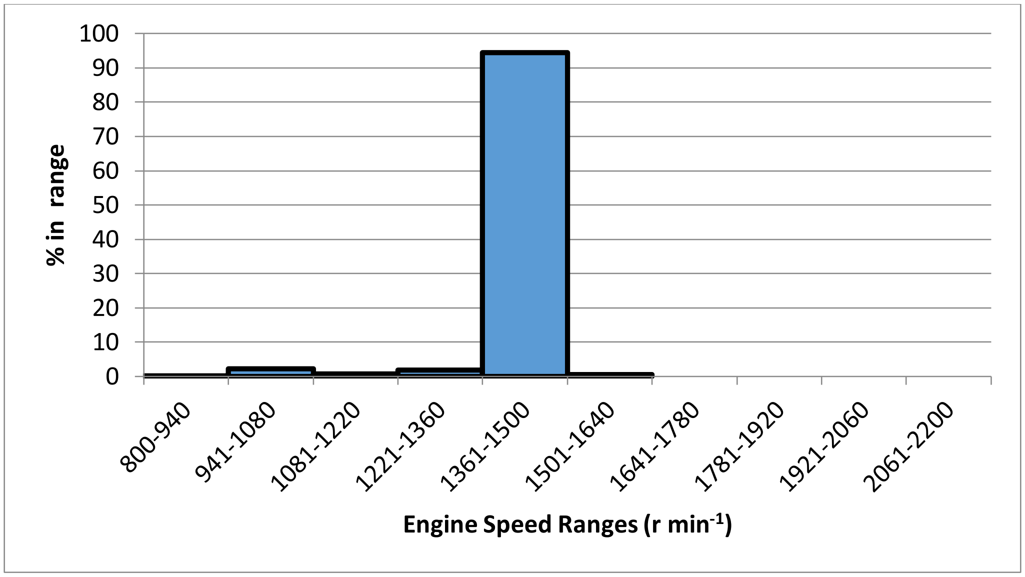


Figure 24: Engine speed distribution of field one.

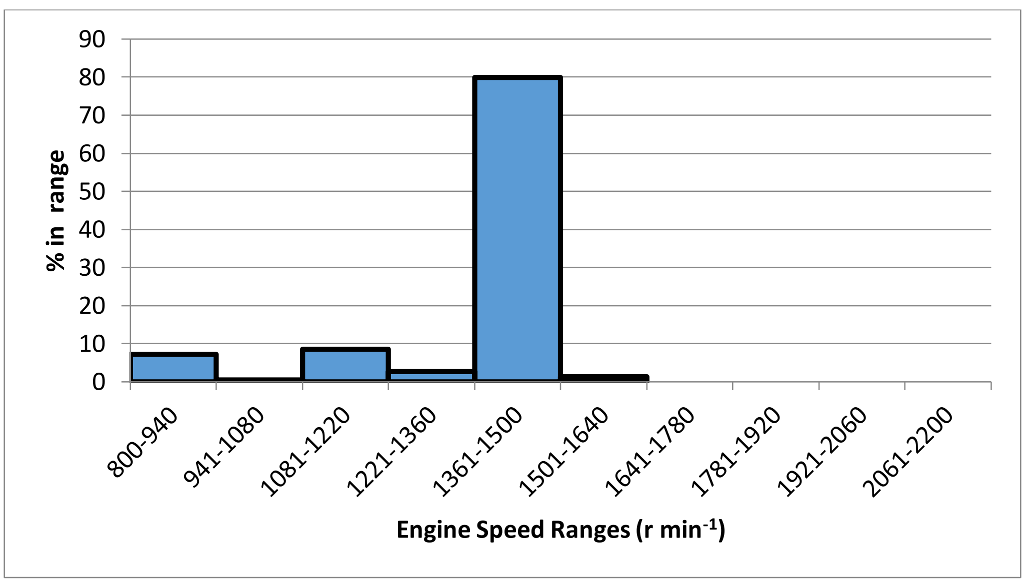


Figure 25: Engine speed distribution of field two.

