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Analysis of a combine grain yield monitoring system

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by

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ABSTRACT

Yield monitoring technology is a key component in the development of precision agriculture capabilities. Because of the increasing usage of yield data in formulating data driven decisions, understanding the capabilities and limitations of the system is necessary for proper use of this data. Constantly varying field conditions are suspected as a causing factor in yield monitor error. Understanding and correcting these factors will increase the value and reliability of yield data for producers.

The following documentation is a component of a project being conducted by John Deere, Ag Leader Technology, and Iowa State University, in order to study the response characteristics of a current combine yield monitoring system. The first technical chapter of this thesis is to describe the development process of test used to simulate harvesting conditions in a controlled environment in order to evaluate different harvest metrics expected to be encountered during a harvest season. This development will be used for the evaluation and continued development of the current yield monitoring system. The second technical chapter of this thesis is an analysis of data obtained from the test stand as well as data recorded throughout the 2013 harvest season in order to identify factors that have the ability to affect yield monitor response. The data obtained from this chapter will be used to identify current yield monitor capabilities and limitations and identify areas of improvement. The scope of this study is to aid the advancement of yield monitoring technology to improve the quality of data available for producers to provide them with more opportunities in their farming operations.

CHAPTER 1. INTRODUCTION

In 2012, Iowa State University began work in collaboration with John Deere Harvester Works on a study of the performance of combine yield monitors on production scale combines. The evaluation of this system was targeted due to the increasing trend of producers using measured yield values from the harvest season to make data driven decisions that encompasses their overall farming operation. To meet producer expectations, this study aims to identify methods to optimize overall yield monitor performance. The benefits provided by this study will make the overall product more attractive to producers by identifying areas producers can monitor to provide increased levels of accuracy in yield data, providing a better data set from which management decisions are made.

The current system for measuring grain yield on a production scale John Deere combines is the Ag Leader yield monitoring system. After preliminary, exploratory research was done between Iowa State University and John Deere Harvester Works, collaboration began with Ag Leader Technology in order to further understand the current process for measuring yield. This allowed for the current limitations and capabilities of the current system to be identified.

1.1 Thesis Organization

This thesis incorporates work done to progress towards the overall project goal, separated into two primary technical chapters. The first technical chapter documents the development process of a test stand designed to simulate actual harvesting conditions in a controlled environment, in order to provide an evaluation of the current yield monitoring system and as platform for development of future yield monitor development. The second technical chapter consists of a performance evaluation of the Ag Leader yield monitor within the test stand, as well as over the course of a harvest season. The evaluation is used to examine the response of the Ag Leader yield monitoring against different treatment factors in order to develop an understanding of the system response to different harvest conditions.

CHAPTER 2. LITERATURE REVIEW

2.1. Development Yield Monitoring Technology

In 1992 the original yield monitor, the Yield Monitor 2000, was developed by Al Meyer. His original design began six years prior in his basement, in which Al recalls, “I had been brainstorming a lot of product concepts and kept a spiral notebook of ideas. After carefully weighting the pros and cons of every idea, I decided there was one that stood out to me as the one that was undoubtedly going to happen, and that every farmer would want: the on-the-go yield monitor.” (Ag Leader Technology, 2013) His product allowed the combine operator, for the first time, to have a visual gauge of instantaneous yield values at any location in a field while harvesting.

As described in patent US5343761, this new technology was, “A system and method for continuously measuring mass flow rate of grain in a harvester where an impact plate is disposed to be impacted by grain exiting a power driven conveyor which is a normal part of the harvest.” The yield monitoring system consisted of two main components; an impact plate sensor for measuring grain mass flow, and an electronic control unit for converting the voltage output of the impact plate into a numerical representation of yield for the combine operator. The impact plate is strategically placed at the top of the clean grain elevator, located on all combines, and situated so all grain traveling into the combine’s grain tank will be thrown by the elevator paddles and directly strike the impact plate giving an output voltage signal. The system architecture is shown in Figure 2.1. The voltage signal is then read by an electronic control unit which applies a specific scale factor to the signal, and converts it into a usable format that can then output directly to the combine display.

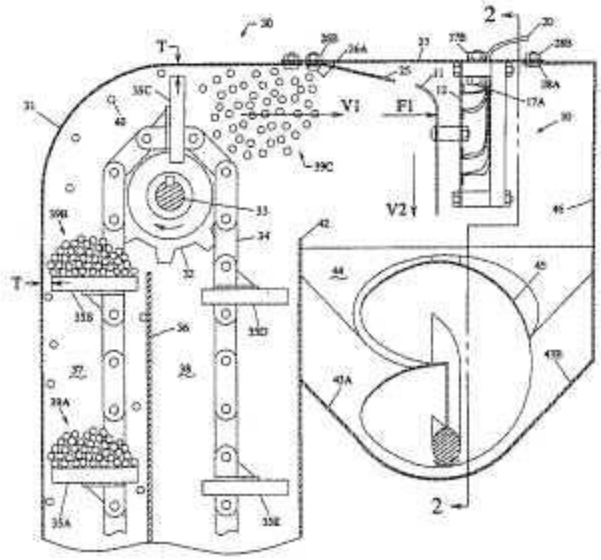


Figure 2.1: Original yield monitor design as portrayed in the original patent (Meyers, 1994)

In his initial year, Al Meyer was able to successfully sell ten yield monitors; by 1995, yield monitor sales had reached over 1,500. This product became the base product for what is now Ag Leader Technology, one of the leaders in precision farming products. Today, Ag Leader Technology supplies products for yield monitoring technologies, advanced planting equipment, intelligent fertilizer application, GPS systems, displays, and farm management software.

2.2. Current Yield Monitoring Technology Opportunities

The invention of the grain yield monitor, shown in Figure 2.2, has opened up the opportunity for producers to make more accurate farm management decisions, based on the yields they are now able to measure and record over the course of a harvest season. As yield mapping technology has continued its advancement, it has opened new doors for producers by providing numerical values for crop performance across a field, allowing them to make data driven decisions across different fields and even different management zones within a single field.

Figure 2.2: Current impact plate model installed on a John Deere combine at the BioCentury Research Farm

The adaptation of GPS systems into agriculture has brought new opportunities to yield monitoring technology. Today, not only can operators see the real time yield values being harvested, but GPS technology can take those values and create a color coded point, grid, or contour map of the field from spatial data, which can be shown on the combine display. The maps developed from the incoming yield values are known as a yield map. These yield maps can be transferred from the display memory onto a computer, tablet, or even a phone in order to help the producer keep track of the data make proper field management decisions.

The more data a producer can obtain from each individual harvest season, the more evidence that individual has to evaluate how different factors affected the harvest results. From these results, producers can determine if the decisions made from the data were financially justified. Not only can yield maps be used to evaluate farm management decisions, but they can also be used determining what practices are needed in future seasons. Using spatial data management software, other variables like soil sampling results, soil type maps, as-applied data, and other known field values or characteristics can be mapped and used as a comparison against yield maps obtained from the harvest season. Using this practice, producers can identify what underlying factors may have accounted for higher or lower yielding regions of the field, and use these results in planning out the next growing season. Considering this, the data produced from yield mapping technology has provided more opportunity to different aspects of the growing season, such as field management, planting, and fertilizer application.

2.2.1. Field Management

Numerous field management decisions can be made by using a yield monitor to evaluate a field. These management decisions can consist of determining if the field needs to be tiled, accounting for any variations in soil quality or type, or which type of seed hybrid should be used for a particular field. Yield maps provide an opportunity to make an accurate decision when it comes to these farm management decisions because it allows producers to identify areas of interest in the field based on productivity. Once decisions are made, the producer can then use yield maps generated during the harvest season to see if there is any noticeable improvement in comparison to the prior season.

As stated by Kravchenko (2000), "Development of GIS technology and the availability of dense yield data via yield monitors now afford the opportunity to precisely characterize yield variability on large scales." The yield data in this particular study was used in evaluating harvest yield against different soil properties and different topographical features. The study, which took place across Illinois and Indiana, examined these factors across eight fields in total. The conclusions developed in this study were obtained by evaluating topography maps and soil sampling maps against the yield maps generated from data recorded by an Ag Leader yield monitor, and determining how different treatments effected yield across each individual field. This study demonstrates how any producer can use yield mapping technology to evaluate crop performance against different treatment factors to serve as a tool in making future field management decisions.

Another example of a field management decision that can be made by a producer using data obtained from a yield monitor is what type of hybrid shows the best performance and increases results for a particular field. To do this, the producer can use a split planter; meaning half of the planter contains a specific seed hybrid, while the other half contains a different hybrid. This should be strategically done so that the number of adjacent rows of a specific hybrid equals the number rows being harvested by each pass of the combine. When it is time to harvest, it is important that the combine harvests the rows containing one particular hybrid each pass. In doing this, the yield data displayed by each point on the yield map comes from only one specific hybrid of crop.

Once the harvest is complete, the producer can look at the yield map and compare the two hybrids. According to Darr (2013), “If crop conditions are similar yield monitors can work quite well [to tell the difference between split planter treatments or split pesticide treatments].” If there is a distinct difference from pass to pass within the field, then there is clear advantage of one selection of seed hybrid to another. Using the results and assuming all other factors remain constant, it would be expected that the producer selects the higher yield of the two hybrids for the following growing season. Using this practice, a producer would be able to use data obtained from a yield monitor and effectively make a decision to increase profit in following seasons.

2.2.2. Variable-Rate Planting

The increase in yield monitoring technology has also opened new doors for producers in the way of variable-rate planting. Yield monitoring and mapping have allowed producers to identify lower producing areas of the fields and evaluate if different planting populations will offer a greater return on their investments.

There are a number of factors throughout a field that can cause lower yielding areas within a field, no matter how uniform a field may be. Using a yield monitor and yield mapping technologies, a producer may be able to scale back planting populations in low producing areas and plant seeds at ideal spacing to account for variations in field conditions in these less productive regions. Along with identifying low yielding regions, producers are also able to identify regions with high productivity. These regions producers may choose to see how far they can push planting populations to see if they can continue to get increased profits.

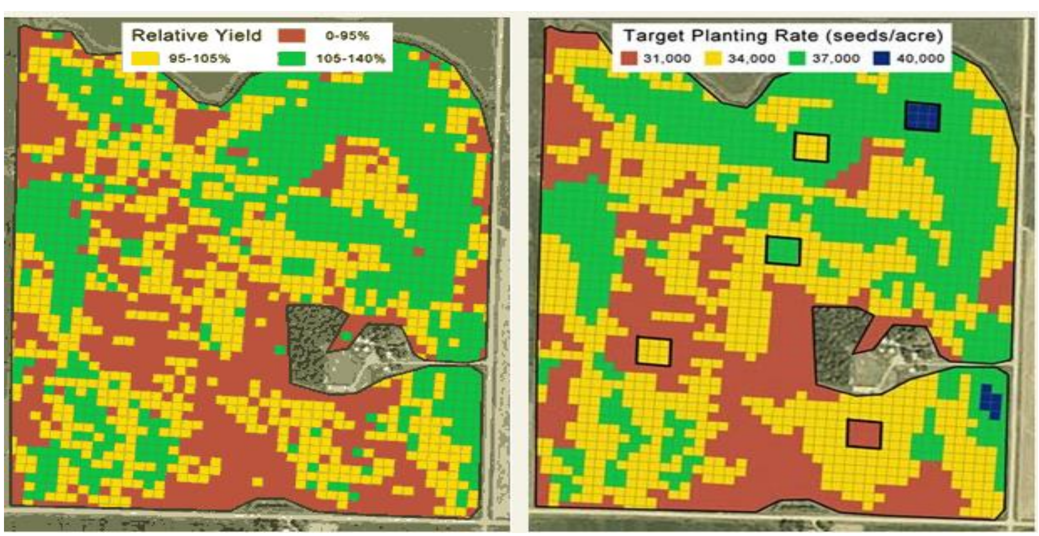


Figure 2.3: Check blocks being used in combination with yield monitors to evaluate variable-rate planting (Butzen, 2011)

A typical method in which producers use yield mapping technology to evaluate different planting populations is by using check blocks, shown in Figure 2.3. A check block is a zone that producers look to analyze, in which they have altered their planting population compared to the rest of the field. If this region is accurately recorded during planting, this particular planting population can be evaluated by using the yield map obtained from that season's harvest. A similar method can also be used by planting check strips instead of check blocks, demonstrated in Figure 2.4. This is where the producer can compare the yields of this region to the surrounding areas around it and see if there are any significant improvements that can be made to overall production at this planting population.

Figure 2.4: Check strips being used in combination with yield monitors to evaluate variable-rate planting (Butzen, 2011)

Using yield monitoring technology in this fashion provides a significant advantage to farmers looking to determine planting rates. Also looking to benefit from this are planting equipment producers. Increasing the ability at which farmers can monitor field performances enhances the marketability of advanced planting equipment for variable-rate application and row-by-row shutoff controls.

2.2.3. Fertilizer Application

Advancements in yield monitoring technologies have also created additional opportunities for variable-rate fertilizer application. For different crop types, there is documentation available to producers as a guide for nutrient application recommendations based on how many nutrients were removed from the soil by the previous crop. In order to obtain fertilizer recommendations for each individual field, a producer can use the yield maps from the previously harvested crop to more accurately determine the rate at which fertilizer should be applied to the field to overcome the nutrient extraction from the previous season.