Table 18: Statistical analysis of engine speed data of field one and two.

Variable	Field one	Field two
Maximum	1546	1557
Minimum	893	877
Range	653	680
Average	1433	1362
Median	1450	1447
Std. Dev.	81	176

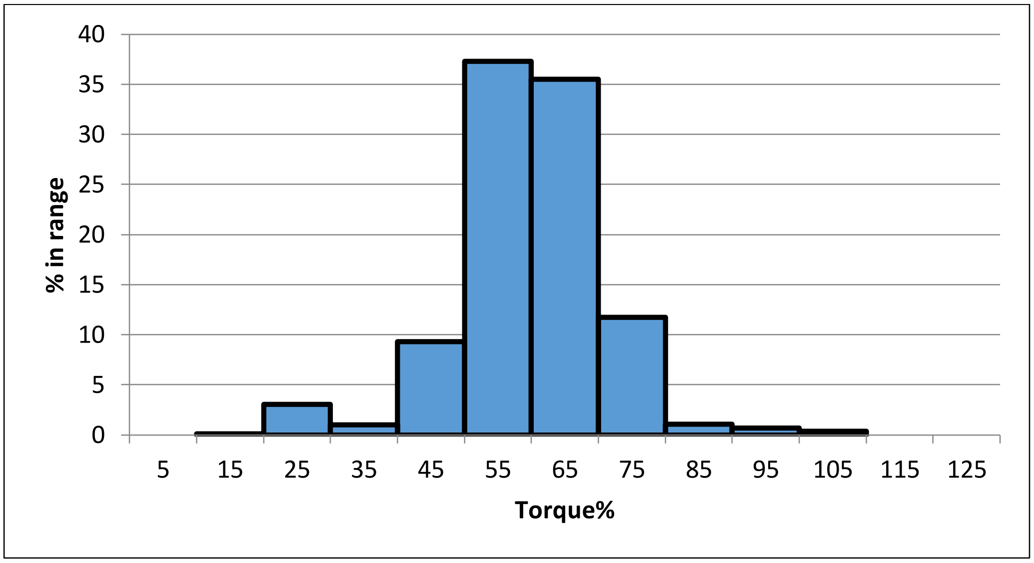


Figure 26: Engine torque distribution of field one.

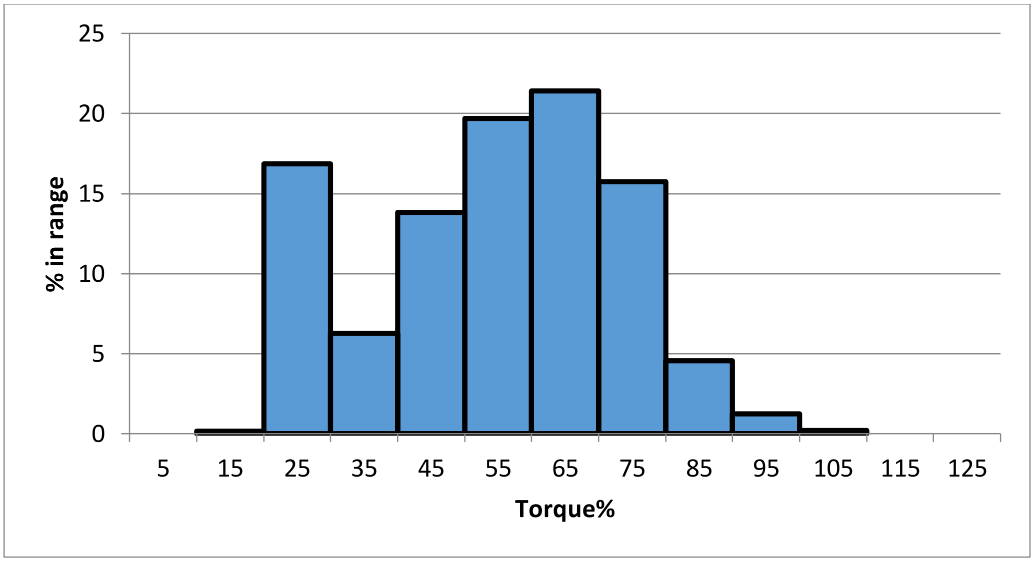


Figure 27: Engine torque distribution of field two.

Engine Torque %

	870	1010	1150	1290	1430	1570	1710	1850	1990	2130	
.25	0	0	0	0	0	0	0	0	0	0	0
.15	0	0	0	0	0	0	0	0	0	0	0
.05	0	0	0	0	0	0	0	0	0	0	0
95	0	0	0	0	1	0	0	0	0	0	1
85	0	0	0	0	1	0	0	0	0	0	1
75	0	0	0	0	12	0	0	0	0	0	12
65	0	0	0	0	35	0	0	0	0	0	36
55	0	0	0	0	37	0	0	0	0	0	37
45	0	0	0	0	9	0	0	0	0	0	9
35	0	0	0	0	1	0	0	0	0	0	1
25	0	2	0	0	1	0	0	0	0	0	3
15	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0
	0	2	0	0	97	0	0	0	0	0	100
800	940	1080	1220	1360	1500	1640	1780	1920	2060	2200	

Engine Speed (r min^{-1})

Figure 28: Percentage of time in speed and torque range for field one.

Table 19: Statistical analysis of engine torque data of field one and two.

Variable	Field One	Field Two
Maximum	1334	1261
Minimum	0	0
Range	1334	1261
Average	725	658
Median	728	679
Std. Dev.	152	227

Engine Torque (%)	870	1010	1150	1290	1430	1570	1710	1850	1990	2130	
125	0	0	0	0	0	0	0	0	0	0	0
115	0	0	0	0	0	0	0	0	0	0	0
105	0	0	0	0	0	0	0	0	0	0	0
95	0	0	1	0	1	0	0	0	0	0	1
85	0	0	0	0	4	0	0	0	0	0	5
75	0	0	0	0	15	0	0	0	0	0	16
65	0	0	0	0	21	0	0	0	0	0	21
55	0	0	0	0	19	0	0	0	0	0	20
45	0	0	0	0	13	0	0	0	0	0	14
35	1	0	1	0	4	0	0	0	0	0	6
25	10	0	0	0	6	0	0	0	0	0	17
15	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0
	11	0	3	1	84	1	0	0	0	0	100
800	940	1080	1220	1360	1500	1640	1780	1920	2060	2200	

Engine Speed (r min^{-1})

Figure 29: Percentage of time in speed and torque range for field two.

It can be seen in Figures 28 and 29, that the planting operations analyzed in this project only required a moderate level of engine power. The rated PTO power of the John Deere 8360R tractor is 240 kW, which indicates rated engine power of approximately 267 kW, assuming 90%

power transmission efficiency from the engine to the PTO as per the ASABE D497.7 standard. The average engine power for field one was only 109 kW, only 40.8% of the rated engine power. The average engine power in field two was only 94 kW, 35.2% of the rated engine power. Coffman et al. (2010) noted that IVTs have the highest potential to be more fuel efficient than standard gear transmissions when the amount of power required to complete an operation can be achieved at a lower engine speed. The average engine speed for each operation was only 1433 r min^{-1} and 1362 r min^{-1} for fields one and two, respectively. The rated engine speed of the 8360R tractor is 2100 r min^{-1}. Therefore, it is concluded that these operations were easily suited to be planted by an IVT tractor.

5.3.3 Operational Cost Analysis

Buckmaster (2003) noted that the operation of farm tractors has the potential to be one of the largest costs of a farm operation. Table 20, displays the costs associated with the planting of field one and two. Once again, field one was the more efficient operation compared to field two. Only the operational costs of the operations were considered in this project. If the fixed costs of the operations had also been considered, the cost to complete the operations would increase substantially.