The initial capabilities of yield monitoring technology used in variable rate application were displayed in the early 90s, when a study was done at the University of Missouri using yield monitoring technology to evaluate the performance of variable rate technology. During the study, variable rate technology was used to apply different rates of nitrogen fertilizer based on yield maps of prior seasons to corn fields in north-central Missouri (Kitchen, 1995). The results from the study are displayed in Figure 2.5. According to Kitchen, “Yields were measured using a combine instrumented with a continuous grain flow sensor which allowed for mapping of yield.” The development of the grain yield monitor allowed for it to be used as the central source of data collection into the study of how variable rate nitrogen application affects yield.

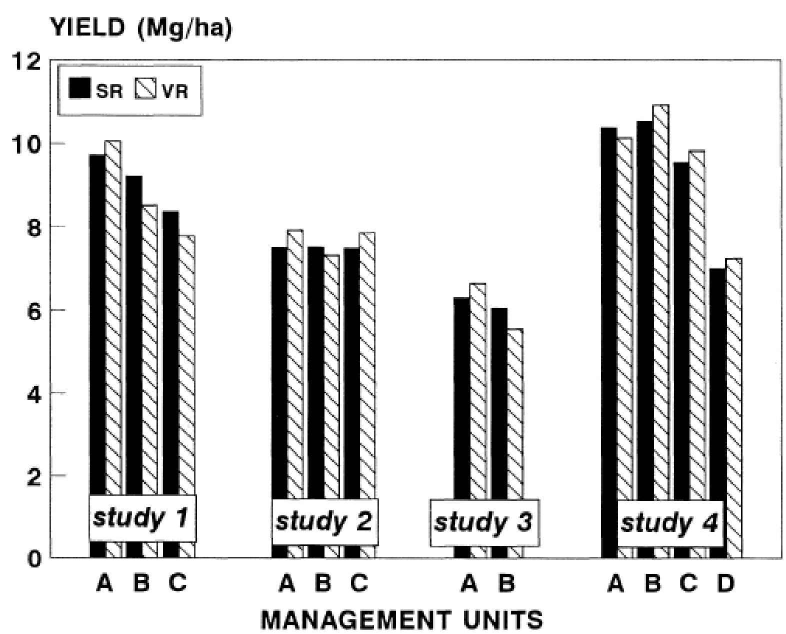


Figure 2.5: Results of variable rate application to standard rate application using yield monitor data (Kitchen, 1995)

With advancements in yield monitoring technology, not only can producers determine fertilizer application rates for an entire field, but also individual management zones within a field. Being able to see exact yields in a field, a prescription fertilizer map can be generated, using previous season's results as an input to determine the appropriate amount of a certain nutrient to be applied of the course of the field. This can prevent producers from applying excessively high or low amounts to certain regions of a field based on field overall field averages, which can leave some regions rich or deficient. Using yield monitoring technology to develop variable application rates has increased opportunities for producers in terms fertilizer application, and has supported the development of newer technologies to make variable rate application more viable.

Not only do yield monitors provide as a basis for variable rate fertilizer application, but also as a proof of concept to identify the level of success or failure that the variable rate application had on the resulting yield. Evaluating yield maps, past and present, against the different treatment levels will conclude whether or not the variable rate fertilization application produced desired levels of results across the range of testing. This concept is also valuable to producers, when evaluating nutrient application rates suggested by an agronomist based off of soil sampling results of a field.

2.3. Study of the Accuracy of Yield Monitors

While yield monitors provide numerous opportunities in the world of precision farming, there is also risk involved when it comes to the quality of data being produced by the yield monitoring system. Additionally, while many important decisions can be made and evaluated using yield monitoring technology, inaccurate decisions and evaluations can also result if yield monitors are producing data that contain significant levels of error. Error in yield monitor values can typically be credited to low quality calibrations or out of date calibrations to appropriately correct for mechanical or biological changes in harvesting conditions.

A yield monitoring system consists of an impact plate located atop an elevator transferring grain that has been cleaned and separated by the combine, into the grain tank. As grain is transferred by the elevator, it is thrown into the impact plate which outputs a corresponding voltage value from the sensor. Each unit comes with a standard factory calibration, developed by the manufacturer which scales the output voltage into a value of mass flow. The scale factor, determined by the calibration, is where significant amounts of error can be introduced into the system. This is because there are several constantly changing factors, such as changing crop conditions, varying field conditions, and alterations to mechanical systems that can affect calibration quality of the system.

According to Grisso (2002), "the advertised accuracies of continuous yield monitors vary from 0.5 to 4%, if the yield monitors are installed and used correctly." In the study, the goal was to quantify the amount of error in a yield monitor, dependent on varying factor of the combine. Two main test variables, combine capacity and slope, were used in this study across three different farmers, to determine their effect on yield monitoring, were combine capacities and slope influences. The combine capacities used to evaluate yield estimation were based on a 20% to 30% reduction of typical harvest speed, a 20% to 30% increase of typical harvest speed, and a typical harvesting speed; the results are displayed in Figure 2.6. The influences of slope on the combine yield monitoring system were evaluated based on whether the combine was traveling uphill or downhill. At the conclusion of testing, it was determined from the data that various combine capacities are important for accurate combine measurement values. From the study, "…yield monitor wet weight errors exceeded 10% when compared to weigh wagon results." (Grisso, 2002)

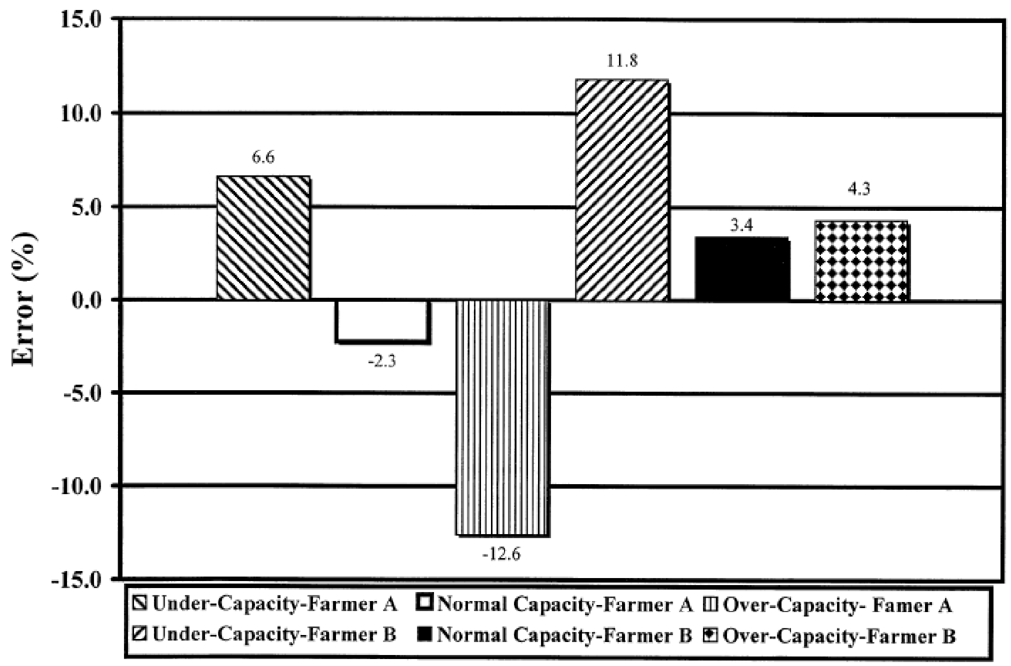


Figure 2.6: Results obtained using yield monitor at different combine capacities (Grisso, 2002)

In a separate study by Fulton (2009), the performance of grain yield monitors were evaluated over varying slopes to examine its impact on performance. Initially, from regular field harvest data, it was found that with the correct use of the yield monitors, they were able to obtain accuracies within 3% actual value. After introducing both pitch and roll into in the system, the mean errors that were then calculated varied by up to 6%. The results of their data showed that the highest flow rates produced the greatest variations in accumulated mass flow estimations. From that, pitch (errors ranged from -6.41% to 5.50%; shown in Figure 2.7) had a much more significant impact on accumulated mass flow estimates than did roll (errors ranged from -3.45% to 3.46%). (Fulton, 2009)

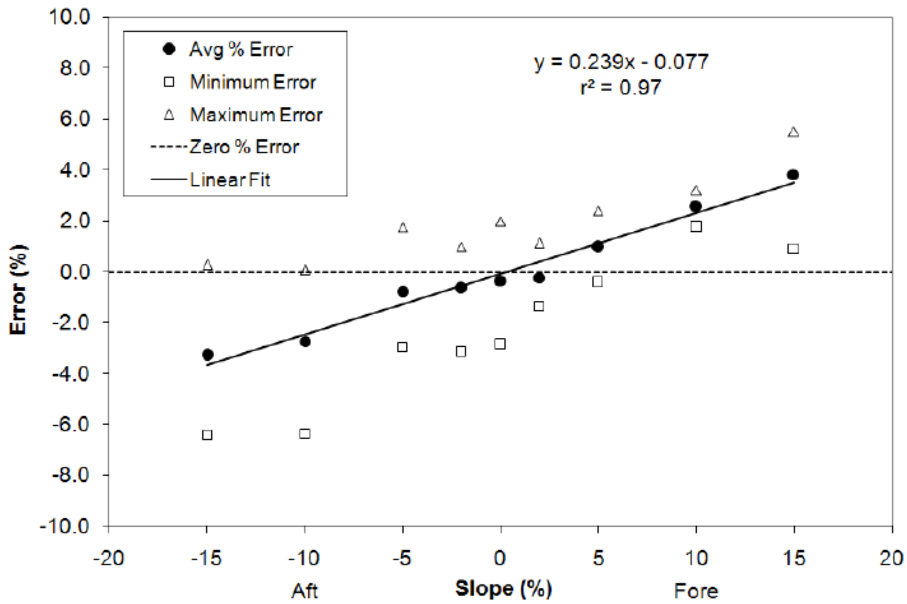


Figure 2.7: Evaluation of yield monitor performance against pitch (Fulton, 2009)

In a separate study performed by Al-Mahasneh (1999), the accuracy of the Ag Leader Yield Monitors was evaluated by using scales to record the actual weight of the grain compared to the mass flow values recorded by the yield monitor to study the effect of harvest length on system performance. For testing purposes, this data was collected between two consecutive harvest seasons of corn and oats. The results of their testing showed that there was a difference in results in the yield monitor within a season from field-to-field, as well as from season-to-season. According to Al-Mahasneh (1999) in the article, “Calibration is considered the most important factor in the performance of the yield monitor and the scale.” From their work, they were able to see the discrepancies that currently exist in yield monitoring technologies today and the overall importance of an accurate yield monitor calibration.

In another study targeting yield monitoring accuracy carried out by Krill (1996), the effect of how pass-to-pass differences impacted the performance of an Ag Leader 2000 yield monitor. In the test procedure each strip, corn, popcorn, and soybeans were used, was considered an individual load and potentially contained different hybrids of the same crop. The results from testing procedure showed that there was little variation in percent error seen across different passes within the same crop. According to Krill (1996), “The data collected indicated that the Ag Leader 2000 yield monitor did an acceptable job of estimating the quantity of harvested grain...the Ag Leader 2000 yield monitor can be an appropriate tool for yield calculation when installed properly and used within the capabilities of the yield monitoring system.” Based off of these conclusions, with a properly calibration system, the Ag Leader yield monitor can be used to successfully quantify the value of grain mass flow through the combine.

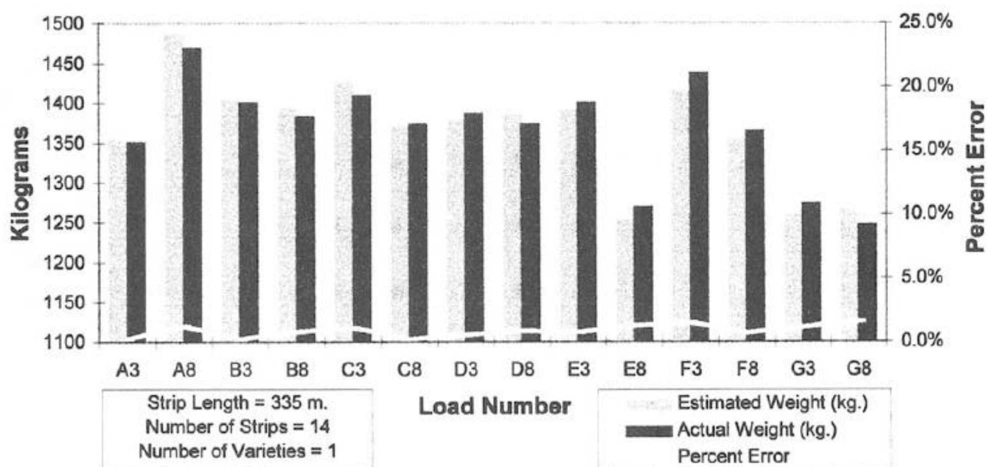


Figure 2.8: Yield monitor error results in corn over a 1995 harvest season (Krill, 1996)

The studies examined explore different concerns producers and those industry may potentially have regarding the accuracy of combine yield monitors. These studies examine physical characteristics that could be believed to be driving factors in yield monitor error. The results of these studies indicate that some factors, such as combine slope, could drive potential for error within the system. These studies, along with future work, will be important in identifying the full capabilities of a combine grain yield monitoring system. Considering this, conclusions derived from other case studies indicate that the Ag Leader yield monitor is capable of providing "…an acceptable job of estimating the quantity of harvested grain." (Krill, 1996)

CHAPTER 3. OBJECTIVES

3.1. Objective 1: Develop a Test Stand to Simulate Actual Harvest Conditions in a Controlled Environment

A test stand that is capable of replicating actual harvest conditions in a controlled environment will provide the ability to test yield monitor response against different treatment factors in conditions identical to what it would experience during the harvest season. The test stand will allow the system to be rapidly repeatable and provide appropriate ground truth grain mass flow data to evaluate against the current system. This testing process will be controlled from a single location to which all relevant data will be logged by single user. The system will have appropriate safety features to prevent injury, spills, and equipment failures.

3.2. Objective 2: Evaluate the Current Yield Monitoring System's Ability to Measure Grain Mass Flow

The ability of current Ag Leader yield monitoring system to properly measure different levels of grain mass flow across varying harvesting conditions will be evaluated. Testing will be performed to obtain data to examine yield monitor performance with respect to different treatment factors. These factors will be examined by replicating them using a test stand in a controlled environment, as well as by using appropriate data collection techniques to examine actual harvest performance. The understanding of how different harvesting conditions impact yield monitor response will be relevant in identifying areas of correction in measured yield values in future yield monitor advancement.

CHAPTER 4. DEVELOPMENT OF A TEST STAND FOR THE EVALUATION OF GRAIN MASS FLOW THROUGH A COMBINE

4.1. Introduction

Grain yield monitors (Ag Leader Technology, Ames, IA) were first introduced on combines in 1992, by the company now known as Ag Leader Technology. The measurement of grain mass flow through a combine has consistently been a concept that is difficult to obtain, while the accuracy of the system can be highly variable in response to varying field conditions. Accounting for variance in field conditions can be difficult because the window for testing these systems falls within a time span of only a few months, and harvest conditions seen within the field are hard to control.

Because of this, understanding the concepts of grain mass flow, through a combine, as well as designing systems to accurately measure values of mass flow have proven to be difficult. For developmental purposes, having a system capable of replicating in-field conditions seen during the harvesting season, in a controlled environment, would be beneficial in helping further understand the concepts of grain mass flow through a combine.

This study is part of a project based upon the analysis of the current production system on John Deere S-series combines (John Deere, Moline, IL). Developing a test stand capable of replicating in-field harvesting conditions in a controlled environment for this project will be major piece in creating an understanding of how different field metrics can impact mass flow. The understanding gained from the development of this test stand will allow for harvest conditions to be simulated for system evaluation.

4.2. Objectives

In developing a test stand, there were several design specifications required in order to be able to properly evaluate and understand grain mass flow through a combine. The overall system needed to be able carry out tests efficiently, with minimal error, and appropriate data collection techniques. The key objectives targeted to properly develop a test stand that will be able to meet the overall project objectives are as follows:

- The system needs an adequate grain storage system capable of holding at least 400 bushels of grain, which would be the peak value required to completely fill a combine grain tank. The grain storage system also needs to be able to precisely meter grain giving the operator the ability to achieve specific targeted grain mass flow increments as well as repeat the process to build confidence in the data set.
- The system needs to provide an accurate ground truth value to be used for sensor evaluation. This ground truth value needs to be an exact value of grain mass flow by weight. Providing an accurate ground truth mass flow value will provide a numerical value that can be used to evaluate the performance of the sensor's ability to accurately measure grain mass flow.
- The system needs to be able to transfer grain into the combine without disrupting the ground truth mass flow value. The grain transfer system requires a peak capacity of grain mass flow at 200 metric tons per hour, in order be able to test over the full capacity range of the combine. To achieve this, the system needs to minimize the amount of transition points that can alter flow rates and result in grain loss. The transfer system also needs to transfer grain while minimizing impact on the integrity of the grain.
- The system needs to have the ability to be controlled by a single operator with minimal user inputs that can impact the testing procedure. Automating processes on the test stand will be

used to reduce the need for manual inputs that are difficult to repeat and can induce error to the system. The control system should be controlled from a user interface located within the cab of the combine, giving the operator complete control over both the test stand and the combine simultaneously.

- The system needs to be able to accurately collect all forms of data that could be used in the evaluation of mass flow and sensor technology used in the testing procedure. Data collection needs to include ground truth data, sensor data, and combine data that will be used in evaluating different harvesting metrics. The data logging system needs to organize data in a usable format, so that it can be processed rapidly at the completion of a set of tests.

Achieving the objectives listed above will result in a test stand capable of simulating harvest conditions in a controlled environment that can carry out tests efficiently, with minimal error, and appropriate data collection techniques. A test stand of these capabilities is an important piece in obtaining the long term goals of the project.

4.3. Materials and Methods

The development of a test stand capable of simulating in-field conditions in a controlled environment took several design components into account to develop the final system. The design components looked at in the system development were:

- Grain storage
- Grain metering
- Ground truth mass flow measurement
- Grain transfer
- Control/data collection system
- Data management

- Data processing

The brainstorming, design, and selection process of these system components is documented in the following sections.

4.3.1. Grain Storage

The grain storage component of the system was an important part of the design process in ensuring that the test stand can hold an adequate supply of grain for the testing process. In order to supply the test stand with an adequate amount of grain the storage capacity required is at least 400 bushels of grain, which is approximately the peak value of storage available within a combine grain tank. The storage system also required the ability to incorporate a metering system and ground truth measurement system, simplifying the development of those design components. Also taken into account in the design of the grain storage system, was the ability to change grain loads in and out of the system.

Several different ideas were considered for grain storage for the test stand. One idea looked at was a bulk bin typically used for grain, and feed storage. Advantages of this selection were that it is a component designed for the storage of grain. This selection also provided a system that different loads of grain could easily be exchanged in and out of. A disadvantage of this selection choice was that, at the capacity required by the test stand system, a significantly large bulk bin would have limited mobility, making it difficult to transport and introducing challenges in the test stand assembly.

Another option considered was a custom built storage system. With a custom storage system, it could be ensured in the design that all system requirements were capable of being reached. The system could be built in with the required capacity of the test stand, and incorporate the ability to accurately meter grain and achieve ground truth flow rate value. The disadvantages of this system are that the time required to build the system would be significantly increased, as opposed to purchasing a component already capable of meeting the system requirements.

The next option looked at for grain storage was using a grain wagon already owned by our research team. Because it is a component that is already available for used, it would minimize the development time of the system. The grain wagon capacity is approximately 740 bushels of grain, which is well within the specifications of the test stand capacity. Because the grain wagon is already designed for the storage of grain, it is already a system that grain loads can easily be changed in and out of. This system is also capable of incorporating grain metering systems as well as a ground measurement system. Another advantage of this system is its mobility. The fact that it can be easily transported makes setup and takedown significantly faster.

Figure 4.1: Final grain storage design component selected for the test stand

Factoring in the advantages and disadvantages of each design component option the final design choice option was the Brent 740 grain wagon (Brent Equipment, Kalinda, OH). This grain storage selection, shown in Figure 4.1, used a component readily available; reducing the test stand cost, and was also capable of meeting all the test stand design specifications. This selection also provided additional advantages such as mobility. Having mobility of the test stand made the setup and take down of the system a faster process.

4.3.2 Grain Metering

The grain metering process was the next design component evaluated in the development of the test stand. The grain metering system needs to give the operator a precise control to target specific flow rates as well as replicate those flow rates to build confidence in the data set. The metering system needs to be able to meter grain mass flow rates values up to a range of 200 metric tons per hour.

One option explored for grain metering was using a variable feed auger to control grain flow. An advantage of this system is that it provides an accurate control over the grain flow rate. While this system is capable of accurately metering grain, it does come with some disadvantages. At the capacity required by the test stand, the components would be fairly expensive and add increased costs to the test stand development. Another disadvantage is that this setup requires a lot of mechanical adjustments to the wagon, which would require additional time to set up, as well as the fact that it would make reusing the wagon during the fall harvest season difficult. This setup, using an auger to meter the grain, would also increase the damage done to the grain during the testing process and shorten the testing life of the grain.

The next idea examined was using the original wagon gate on the test stand and controlling it by hand at the start of each test run. This design would minimize the cost because it would consist only of parts already in place on the wagon. This design would also require very few alterations to the wagon itself and would keep the wagon's functionality. A disadvantage of this set up is that the control over the gate is not very precise because of the size of the gate and the fact that the gate height is set manually by the operator at the beginning of each test repetition. The width of the gate does not provide much ability to precisely control the incrementing grain mass flow rates.

Another option explored was building a customized gate for the wagon. This customized gate would be controlled electronically by linear actuators (Surplus Center, Lincoln, NE) providing a more precise and repeatable process. Because this gate would be relatively small in size, the cost of the gate would be fairly inexpensive and the system would be able to be built to ensure it met the required system grain mass flow capacity of 200 metric tons per hour. This setup would also not induce any additional damage to the grain quality or obstruct the continuous grain flow of the system.

Figure 4.2: Customized wagon gate developed for metering grain into the test stand

Wagon Flow Testing

To ensure the use of gate of was a reasonable option, the flow of grain from the wagon with respect to time needed to be approximately linear. Initial testing was required to prove the concept that grain flow from a wagon was linear and not affected by head pressure causing a variation in mass flow as grain level in the wagon changes. If linear mass flow was achievable from the wagon it would verify using a gate to meter grain as a viable option.

To test the concept of linear mass flow, a wagon of grain was positioned over a grain auger. This auger transferred grain into a grain cart equipped with scales. Serial data was logged from the scale head in order to observe and evaluate grain mass flow through the wagon gate. The testing procedure consisted of emptying the entire grain wagon into the grain cart while logging serial data. This process was repeated multiple times at different gate opening positions. From the data set produced, displayed in Table 4.1, it was concluded that grain mass flow from a wagon could be considered to be constant, and thus using a gate to meter grain could be considered as a viable option.

Table 4.1: Table of the result of the testing procedures used to verify the concept that grain mass flow from a wagon is constant

Run	Average Flow		Standard Deviation		R^2
#	[lbs/sec]	[bu/sec]	[lbs/sec]	[bu/sec]	
1	77.12	1.38	6.85	0.12	1.00
2	66.01	1.18	3.73	0.07	1.00
3	100.86	1.80	3.81	0.07	1.00
4	39.07	0.70	5.36	0.10	1.00
5	23.57	0.42	4.33	0.08	1.00
6	104.69	1.87	7.12	0.13	1.00

The final system design choice was building a customized gate, shown in Figure 4.2, to control the grain metering process. The design consisted of a gate that fit into the slot already in place on the wagon for the original gate so it did not require any alterations to the wagon other than removing the current gate. The customized gate consisted of four smaller gate openings each controlled by linear actuators. These smaller gates allowed for a more precise control over the grain mass flow because of their opening size. Each linear actuator also contains a built-in potentiometer so that the gates could then use a set point to set the appropriate position, in advance, based on the potentiometer output. This type of control made the testing process more repeatable. Increased repeatability was important in order to build up confidence in the data sets produced by the test stand. The selection process for the grain metering design component produced a system that provided the least amount of damage to the grain, minimized the cost of the system, and was precise as well as repeatable.

4.3.3. Ground Truth Mass Flow Measurement

Determining a method for accurately measuring the ground truth mass flow value was the next design component to be determined in the test stand development. The ground truth mass flow measurement was a very important component because it provides an actual, accurate value to evaluate the performance of sensors used to measure mass flow against. The data output of this system needs to be in a format that it can be logged and used in future data analysis.

The first method looked at to provide an accurate ground truth measurement was a portable axle scale system. This system could be placed directly under the wheels of the wagon to provide accurate mass value that could be logged via a serial output. A disadvantage of this system is that it is relatively expensive and for the best accuracy they need to be place on flat level surface.

Figure 4.3: Ground truth measurement system installed on the test stand wagon, (left) load cell mounted on the front half of the wagon frame, (right) load cell mounted on the back of the wagon frame

The next option considered for measuring the ground truth mass flow rate was a four point cart scale kit, to be installed directly on the wagon. This system consists of load cells that mount on all four corners of the grain wagon frame and output values back to a scale head that displays the total weight. The scale head is also equipped with a serial output which would be used for data logging.

The final design choice for the ground truth measurement system was the four point scale kit shown above in Figure 4.3. This was chosen because it could be installed on the wagon once and it would never have to be moved or positioned again. The system was also chosen because it is rated at an accuracy of ±1% (Central City Scales Incorporated, Central City, NE) if the system is properly calibrated. To calibrate the system, the wagon was filled with grain and the measured value was observed. The entire load was then weighed on a certified elevator scale to observe the true value. Using the scale kit manual, these weights were used to accurately calibrate the system.

4.3.4. Grain Transfer

The selection of the method of grain transfer was the next step in determining how grain was going to be delivered from the test stand wagon to the combine. This system requires grain to be transferred at a peak flow rate of 200 metric tons per hour. The selection method needs to deliver grain from the test stand wagon onto the combine sieves, so that grain can be transferred through the combine and fill the grain tank identically to how it would be in actual harvesting conditions. This system should have minimal transfer points to avoid altering the ground truth mass flow data and to minimize grain loss. It should also look to reduce the amount of damage done to the grain as much as possible. When looking at the method of grain transfer, two factors were analyzed: the routing of grain and the method of delivery.