Table 20: Economic analysis of fields one and two.

Variable	Field One	Field Two
Repair and Maintenance (4WD) ($)	0.002	0.001
Fuel/Oil Cost (Specific Method) ($)	72.3	47.5
Labor Cost ($)	31.4	22.3
Total Cost ($)	104	69.8
Area (ha)	15.9	8.9
Cost ($ ha^{-1})	6.54	7.84

It was noted in the previous section, that the total amount of unproductive time in field two would have been 8 minutes if the operator in field two had been as time efficient as the operator in field one concerning unproductive time. This means that 27 minutes (35-8) of time would not have been required to plant field two. The monetary cost of the 27 minutes can be seen in Table 21.

Table 21: Economic cost of 27 minutes in field two.

Variable	Field Two
Repair and Maintenance (4WD) ($)	0.0001
Fuel/Oil Cost (Specific Method) ($)	11.50
Labor Cost ($)	8.4
Total Cost ($)	19.9

5.3.4 Performance Indicator for Decision Support

The information and analysis presented in the previous sections serve as an example of how the benchmarking methodology presented in Chapter 4 can be used by farm managers to measure the productivity, efficiency, performance and cost of machine operations. The methodology also has the potential to examine the effects of unique spatial features of agricultural fields on machinery operations. Farm managers, can benchmark machines, operators and the fields themselves. Farm managers, could compare benchmarking records to determine which machines are performing the best and consider measures to improve the performance of machines that are performing sub-par. Machine operators, could be compared to see which operators are the most time efficient and attempt to determine the reasons why some operators are less time efficient so action can be taken to improve time efficiency. Agricultural fields are not created equal. In this study, field one had a water way cutting through the field. The water way was found to affect both turning performance and field efficiency. If field one was benchmarked every year, the farm manager could determine what is likely the best job an operator can do in the field considering the fields unique shape due to the water way and consider that performance to be the benchmark.

A farm operator interested in benchmarking a machine operation is advised to collect geo-referenced data from the machines of interest and enter that data into ArcGIS™. Once in ArcGIS™, the data points can be viewed and relevant data can then be selected. It is highly recommended that equations needed to determine desired information be entered into a Microsoft Excel spreadsheet to allow for quick calculations. The wide range of Microsoft Excel functions are very useful to determine benchmarking information. Once the information is determined, evaluation and comparisons can begin.

CHAPTER 6: SUMMARY AND CONCLUSIONS

Two corn planting operations conducted on a farm in the American Midwest were benchmarked and evaluated concerning productivity, efficiency, performance and cost. A review of literature revealed that tractor operations have the potential to be very expensive to farm operations. The review of literature also revealed that farmers do not have the means to evaluate the efficiency of their machine operations and that collection and analysis of relevant data concerning those operations would be required for farm managers to budget both time and money accurately to complete machine operations in the future.

To benchmark and evaluate off-road machine operations, a methodology was created to identify relevant geo-referenced data with the use of ArcGIS™ and analyze that data by utilizing certain Microsoft Excel functions. The ASABE general fuel consumption prediction method and the prediction method for specific tractor models developed by Grisso et al. (2008a) were utilized to estimate tractor fuel consumption for each operation.

The methodology created was used to evaluate the effect of a water way in a field on the planting operation conducted in that field. The presence of the water way, caused the field to be shaped like a right angle triangle. It was determined that the average time for the tractor operator to complete a turn at the water way edge of the field was 5.8 seconds greater compared to the opposite end of the field where no water way was present. Total turning time for the operation increased by 13.5% due to the presence of the water way. Some assumptions were made to estimate what the field efficiency of the operation would be if the water way did not exist. It was estimated that field efficiency would increase from 50.2 to 69.9% if the water way was not present. Therefore, the conclusion reached in past research that field shape can affect field efficiency was affirmed in this project.