Grain Routing

When evaluating how grain was to be routed for delivering the grain to the combine from the test stand, three different routing arrangements were considered. The different routing arrangements are described below:

1. Grain will be transferred from the test stand wagon back at an angle behind the combine. From there, grain will be transferred to another system that will carry grain into the back of the combine and dump onto the combine sieves. (see Figure 4.4)
2. Grain will be transferred underneath and to the other side of the combine. From there grain will be transferred up into a hopper that feeds into the clean grain elevator. (see Figure 4.4)
3. Grain will be transferred from the test stand wagon to the left hand side of the combine. The rotor covers will be removed and grain will be dumped in by the rotor onto the combine sieves. (see Figure 4.4)

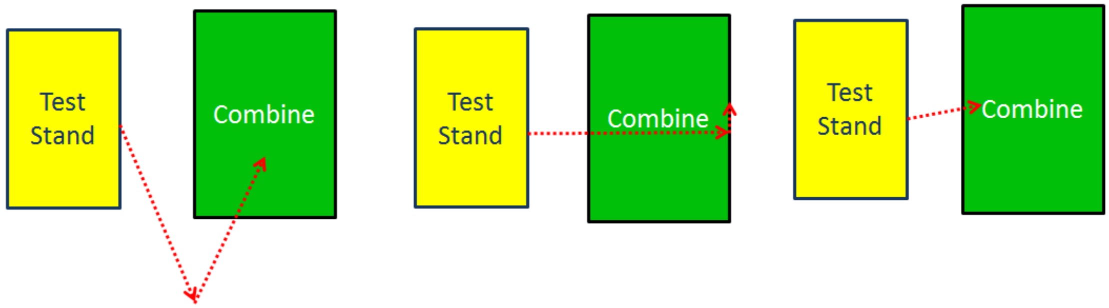


Figure 4.4: System diagram of grain routing options, (left) routing option 1, (middle) routing option 2, (right) routing option 3

Option three was chosen as the final routing method. This routing arrangement transferred grain the least distance while minimizing the number of components required. This will reduce the overall cost of the system, reduce the number of transfer points that can alter the ground truth mass flow, and will reduce the number of points at which a failure could occur.

Grain Delivery

Once the grain routing arrangement was decided, the grain delivery method could then be specified. Two different grain delivery methods where looked at for transporting grain from the test stand wagon into the side of the combine. Those methods were by way of either a steel auger or a belt conveyor.

Figure 4.5: Belt conveyor selected as the method of grain delivery

The steel auger was the cheaper of the two selections, but the steel auger also would do the most damage to the quality of the grain. In contrast the belt conveyor was slightly more expensive but also had the least amount of impact on the quality of the grain. Therefore, the final choice was to use a belt conveyor (Westfield, Rosenort, MA, CA), shown in Figure 4.5, to deliver grain from the test stand wagon into the side of the combine. With the amount of testing expected to be done, the minimal amount of grain damage played a key role in the decision because grain damage has the ability to impact testing results, as well as induce additional costs to replacing grain in the system.

4.3.5. Controls/Data Collection System

The test stand control system was designed using a National Instruments CompactRIO (National Instrument, Austin, TX), which is programmable with LabVIEW (National Instruments, 2014). This device is capable of supporting digital inputs and outputs, analog inputs and outputs, controller area network (CAN) channels, and RS-232 serial communications. The system design used the digital and analog inputs and outputs to control the main functions of the test stand design. The RS-232 serial communication was used to log ground truth data from the serial output on the scale head. The controller area network (CAN) module was used in logging data located on the combine bus for the evaluation of how different combine and field metrics affect the system.

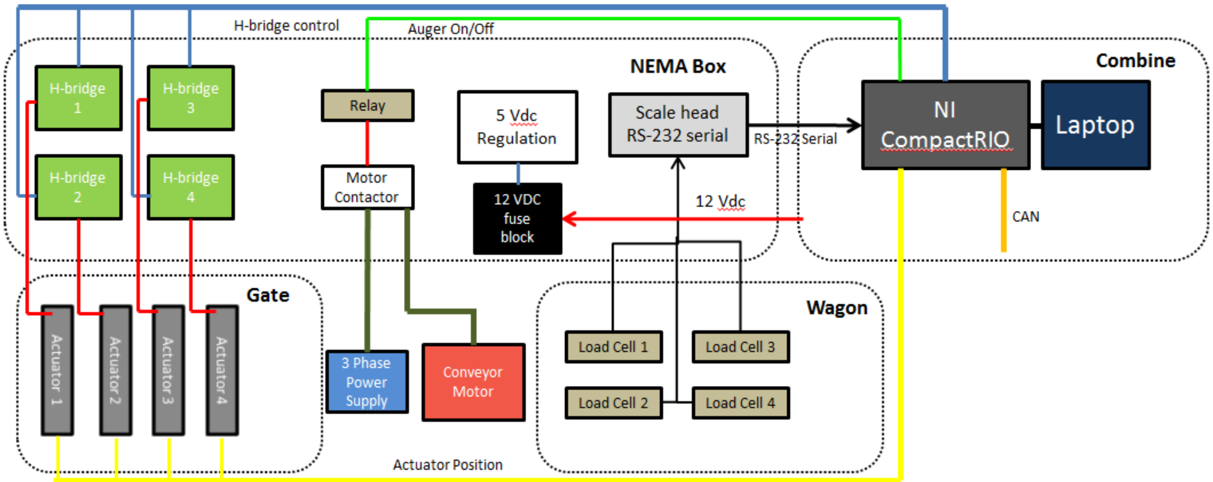


Figure 4.6: Electronic wiring schematic used in the test stand development.

Using the digital output and analog inputs, the linear actuators on the grain metering system were controlled to give the operator a precise method for controlling the test stand grain mass flow. Three digital output channels from the National Instruments CompactRIO were used for controlling each individual actuator. These three digital outputs run to an H-bridge motor controller where they control the enable, forward, and reverse functions of the H-bridge. This allows the CompactRIO to supply 12 volts to the linear actuator, while also controlling the direction. A constant five volt power supply is also supplied to the linear actuators to power the component's internal potentiometer. The internal potentiometer then sends an analog output that can be read by the operator and used in the system's code logic for more precise control.

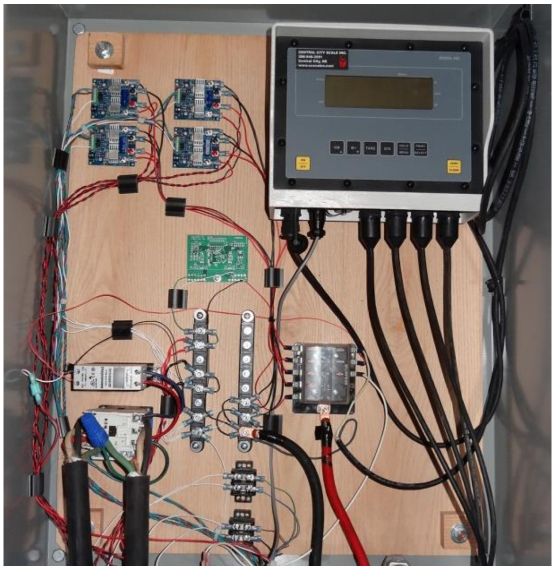


Figure 4.7: NEMA enclosure used to house the test stands electrical components

The system's grain delivery system was

wired to be controlled by a manual switch from the cab of the combine. This manual switch supplies power to trip a relay supplying 12 volts to enable a three phase motor contactor. Once the motor contactor is enabled, the three phase power is supplied to the electric motor, which drives the belt conveyor component that makes up the grain delivery system on the test stand.

The ground truth data system is made up of a standard four point grain wagon scale system supplied by Central City Scales. This system is composed of four load cells mounted on four corners of the wagon's frame with their outputs running to Avery-Weightronix 640M scale head which calculates the mass of the wagon load based on these inputs. Data from the scale head is transmitted to the CompactRio through an RS-232 serial communication. The total mass of the system can then be used by the operator to determine the length of a test by the total mass load. The scale data can also be logged and processed to determine the ground truth grain mass flow value of the system during the testing process.

In order to ensure all necessary information of the combine metrics are captured, all combine data being transmitted across the controller area network (CAN) bus is also logged by the CompactRIO. This ensures that any useful information that may be needed, regarding the combine, is available for future processing. Informative values that can be obtained from the CAN data that were initially targeted include grain mass flow sensor values, grain moisture, combine pitch, and combine roll. This data is necessary for future testing to determine how simulated harvest conditions impact the calculated value of the grain mass flow sensor.

The test stand is supplied with 12 volts of DC power provided by the combine battery. The 12 volts of power is run into a single fuse block. From the fuse block, power is broken off to all components that require power, and equipped with appropriately sized fuses to prevent an electrical failure within the system. For the system components that require five volts of power, one of the 12 volt power leads is stepped down to five volts and broken off to supply these components.

All electronic components that were not firmly attached to the test were positioned within a NEMA enclosure, displayed in Figure 8, which was then mounted to on the back of the test stand. The electrical enclosure is designed to provide protection to enclosed components from other outside elements. This is to protect all enclosed components from conditions that could cause damage, resulting in an electrical malfunction on the test stand. From the NEMA enclosure all wires are then routed from the test stand to the National Instruments CompactRIO located in the cab of the combine in a well laid out and organized manner.

The National Instruments CompactRIO was used as the system control unit because it supported all of the required modules and was programmable with LabVIEW. The LabVIEW software contained all of the functionalities required by the test stand in a format that is very functional. Also supported in this software was the development of a user interface. The user interface, shown in Figure 4.8, was developed to provide the operator with a user friendly control panel that is directly controlled through a laptop connection within the cab of the combine.

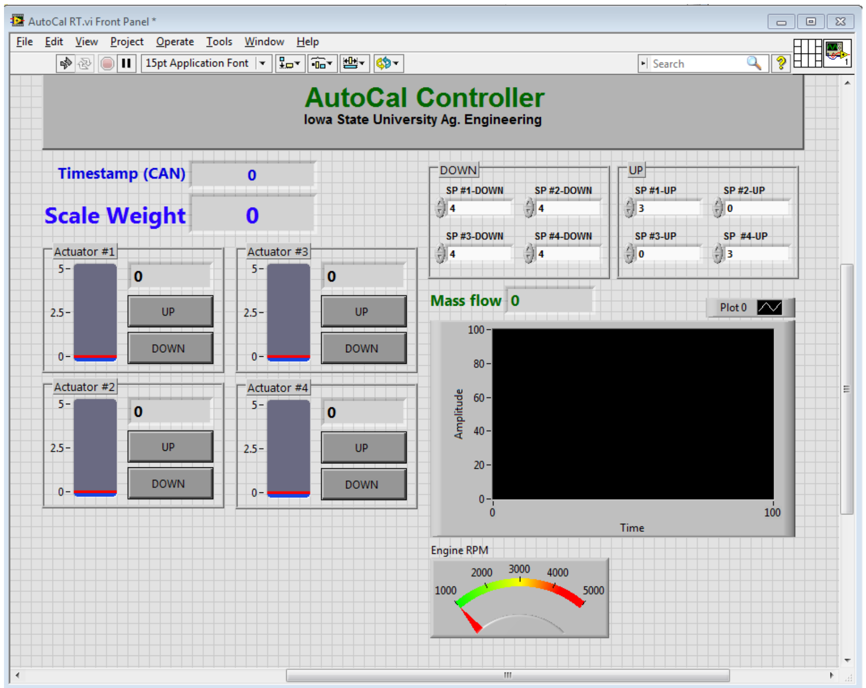


Figure 4.8: Image of the test stand controller interface developed in LabVIEW

The collection of these components allows for a smoothly automated system that is capable of supporting the requirements of the test stand. This configuration supports all functions of the test stand design and simplifies the testing procedure in an electronically safe setup. The control architecture creates a system that is precise, capable of rapid testing, while minimizing the potential for user error.

4.3.6. Data Management

The organization of data from the test stand was an important step in maximizing the potential. Obtaining the data, as well as storing it in a usable manner, was necessary to make the data processing and evaluation process possible. Without proper data management, the test stand would not provide data that can be processed efficiently for sensor evaluation.

To properly organize the data, the LabVIEW program was designed to organize data into three separate text files while logging. Each log file is set up to save a text version of the three different data types; analog input data, serial input data, and CAN input data. Text files were used because of their simple format and because they can be easily read in by most programming software.

Name	Date modified	Type	Size
CAN-000.txt	3/1/2013 1:11 AM	Text Document	7,780 KB
CAN-001.txt	3/1/2013 1:26 AM	Text Document	6,429 KB
CAN-002.txt	3/1/2013 1:36 AM	Text Document	6,366 KB
loadcells-000.txt	3/1/2013 1:11 AM	Text Document	13 KB
loadcells-001.txt	3/1/2013 1:26 AM	Text Document	11 KB
loadcells-002.txt	3/1/2013 1:36 AM	Text Document	11 KB
scale-000.txt	3/1/2013 1:11 AM	Text Document	21 KB
scale-001.txt	3/1/2013 1:26 AM	Text Document	18 KB
scale-002.txt	3/1/2013 1:36 AM	Text Document	17 KB

Figure 4.9: Example log files displaying the logging file architecture of the test stand

Each time the program is started at the beginning of a test run, it will generate three new log files, each annotated with the same test repetition tag. This value is incremented at the conclusion of each additional adjacent test run on the test stand. This logging file structure, displayed in Figure 4.9, was implemented because it makes syncing the appropriate files together simplified for future data processing.