A review of engine performance in field two revealed that slope (%) of the individual rows in the field did not correlate with energy efficiency based on an R^2 value of only 0.0511. Engine performance varied significantly between certain rows. The variation in engine performance was believed to be caused by the operator due to the variation in engine speeds between rows.

A comparison of the two operations revealed that the first operation benchmarked was the more productive and efficient operation. Actual field capacity, field efficiency, fuel efficiency and cost for the first operation being 9.46 ha h^{-1}, 56.3%, 4.27 L ha^{-1} and \$6.54 ha^{-1}, respectively, compared to 7.48 ha h^{-1}, 44.5%, 5.01 L ha^{-1} and \$7.84 ha^{-1} for the second operation. The tractor/planter was unproductive 49% of the time needed to complete the second operation compared to only 11.2% of the time for the first operation. The large amount of unproductive time decreased the productivity and efficiency of the second operation and increased the overall cost. Benchmarking of every machine operation conducted on this farm could lead to an overall benchmarking and evaluation of machine operations on this farm as a whole.

CHAPTER 7: RECOMMENDATIONS FOR FUTURE WORK

Several opportunities for future research were noted at the conclusion of this project. The benchmarking of individual machine operations conducted on a farm could be analyzed together and used to benchmark machine operation on the farm as a whole. Benchmarking productivity, efficiency, performance and cost of all the machine operations conducted on a farm, would have the potential to lead to more accurate budgeting of time and money to complete future operations. This type of research could significantly impact the food and fiber economy by giving farm managers the ability to accurately forecast cost.

The process used to identify relevant data in this project was very time consuming. If this methodology is to be used widely by mainstream farm operators, it is recommended that the data selection and analysis process be partially or even fully automated. A computer program could be created to automate the benchmarking process.

It is highly recommended that CAN bus or ISO bus technology be integrated into implements such as the planter and be connected to the tractor to convey performance data from the planter to the tractor to allow for the planter state of operation and operational transition points to be specifically determined. It would also allow for the benchmarking of planter performance along with the tractor.

It is recommended that technology be developed to allow machine operators to make electronic notes concerning the situations they are currently facing during a machine operation. This note or input could be electronically attached to the data so the cause of unproductive time or peculiar machine performance could be noted by the person reviewing the data so that speculation about possible machine or operator issues can be avoided.

Agricultural fields that are shaped differently can present a challenge to machine operators concerning the travel path that should be taken to finish the operation as soon as possible. It is recommended that a computer program be created to analyze field shapes along with machine turning characteristics to determine the optimal travel path the machine operator should follow in each individual field. The type and condition of the soil in a field has the potential to affect machine turning performance and tractive efficiency. It is recommended that the soil type and the condition of the soil in individual fields be taken into account to help determine the optimal travel path a machine should follow. The type and condition of the soil in a field should also be considered when evaluating machine travel speed for benchmarking purposes.

The operation of a machine's hydraulic system has the potential to load the machine's engine. Therefore, it is recommended that data be collected in the future concerning the state of a machine's hydraulic functions to determine if the engine is experiencing an increased torque load to operate the hydraulic system.

The data that were analyzed in the project were considered to be accurate. However, it is recommended that research be done in the future to verify the accuracy of data collected from off-road machines. If machine operations are to be benchmarked, the data analyzed must be accurate to ensure the benchmarking information is reliable.

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APPENDIX A: FIELD ONE AND TWO BENCHMARKING INFORMATION

Table 22: Benchmarking record of field one and two.