4.3.7. Data Processing

Developing a quick and efficient method of processing data obtained from the test stand is necessary to allow for an individual data set to be used immediately for evaluation, if needed. Using a script file to process data automatically will allow for quicker data analysis and maximize the amount data collection that can be done. Combining test logs into a single organized file for a particular test plan inherently creates a file that can easily be handled by most statistic based software packages.

To automate data processing, a MATLAB (MathWorks, Natick, MA) script file was developed to take multiple sets of log files from a single folder location and process them simultaneously. This script file combined all three text files from multiple test runs and organized data by test repetition number and round time values. In this method, a single data set was designed to be converted into a single, organized spreadsheet. From there, a collection of test reps could be analyzed using software packages such as MATLAB, Excel (Microsoft Office, Redmond, WA), and Minitab (Minitab, State College, PA).

4.4. Results

The final design components selected for the development of a test to evaluate grain mass flow through a combine resulted in a completed system that was able to meet all specifications that were required by the project. To meet the project goals, the overall system needed to be able carry out tests efficiently, with minimal error, and use appropriate data collection techniques. The key objectives that were achieved by the test stand were:

- The test stand was able to reach the required capacity for storage and grain mass flow delivered to the combine while minimizing damage to the grain.
- The test stand provided an accurate ground truth mass flow value to be used for the evaluation of commercially available sensor's ability to measure mass flow.
- The system was completely automated and was able to be controlled from a central location within the cab of the combine.
- The test stand was able to log data into an organized format that was able to be mass processed using a MATLAB script file.

4.4.1 Test Data Results

From the test stand, data was obtained that verified that the design requirements of the system were met. The test stand data provides information capable of developing an understanding of grain mass flow through a combine and the ability of sensors to measure it.

Data Trends

Testing was done to view the ability of the test stand to alter mass flow, simulating a change in yield within a field that could be detected by the mass flow sensor. To test this concept, a test stand run was started and the test stand gate was opened to a set position to simulate harvesting conditions. Once the grain tank was partially full, the test stand gate was closed to simulate a break in grain flow. After a few seconds the test stand gate was opened again to a set point higher than the initial position to simulate harvesting conditions in a higher yielding region. From processing the data logged during that run, the plots displayed in Figure 4.10 were produced.

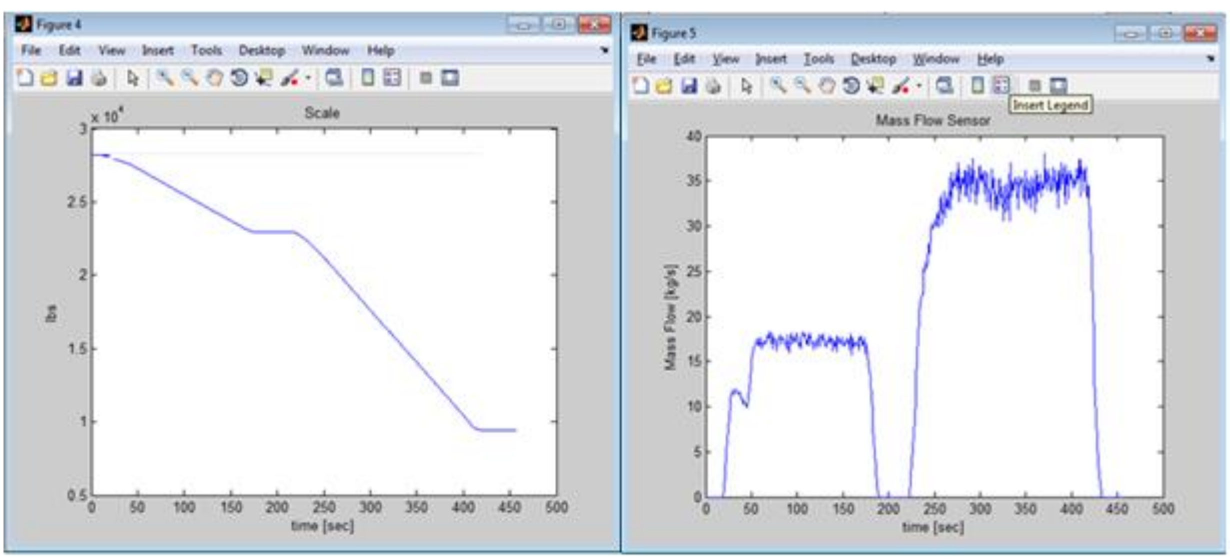


Figure 4.10: testing performed to show the ability of the test stand to simulate change in yield within a field, (left) 10a: plot of the ground truth scale weight of the test stand vs time, (right) 10b plot of the combine mass flow sensor vs time

The results in Figure 4.10, verify the ability of the test stand to simulate changes in yield experienced during a harvest season. The graph in Figure 4.10a is a plot of the ground truth scale weight of grain in the test stand while the graph in Figure 4.10b displays the response of the grain mass flow sensor on the combine. From approximately ten seconds into the test to 180 seconds into the test, the slope of the ground truth total mass remains constant from the initial test stand gate position. From that point the total mass in the test remains constant until approximately 210 seconds into the test which is the point at which the test stand gate is closed. From that time until 420 seconds, the ground truth mass begins to change again with an increased slope greater than that from the ten to 180 second time period representing the time at which the test stand gate was opened to a setting higher than the initial position. This response is shown on the graph in Figure 4.10b which contains three discrete ranges at which the mass flow sensor outputs: approximately 18 kilograms per second representing the initial test stand gate position, 0 kilograms per second representing the test stand gate is closed, and approximately 34 kilograms per second representing an increase in the test stand gate opening. The difference in response times from the graph in Figure 4.10a and the graph in Figure 4.10b is due to the system time delay shown in Figure 4.11 below.

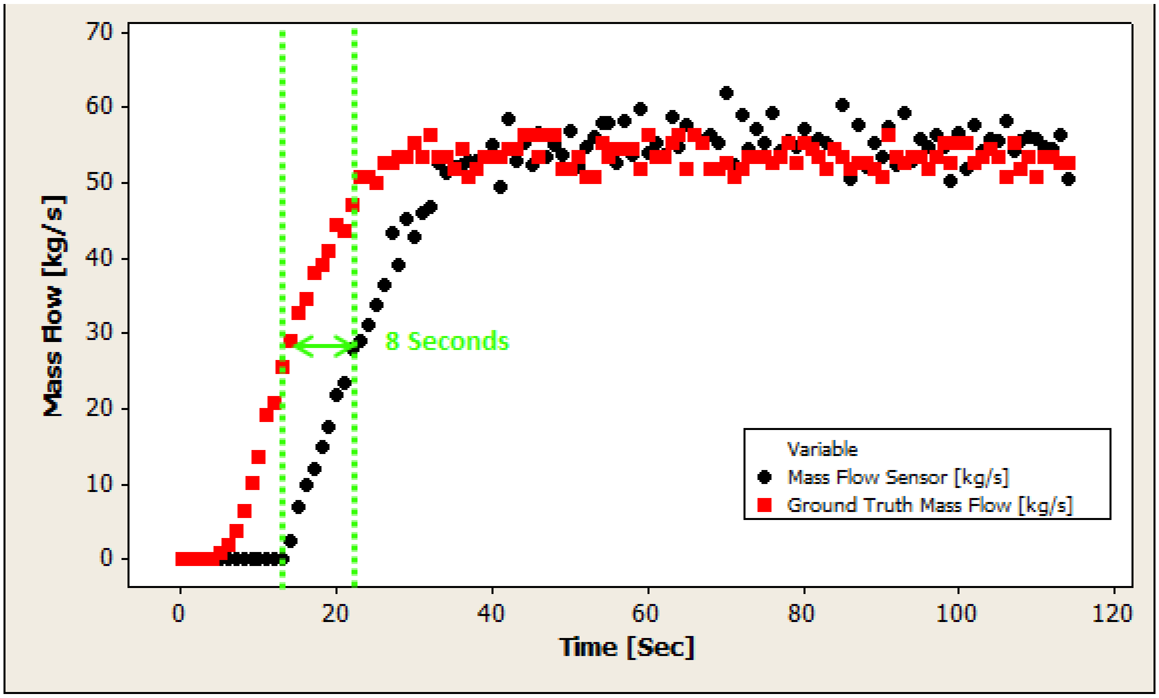


Figure 4.11: Graph portrays the time delay from the test stand ground truth mass flow value to combine mass flow sensor value

Figure 4.11 shows that on an individual test run, there is a time delay of 8 seconds between the ground truth mass flow data and the mass flow data obtained by the combine mass flow sensor. This delay is a result of the time required for grain to flow from the test stand wagon to the point at which it reaches the mass flow sensor. From the time the test stand wagon first sees a change in mass, grain first flows out of the wagon into the conveyor hopper, transferred by the conveyor to the combine where it enters just below the rotor, and then delivered into the clean grain elevator by the cross auger below the combine sieves. It is then transferred up the clean grain elevator, where it is detected by the combine mass flow sensor. To estimate the average time delay of the system, a data set of 44 test runs taken over the course of three days, was examined. From this data set, it was calculated the average time delay of the system was 7.19 with a standard deviation of ± 1.05 seconds.

Repeatability

To build confidence in the data sets produced by the test data, the process needs to be repeatable. In order to evaluate the repeatability of the test stand, a data set containing 44 test runs ranging from 40 metric tons per hour to 200 metric tons per hour, at which individual runs were repeated, was examined. Table 4.2 shows the results from the evaluation of repeatability.

Table 4.2: Results from the evaluation of repeatability within the test stand. Table shows the targeted flow rate value, the number of test repetitions performed at that flow rate, and the standard deviation of those test runs.

Approximate Flow Rate [MT/hr]	Number of Test Runs	Standard Deviation of Tests [MT/hr]
40	5	0.87
60	5	3.45
80	5	0.66
100	5	2.24
120	4	0.87
140	5	1.91
160	5	1.71
180	5	2.17
200	5	5.58

The data sets contain information from test runs beginning at targeted flow rates 40 metric tons per hour, and increase in increments of 20 metric tons per hour. At each flow rate, between four and five tests runs were observed with testing taking place over the course of three days. From Table 2, the maximum standard deviation of 5.58 metric tons per hour occurred at a single flow rate target of 200 metric tons per hour, while the minimum standard deviation of 0.66 metric tons per hour occurred at 60 metric tons per hour. Being able to maintain system repeatability allows for multiple repetitions to be performed at different testing metrics, to build confidence in the evaluation of those data sets. As shown by the data set, the test stand is capable replicating individual test runs with reasonable accuracy.

To evaluate the consistency and repeatability of the test stand over its full range, the 95% confidence intervals of test results across nine different targeted flow rates were plotted for comparison. The confidence intervals are representative of all ground truth, grain mass flow values sampled once per second over the span of five different test repetitions at each level of grain mass flow. From examining Figure 4.12, the greatest variation in grain mass flow is one metric ton per hour, which was viewed at a targeted grain mass flow level of 200 metric tons per hour. From the analysis, this means that during the 711 ground truth grain mass flow values recorded across the five different test repetitions, the value recorded is expected to fall within ±0.5% of the average.

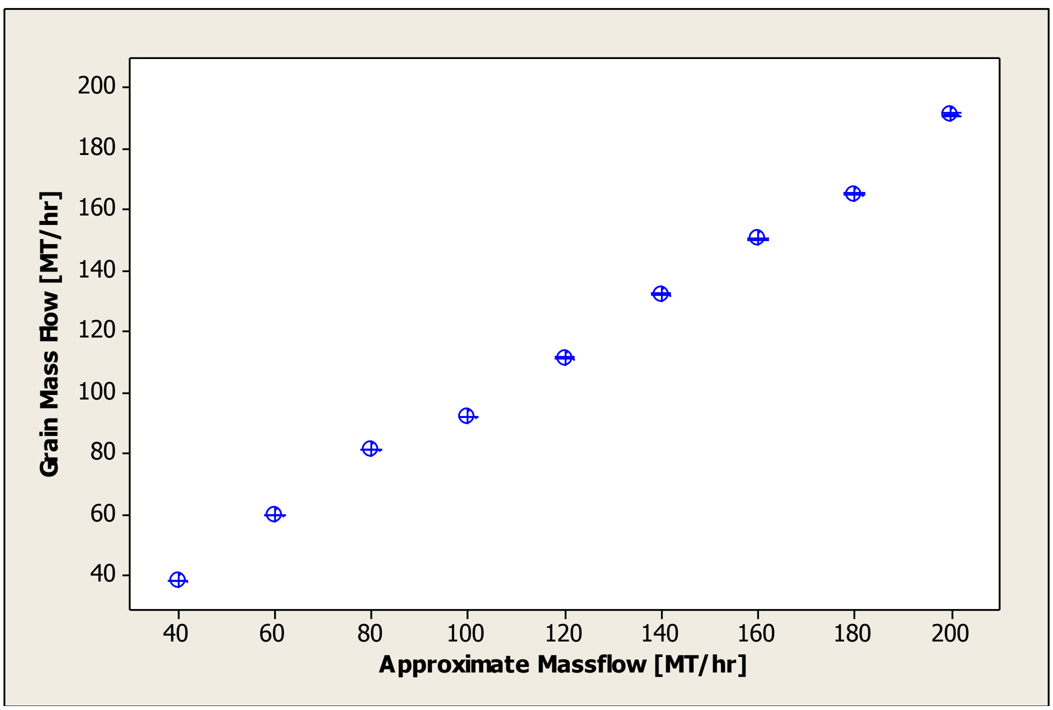


Figure 4.12: Plot of the 95% confidence interval of ground truth mass flow rates recorded at respective targeted levels of grain mass flow

Test Stand Capacity

Figure 4.13 shows a plot of grain mass flow with the test stand operating at maximum capacity. The targeted maximum capacity of the system was 200 metrics tons per hour. This is to ensure that the test stand could produce grain mass flow rates over the full scale range of the combine capacity. From the graph, it is shown that the grain mass flow capacity of the test stand was able to reach and exceed the value of 200 metric tons per hour.

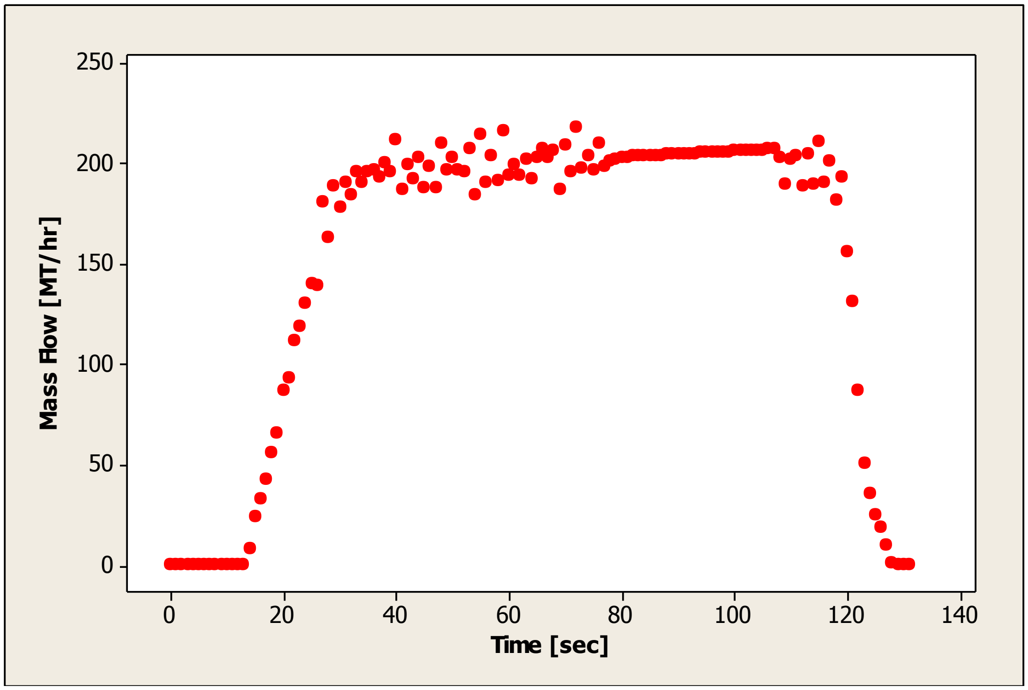


Figure 4.13: Data results demonstrating the test stands ability to meet the capacity requirements of 200 metric tons per hour

Test Stand Consistency

For testing at specific flow rates, the test stand needs to be able to delivery grain to the combine at constant flow rate. To determine the consistency of grain mass flow delivered by the test stand, the linearity of the ground truth total mass with respect to time delivered to the test stand during an individual test run was plotted and observed. Figure 4.14 displays the linear regression of the ground truth total mass value delivered by the test. The coefficient of determination calculated in the regression equation was 0.9999, which verifies that the test stand developed is able provide to a constant ground truth grain mass flow value to the combine.

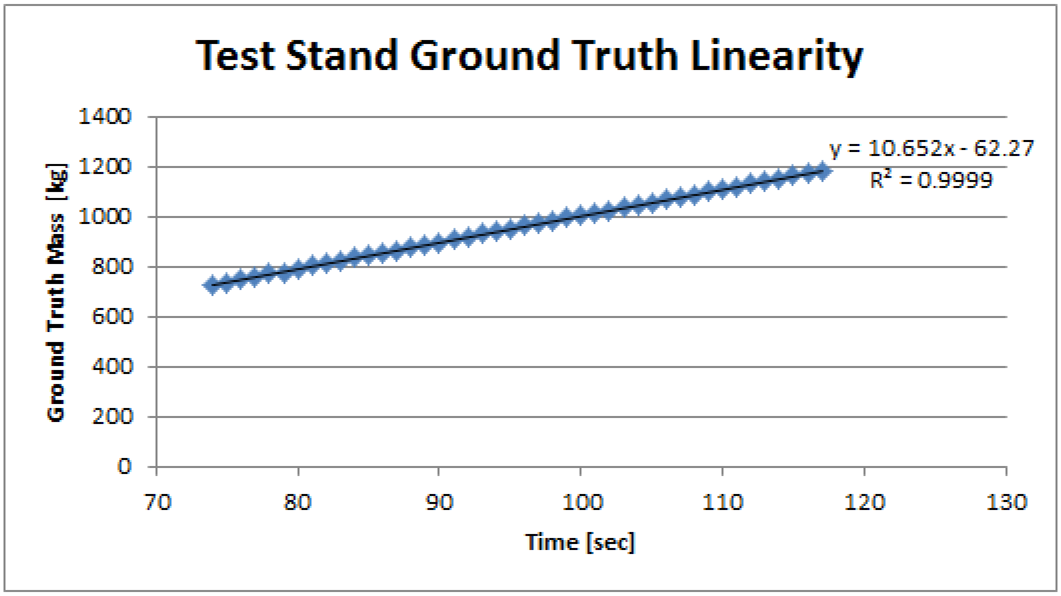


Figure 4.14: Plot of the linear regression verify the test stands ability to deliver a constant mass flow value to the combine

This is representative of the data set obtained from the evaluation of the test stand wagon, shown back in Table 4.1. As shown before, the test stand wagon was capable of producing consistent flow rates that, and when analyzed, proved that grain mass flow was perfectly linear and had a coefficient of determination equal to exactly one. These results prove that data displayed in Figure 4.14 can be repeated on a consistent basis. This same procedure was repeated over 45 test runs at nine discrete levels of grain mass flow. The average coefficient of determination at each level of grain mass flow is displayed in Table 4.3. Overall, the test stand shows that it is able to achieve constant grain mass flow rates over different levels of grain mass flow, and that it is able to consistently repeat these tests.

Table 4.3: Linear evaluation of test stand across all ranges of grain mass flow

Approximate Grain Mass Flow [MT/hr]	Number of Data Runs	Average R^2
40	5	1
60	5	1
80	5	0.9999
100	5	0.9998
120	5	0.9998
140	5	0.9996
160	5	0.9994
180	5	0.9993
200	5	0.9986

Replication of Field Data

To identify the ability of the test stand to replicate results observed during actual harvest conditions, moisture evaluations from test stand data and 2013 harvest data were compared against one another. From the test stand, data evaluated was collected at a constant grain mass flow rate of 20 kilograms per second at both high (greater than 20%) and low (less than 17%) moistures. The field data set was obtained from test runs with similar average flow rates and divided up by moisture content obtained from a grain sample, to determine the difference between high and low moisture corn. Figure 4.15 shows the side-by-side 95% confidence interval plots of each data set. From the results, it can be seen that in both cases, the average errors between high and low moisture were statistically different. Looking closer, it can be seen that the low moisture test stand data fell within a confidence interval of (-0.83%, 1.18%), while the low moisture field data had a confidence interval (-1.97%, 1.69%). Looking at the high moisture results, the high moisture corn from the test stand had a confidence interval of (4.84%, 7.50%), while the high moisture corn from the harvest data set had a confidence interval of (2.75%, 5.40%). Using these values, it can be concluded that both the test stand data, and the data from the harvest season show a difference between high and low moisture corn, but also so that there is a similar trend between the two sets of data.

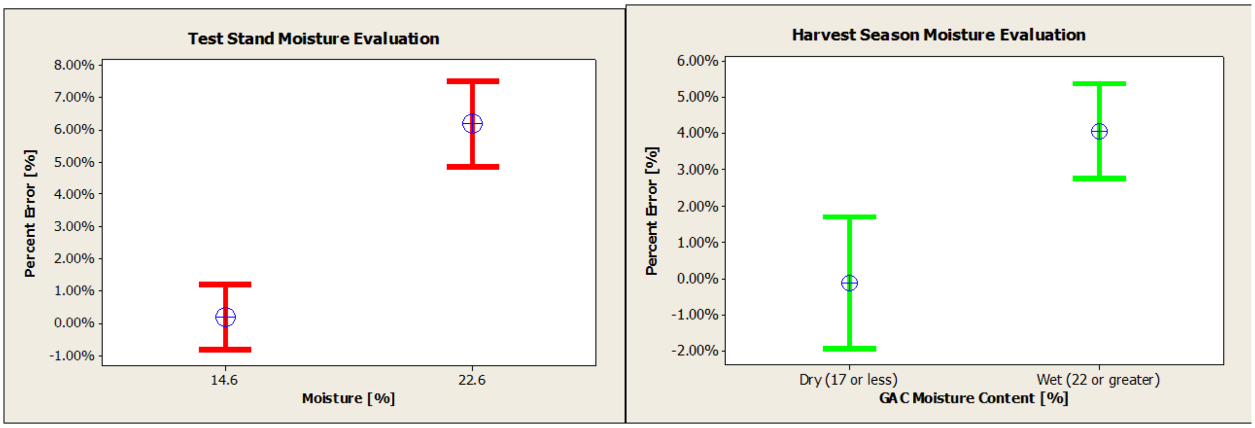


Figure 4.15: Side-by-side comparison 95% confidence interval plots of evaluation of moisture data from the test stand and actual harvest conditions

4.5 Conclusions

From analyzing the results of the test stand development, it has been shown that the test stand was able to achieve requirements capable of meeting the goals set in place by the project. Meeting these requirements enables the ability to perform tests in a controlled setting to replicate actual harvest conditions. With appropriate data collection techniques in place, information relevant to the design and development of an automated calibration system can be obtained. Because of this, the development of the test stand established it as a major component of being able to develop an understanding of yield monitor performance against different field metrics and allowing for the accomplishment of the overall project goals.

CHAPTER 5. PERFORMANCE EVALUATION OF A GRAIN MASS FLOW SENSOR

5.1 Introduction

Since being introduced into the agriculture industry and specifically onto combines, the yield monitor has given producers the ability to view instantaneous yield values of harvested crop while harvesting within a field, as well as providing the operator with a total yield over a particular time period. With advancements in technology, this system has been combined with GPS systems and allowed for mapping of spatial data to generate yield mapping capabilities. The yield monitoring system has not only provided producers with instantaneous yield values, but also the ability to compare other field metrics to productivity and identify the driving factors associated with high production as well as low production that is observed over harvested regions.

The grain yield monitoring system measures mass flow through an impact plate mounted at the top of the combine's clean grain elevator. As grain flows up the clean grain elevator and into the combine grain tank, it is projected against the impact plate. Based upon the force delivered by the grain, the impact plate outputs a corresponding voltage. The measured sensor voltage is then scaled by a value obtained from a calibration curve that converts the output voltage into a mass flow rate value measured in kilograms per second. Based on machine parameters, the measured mass flow rate can be used to provide the operator with an instantaneous yield value per unit area, as well as total yield over a definable harvest period.

As previously stated, the advancement of technology has introduced new, increasing opportunities for yield monitors to be included within producers' overall operations. As yield monitoring technologies become incorporated more into the overall day-to-day decision making processes the producers encounter, it is increasingly important to understand the level of accuracy that these system provide. As described above, yield monitors measure the harvested yield based off of a physical value obtained from the measurable force of impact of the grain against the yield monitor sensor plate. It is important to note this because the physical properties of corn, within a harvest season, can vary greatly as a result of weather conditions, field conditions, and farm management practices. When measuring a physical characteristic of anything, it is always important to note when physical properties of the interested target change, due to the fact that these physical changes could impact the accuracy of the measurement.

This study consists of the evaluation of yield monitor performance in both a controlled environment and real harvesting conditions to determine the effect different variables encountered during harvest have on overall system accuracy. The purpose of this study is to develop a further understanding of what crop characteristics affect yield monitor accuracy and to what level they have an effect on the accuracy. The understanding gained about the yield monitoring system performance in respect to variations in harvest condition may aide in providing opportunities to identify the capabilities and limitations of the current yield monitoring systems, develop criteria for system recalibration when field conditions change, and discover potential developmental areas for the improvement of the current system.

5.2 Objectives

The goal of this study is to evaluate the performance of a combine yield monitoring system's ability to accurately measure the quantity of harvested grain. Understanding the level of system accuracy is important in evaluating the system capabilities, limits, and areas of improvement. In the evaluation of performance, the system will be evaluated in both a controlled environment to simulate and control different variables encountered while harvesting, as well as in the field during a typical harvest season to examine performance in actual field conditions.