Input Data	**Field One**	**Field Two**
Size of Field (hectares)	15.9	8.9
Labor Rate (dollars/hour)	18.7	18.7
Rated PTO Power (kW)	240	240
Rated Engine Speed (r min^{-1})	2100	2100
Full Throttle Engine Speed (r min^{-1})	2225	2225
Price of Diesel Fuel ($/gallon)	3.66	3.66
Machine List Price ($)	296,000	296,000
Number of Turns in field	20	11
Implement Width (meters)	18.7	18.7
Performance Indicators		
Avg. in-row speed (km h^{-1})	7.66	7.36
Avg. turn- row speed (km h^{-1})	7.27	7.17
Max. in-row speed (km h^{-1})	8.47	12.9
Min.in-row speed (km h^{-1})	0.00	0.00
Max. turning speed (km h^{-1})	9.21	8.47
Min. turning speed (km h^{-1})	0.00	5.16
Average Turn Time (sec)	23.7	24.9
Time spent turning (min)	7.9	4.57
Time in field (h)	1.68	1.19
Unproductive time (min)	11.3	35
Theoretical Field Capacity (ha h^{-1})	16.8	16.8
Actual Field Capacity (ha h^{-1})	9.46	7.48
Field Efficiency	56.3%	44.5%
Economic Costs		
Repair & Main. (4WD) ($)	0.0025	0.0012
Repair & Main. (2WD) ($)	0.0058364	0.0029506
Fuel/Oil Cost ($) (ASABE)	77.4	49.6
Fuel/Oil Cost ($) (specific)	72.3	47.5
Labor Cost ($)	31.4	22.3

Table 23: Engine performance record of field one and two.

Variable	Field One	Field Two
Average engine speed (r min^{-1})	1433	1362
Average torque (Nm)	725	658
Average Power (kW)	109	94
Fuel consumption (L h^{-1}) (ASABE method)	43.4	39.96
Fuel consumption (L h^{-1}) (specific method)	40.5	37.4
Fuel efficiency (L kWh^{-1}) (ASABE method)	0.397	0.417
Fuel efficiency (L kWh^{-1}) (specific method)	0.371	0.398
Fuel efficiency (L ha^{-1}) (ASABE method)	4.57	5.23
Fuel efficiency (L ha^{-1}) (specific method)	4.27	5.01
Total volume of fuel consumed (L) (ASABE)	72.7	46.6
Total volume of fuel consumed (L) (specific)	67.9	44.6
Total energy required (MJ ha^{-1})	41.5	45.2

Table 24: Inputs for specific tractor model fuel prediction method.

Fuel Prediction for Specific Tractor	Field One	Field Two
Inputs		
Rated PTO Power (kW)	240	240
Drawbar Power at Maximum Power (kW)	208	208
Drawbar Power at 75% Pull Max Power (kW)	163	163
Drawbar Power at 50% Pull Max Power (kW)	111	111
Drawbar Power at 75% Pull Reduced Speed (kW)	163.5	163.5
Drawbar Power at 50% Pull Reduced Speed (kW)	110.8	110.8
SFC (kg kWh^{-1}) at 75% Pull Max Power	0.281	0.281
SFC (kg kWh^{-1}) at 50% Pull Max Power	0.317	0.317
SFC (kg kWh^{-1}) at 75% Pull Reduced Speed	0.264	0.264
SFC (kg kWh^{-1}) at 50% Pull Reduced Speed	0.271	0.271
RPM_F	2225	2225
RPM_R	1433	1362
RPM_{75F}	2159	2159
RPM_{50F}	2170	2170
RPM_{75R}	1785	1785
RPM_{50R}	1440	1440
Fuel Consumption (L h^{-1}) an N_{Red}		
N_{Red}	35.6	38.8
Q_{75F}	54.6	54.6
Q_{50F}	41.8	41.8
Q_{75R}	51.4	51.4
Q_{50R}	35.8	35.8
Ratio of Equivalent Power		
X_{75F}	0.784	0.784
X_{50F}	0.533	0.533
X_{75R}	0.785	0.785
X_{50R}	0.532	0.532
X	0.408	0.351
Equations		
a	0.211	0.211
b	0.0617	0.0617
c	0.00327	0.00327
d	-0.00257	-0.00257
e	0.0605	0.0605

Table 24 (cont.)

f	0.145	0.145
g	17.3	17.3
h	33.6	33.6

Table 25: Factors and constants for field one and field two.