The first objective is to evaluate the effect that different harvest conditions have on the accuracy of the yield monitoring system in a controlled environment. To complete this, testing was to be performed in conditions that allow for an independent variable to be modified while keeping all other variables constant, in order to examine how the independent variable directly affects the ability of the system to measure yield without any other biasing factors. Different factors to be examined in the controlled environment include physical characteristics of grain, primarily variables such as moisture and crop type, as well as harvesting conditions, primarily variables such as terrain effects (pitch and roll) and flow variations caused by changes in total yield.

The second objective is to evaluate the performance of the combine yield monitoring system during a typical harvest season and determine if varying factors encountered throughout the season directly impact system accuracy. To do this, the combine yield monitoring system will be evaluated over the course of an entire harvest season in central Iowa. During the season, various forms of data need to be collected to provide ground truth measurements for an actual comparison. These forms of data should contain various levels of information that is capable of identifying the various changes to harvesting conditions that are experienced throughout the harvest season and can be processed for evaluation. This harvest data should include all forms of data off of the combine that may be relevant factors in yield monitor performance, crop conditions to evaluate across different physical characteristics of the grain, and ground truth values that provide an accurate total yield value for comparison against measured values.

The combination of data collected from a controlled testing environment and from actual harvesting conditions will be used in evaluating the overall performance accuracy of the system. These data sets will provide the ability to make scientific analyses to answer hypotheses in regards to what factors drive the accuracy level within a combine yield monitoring system. The conclusions derived from this study will identify characteristics affecting yield monitor performance can be accounted for with advanced development of the combine yield monitoring system.

5.3 Materials and Methods

Evaluating the performance of combine yield monitoring system, with respect to different field conditions, is difficult because of the high variability in crop conditions and the minimal amount of control that is available over those conditions. To develop an accurate representation of this, two key forms of testing were used in system evaluation. The first form of testing was controlled testing that used a test stand that allowed for testing that was capable of simulating specific factors, while keeping all other conditions constant. This controlled testing helped eliminate biasing that may have occurred within actual harvesting conditions, due to the fact that while harvesting several factors may change simultaneously. The second form of testing occurred during actual harvesting. During actual harvesting, it was crucial that all forms of relevant data were captured throughout the testing procedure, since multiple field characteristics can change simultaneously. In-field testing provided data of exact conditions experienced during the harvest that may be more telling of the overall performance level.

5.3.1 Test Stand Data

The testing performed in a controlled environment, in order to evaluate the performance of a combine yield monitor, will occur on the test stand designed to run grain back through the combine capable of simulating harvesting conditions that is explained in Chapter 4. All controlled testing using the test stand occurred at the BioCentury Research Farm managed by Iowa State University. The testing occurred on an S-series John Deere combine equipped with a current model of the Ag Leader yield monitoring system. During the testing process, multiple harvest conditions were identified as independent variables and simulated within the controlled environment. Harvest variables tested included:

- Mass flow rate variations
- Crop moisture
- Combine Pitch
- Combine Roll

Mass Flow Variation

Throughout a particular field a combine is likely to experience several variations in levels of mass flow through the combine, due to changes in field performance as well as harvesting speeds. Because of the typical variance in production within and across different fields, a combine is likely to encounter different sections within a field with varying levels of productivity. Assuming that the harvesting speed remains relatively constant, the combine will undergo a change in mass flow being transferred through the machine and into the grain tank. This theory is also true in the event that field productivity remains constant, but harvesting speed undergoes a change.

Because the combine yield monitoring system uses a sensor to measure mass flow which it then converts into yield, it is important to understand the capabilities of this sensor across various ranges of mass flow. The combine mass flow sensor determines mass flow by converting the sensor output voltage, using a calibration curve that relates voltage to mass flow. Because of this, the relationship between voltage and mass flow is not necessarily linear, and the response of the sensor, with respect to mass flow, can vary across flow rates.

To examine how variations in grain mass flow affect system accuracy, multiple grain tank loads were simulated with grain mass flow rate as the independent variable using the test stand. The test runs spanned over nine discrete levels of grain mass flow varying between 10 kilograms per second and 60 kilograms per second (peak combine capacity), with five repetitions performed at each level. A complete overview of tests performed is shown in Table 5.1. For each run, the test stand gates were set to a constant position and left there for the entire test repetition, while the combine grain tank was filled until it was between one half and three quarters of the way full. Throughout the run, all CAN data and ground truth mass values were logged for post-processing. The purpose of these test runs was to evaluate the physical capabilities of the combine yield monitoring system across its full scale range, as well as provide a set of baseline data across different flow rates to be used in examining how different independent variables drive error in grain yield monitors.

Table 5.1: Table of mass flow treatments for testing of grain mass flow variations

Grain Mass Flow [kg/s]	Number of Repetitions	Crop Type
11	5	Corn
17	5	Corn
22	5	Corn
28	5	Corn
33	5	Corn
39	5	Corn
44	5	Corn
50	5	Corn
56	5	Corn

Crop Moisture

Another relevant factor that can impact the combine yield monitoring system’s ability to measure mass flow is moisture. Throughout a harvest season, the crop moisture is typically highly variable. Moisture conditions can change gradually over the course of the season, from field to field, and even vary across different regions within a single field.

Crop moisture is a variable that can impact the ability of the system to measure mass flow because it can alter the physical characteristics of each individual crop. Because the yield monitor calculates yield from measuring the impact from harvested grain traveling to the combine grain tank, it is important to consider how changes in grain’s physical characteristics affect system performance. Changes in crop moisture have the ability to impact the physical surface of the grain, vary the test weight, and change viscous characteristics of grain flow. These factors are important to consider because if they change, they may have bias the sensor’s ability to measure mass flow.

In order to determine the effects of crop moisture on the combine yield monitor's ability to measure mass flow, test runs were performed with both low moisture corn and high moisture corn. For low moisture corn testing, the test stand was filled with dried grain from the elevator. To simulate high moisture corn, grain was cycled through two grain wagons and soaked with a continuous stream of water as it left the wagon. The grain was then tested with a hand moisture sampler to determine the new moisture content. These steps were repeated until moisture levels greater than twenty percent were achieved. The data sets obtained from the two moisture scenarios provided a representation of both high and low moisture crop for system analysis. The entire test set of repetitions performed are shown in Table 5.2.

Table 5.2: Table of treatment factors for testing of grain moisture variations

Grain Mass Flow [kg/s]	Number of Repetitions	Crop Type	Moisture [%]
10	5	Corn	14.6
20	5	Corn	14.6
35	5	Corn	14.6
10	3	Corn	22.6
20	3	Corn	22.6
35	3	Corn	22.6

Combine Pitch/Roll

While a combine is harvesting, it is likely to encounter various different terrains throughout a harvest season. With varying terrains the combine is subject to a variety of machine dynamics. Machine dynamics of interest primarily consist of those relevant to the combine orientation, specifically the pitch and roll of the machine, shown in Figure 5.1.

Figure 5.1: Diagram identifying combine pitch and combine roll orientation

Pitch and roll are relevant factors because of the physical setup of how the system measures grain mass flow. With the yield monitoring system measuring the resulting impact of the stream of grain transferred up the clean grain elevator, pitch and roll are important factors to analyze because a change in combine orientation may impact the trajectory at which grain takes, prior to impacting the mass flow sensor. Change in trajectory may change where grain strikes the impact plate and induce the possibility of some grain contacting the side walls of the elevator before it reaches the impact plate. Due to the fact that most combines will operate in fields where they will encounter significant changes in pitch and roll, it is important to understand the capabilities of the combine yield monitoring system in these conditions.

Table 5.3: Table of treatment factors for testing of combine roll variations

Grain Mass Flow [kg/s]	Number of Repetitions	Crop Type	Roll [degrees]
22	5	Corn	-3
33	5	Corn	-3
45	5	Corn	-3
22	5	Corn	0
33	5	Corn	0
45	5	Corn	0
22	5	Corn	3
33	5	Corn	3
45	5	Corn	3
22	5	Corn	6
33	5	Corn	6
45	5	Corn	6

To simulate changes in combine orientation, the test stand was used to replicate harvesting at different machine orientations. For each test run, wood blocks were placed under specific tires to induce pitch or roll into the harvesting conditions. Combine position was kept at a constant incline for the entire duration each individual test repetition. The testing process for roll and pitch analysis are shown in Table 5.3 and Table 5.4, respectfully. All data was recorded for each run, along with the induced pitch or roll value, to be incorporated into post processing.

Table 5.4: Table of treatment factors for testing of combine pitch variations

Grain Mass Flow [kg/s]	Number of Repetitions	Crop Type	Roll [degrees]
22	5	Corn	-3.5
33	5	Corn	-3.5
45	5	Corn	-3.5
22	5	Corn	0
33	5	Corn	0
45	5	Corn	0
22	5	Corn	3.7
33	5	Corn	3.7
45	5	Corn	3.7

5.3.2 Field Data

The evaluation of the performance of a grain yield monitor during actual harvesting conditions data was performed during the course of the 2013 fall harvest season. Testing throughout the entire season took place on a single S-series John Deere combine equipped with a current version of the Ag Leader yield monitoring system. Testing was performed in central Iowa, over 846.5 harvested acres across 10 different fields that were all managed by Iowa State University. Of the harvested acres, 636.5 of the acres harvested were of corn, and the remaining 210 acres harvested were soybeans.

Field Test Procedure

Through the entire harvest season, every instance of the grain tank being emptied and filled was considered as a load and taken as an individual test run. Each load ranged in size, depending on field configuration and harvesting techniques. Load sizes obtained during the test runs ranged from approximately 70 bushels up to 400 bushels of harvest grain. For each individual load, the combine was unloaded into a scaled grain cart to obtain the ground truth load weight for the evaluation process of the yield monitor. Grain tank loads were unloaded with the combine and grain cart stationary to avoid any biasing effects that dynamic unloading may induce due to weight shifting or cart positioning. Also for each grain tank load, a small sample was obtained from the grain tank so a grain analysis can be obtained using a GAC (grain analysis computer).

While each grain tank load was being harvested, a CAN log was taken in order to obtain all relevant information to the harvesting process and harvesting conditions being passed between the ECUs on the combine's controller area network. The data passed on the combine's controller area network contains all the information being sent by the combine's yield monitor, as well as other variables relevant to the harvesting conditions including combine pitch, combine roll, vehicle speed, and several other parameters that have the potential to be used in post processing and for the evaluation of the yield monitor performance.

The data collection process is crucial to the evaluation of the yield monitoring system, due to multiple factors. First is the fact that harvesting conditions, such as test weight and moisture, observed in the field are difficult to control and can be highly variable. In order to attain a complete and accurate data set, it is important to be thorough and record these values for each individual test run. Second is that the window for the harvest season is short, with the field testing capabilities ranging over only a couple of months. If important data is missed or unknown at the time of the harvest season, it can take a full year before it is possible to go back and repeat certain test runs. Collecting all possible forms of data reduces the possibility that important events or relevant statistics are left out of the data collection process.

Testing Conditions

During the 2013 fall harvest season, a variety of harvest conditions were experienced over the 846.5 acres harvested that were used as metrics of evaluation of the performance of the combine yield monitor. These different testing conditions were measured and evaluated using a combination of data obtained from recorded data, controller area network (CAN) logs, and grain analysis computer data. Breaking down the individual test runs, by using the data collected, enables examination of how different harvesting conditions and harvest procedures impact yield monitor performance, how much these factors impact performance, and provides a basis as to how to account for these different factors.

Grain Analysis Computer

Throughout the harvest season, a grain sample was taken from the grain tank at the end of every test run. Each sample was then run through a DICKEY-John 2500-UGMA (GAC) Grain Analysis Computer (DICKEY-John, 2014). The GAC provides data for analyzing the physical characteristics of each grain tank sample. For this study, moisture and test weight were the primary physical characteristics focused on. Because these factors cannot be controlled during the field testing season, these statistics can be used as identifiers of characteristics for each run, allowing for future analysis to be performed, in regards as to how these physical characteristics impact system performance.

These physical characteristics are important to identify because they have the potential to be driving factors in the performance level of the combine yield monitoring system. The combine yield monitoring system calculates yield from measuring the impact from harvested grain traveling to the combine grain tank. Therefore, it is important to consider how changes in grain's physical characteristics can affect the impact force detected by the sensor and, consequently, on the sensor's ability to measure mass flow.

During the 2013 harvest season, a total of 577 grain tank samples were obtained in corn. Using the GAC, the moisture content of each of these samples was obtained; Figure 5.2 shows the distribution of these results. The moisture content of a grain tank load during the 2013 harvest season ranged from 13.25% to 27.25%, with an average moisture content of 18.87%. The test weight of the grain was also obtained from the GAC. The test weight values observed during the 2013 harvest season ranged from 50.75 pounds to 62.25 pounds, with an average test weight of 56.71 pounds. The test weight distribution is shown in Figure 5.3.