Factors and Constants	**Field One**	**Field Two**
4 wheel drive and crawler tractors		
RF1	0.003	0.003
RF2	2	2
2 wheel drive tractors		
RF1	0.007	0.007
RF2	2	2
All machines		
Rated Torque	1213	1213
PTO power req. for operation (P)	97.9	84.3
PTO rated (Pr)	240	240
X(P/Prated)	0.408	0.351
partial throttle engine speed (nPT)	1454	1468
full throttle engine speed (nFT)	2225.00	2225.00
N	0.6535955	0.66
partial throttle multiplier (PTM)	0.7597944	0.755540 9

APPENDIX B: NORTHERN SECTION OF FIELD ONE

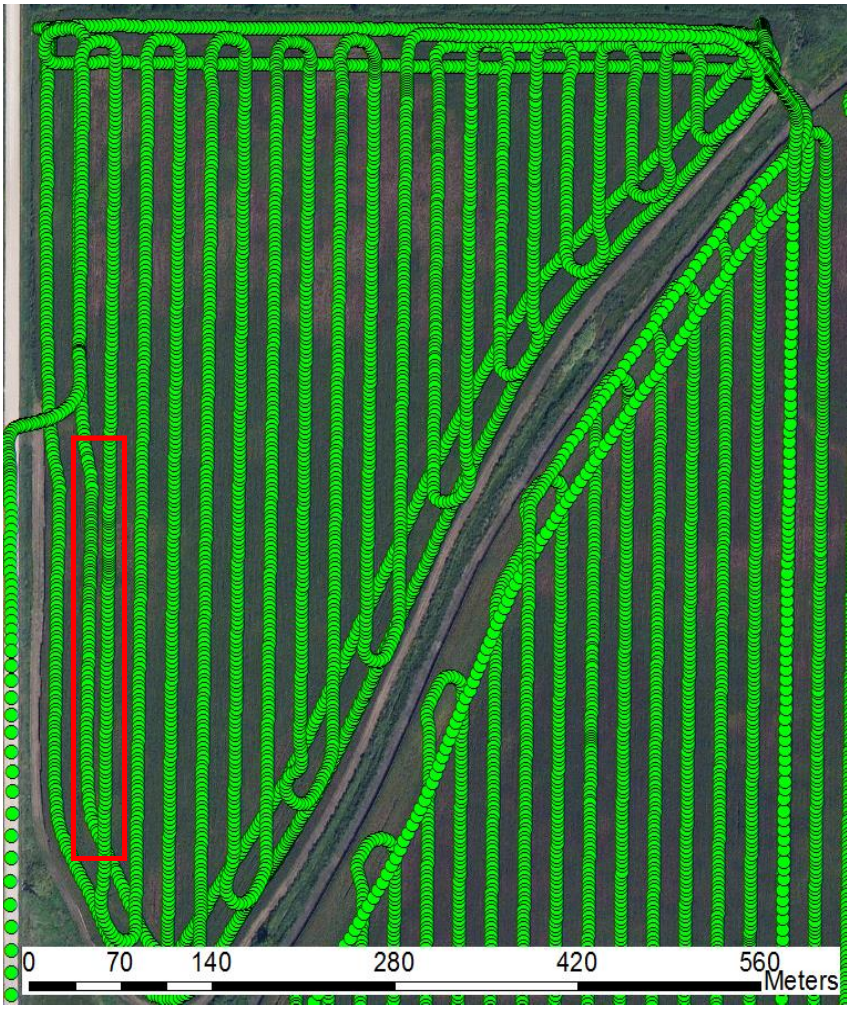

Figure 30: Northern section of field one with two rows of peculiar spacing boxed.