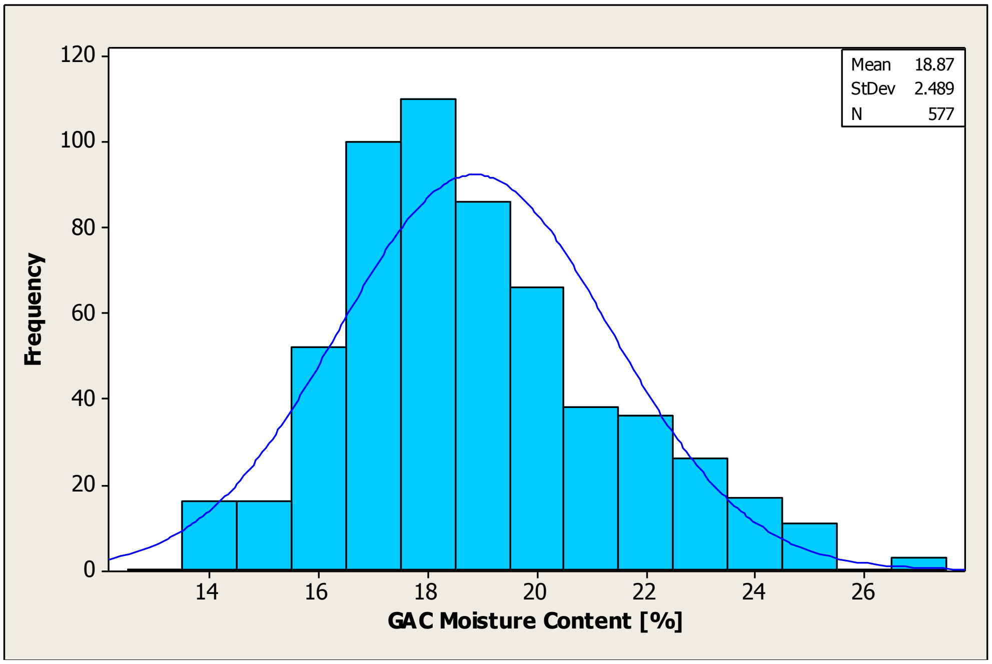


Figure 5.2: Distribution of the corn moisture content during the 2013 harvest season

The same data was also obtained for soybeans harvested during the 2013 harvest season. In all, 85 grain tank samples of soybeans were obtained and processed using the GAC. Moisture content ranged from 9.9% to 12.9%, with an average moisture content of 11.4%, as shown in Figure 5.3. The test weight experienced during the season ranged from 50.5 pounds to 62.5 pounds, with an average test weight of 56.71 pounds.

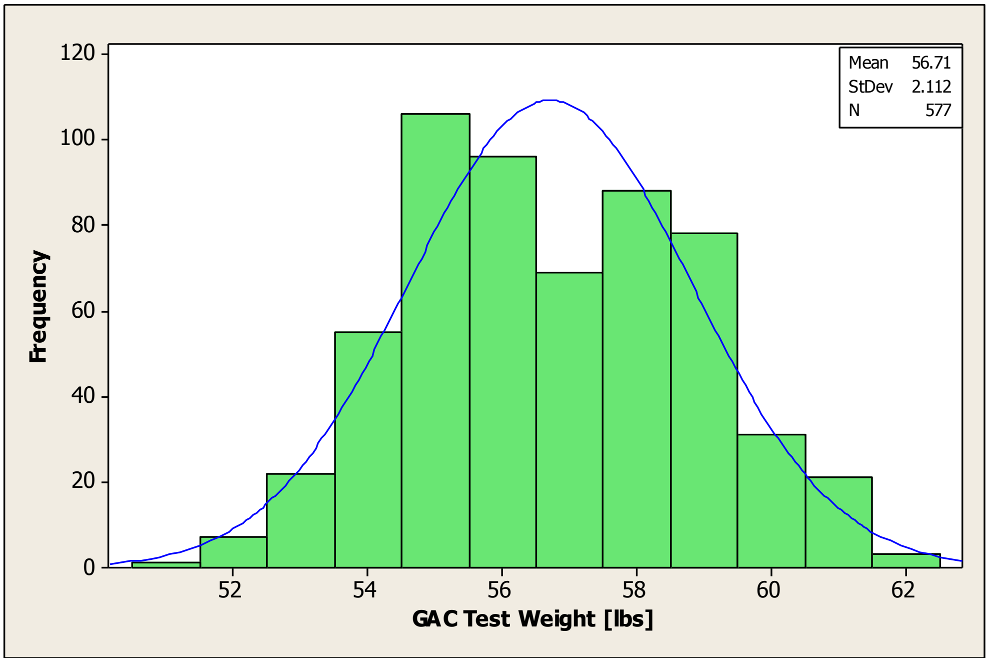


Figure 5.3: Distribution of corn test weights recorded during the 2013 harvest season

Controller Area Network

While each test run is being performed, all data on the combine's CAN Bus is logged and stored on a laptop in the cab. The CAN Bus is the platform by which all of the combine ECUs use to communicate with one another. Logging this data captures all of the information pertaining to the combine. These data logs can then be processed and broken down into individual signals that may be important in the evaluation of the combine yield monitoring system. The data set obtained contains a variety of signals that may be relevant, including:

- Combine Pitch
- Combine Roll
- Moisture
- Grain Mass Flow

Obtaining this large set of data is important because it allows for all factors that may influence yield monitoring performance to be recorded and examined individually to evaluate any potential driving factors of error. The data set also allows for an identification of what conditions were encountered during the harvest season, as well as the frequency at which they occurred.

An example of CAN data that can be extracted from the harvest data is shown in Figure 5.4, as well as in Figure 5.5. In these figures, the entire range of average mass flow rates from the harvest of corn and soybeans during the 2013 harvest season, respectively, are displayed. From Figure 5.4, it is shown that the average mass flow values for corn over an entire grain tank fill was 15.53 kilograms per second. The range of average mass flow values over the harvest season extend as low as 2.5 kilograms per second, up to 27.5 kilograms per second. Figure 5.5 displays the same data from the 2013 harvest season of soybeans. The average mass flow values, recorded over a grain tank fill was 5.44 kilograms per second. These values ranged from 1 kilogram per second up to 7.75 kilograms per second, for an average flow rate during a grain tank fill.

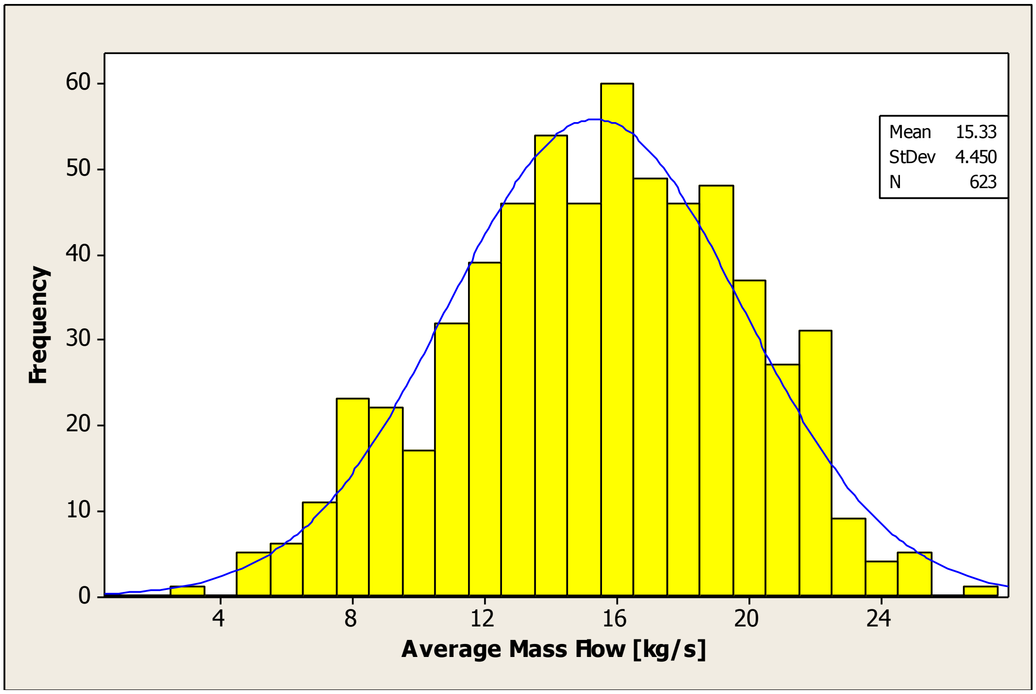


Figure 5.4: Distribution of average CAN signal corn mass flow rates over each grain tank load during 2013 harvest season.

Figure 5.4 and Figure 5.5 demonstrate how individual signals can be extracted from CAN log and used in post-processing to evaluate different metrics for evaluation on agricultural equipment. This is useful because it allows multiple measurement systems already in place to be used to record signals simultaneously in a simple, standardized format. Taking advantage of these capabilities allows for multiple different factors to be taken into account during the evaluation of different systems. Logging the entire range of messages on the CAN Bus also means that if data not previously thought to be important is desired, it is stored and available for future use in the logs eliminating the need to perform test repetitions again. This data set is a crucial piece in the evaluation of the combine yield monitoring system against different test metrics during the 2013 harvest season.

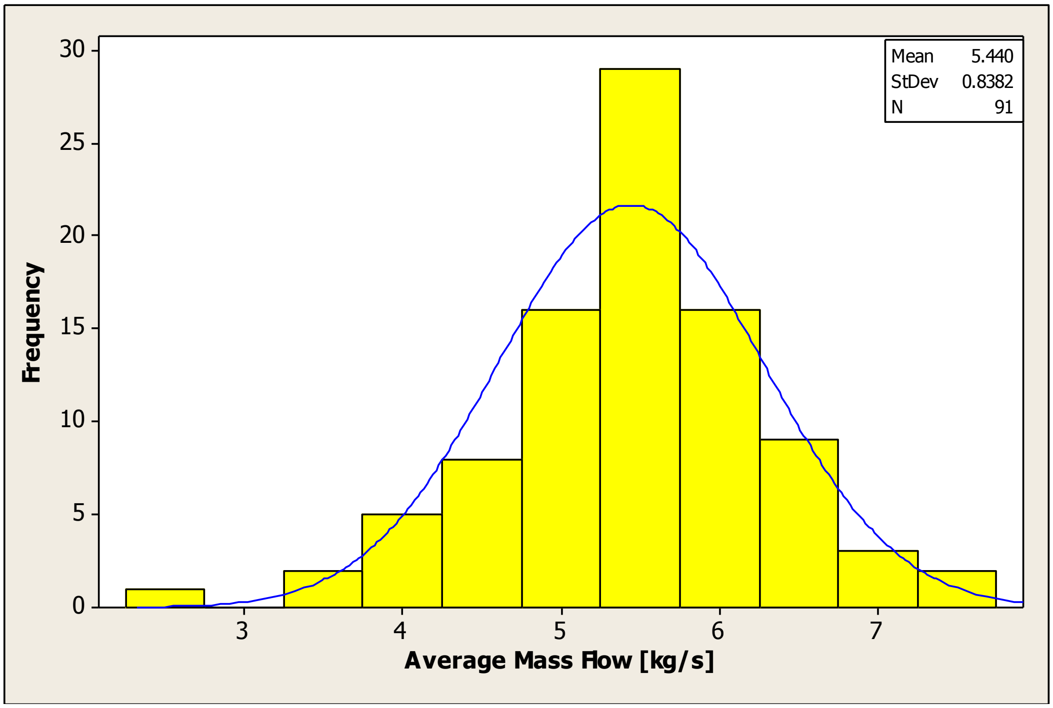


Figure 5.5: Distribution of average CAN signal soybean mass flow rates over each grain tank load during 2013 harvest season.

5.4 Results

Throughout this section, the data analysis and resulting observations from defined test procedures from the test stand and the 2013 harvest season are described. Understanding the effects that different factors have on combine yield monitoring performance, in both a controlled environment and an actual harvest environment will allow for a proper system evaluation to be obtained. The results were able to produce evident trends seen in different harvest conditions. For all test factors analyzed, the data was normalized so the baseline data sets were centered around zero. This was done because, for both test stand and field data, the combine yield monitor used the default calibration value to eliminate any biasing effects towards certain crop conditions, if the monitor would have been calibrated within a field.

5.4.1 Test Stand Data Analysis

The analysis, performed on the test stand developed for simulating different harvest conditions experienced throughout a field, allowed for a single independent variable to be identified and varied while holding all other test conditions constant. This was an important factor in the analysis of the combine grain yield monitoring system because the variables experienced in the field can be impossible to control manually. To analyze the different factors, the CAN data collected was processed in MatLab and statistically analyzed to conclude the impact of each individual treatment. The capability of the test stand allowed for the analysis that is laid out in the following documentation.

Response to Mass Flow Variation

One of the first variables identified, when evaluating the current combine grain yield monitoring system, was the system's response to variations in grain mass flow. Looking at Figure 5.6, it appears that the measured value of grain mass flow by the combine yield monitoring system has greater variation as the steady state grain mass flow rate increased across each test run. Four discrete levels of steady state mass flow were plotted to provide a visual representation of grain mass flow values measured by the combine yield monitoring system against time. In the test run in which the steady state mass flow rate is approximately just over 10 kilograms per second, the measured grain mass flow values are have little variation from one point to the next. In contrast, the test run in which the steady state mass flow rate falls in the range of 50 to 60 kilograms per second, the measured values appear to be more spaced out than those in the 10 kilogram per second range and would result in a high amount of variance from one point to the next. The middle two test runs show that, in conglomeration with previous test runs, the variance in point to point values increase as steady state mass flow rate increases. The theories developed from this data are then able to be statistically analyzed.

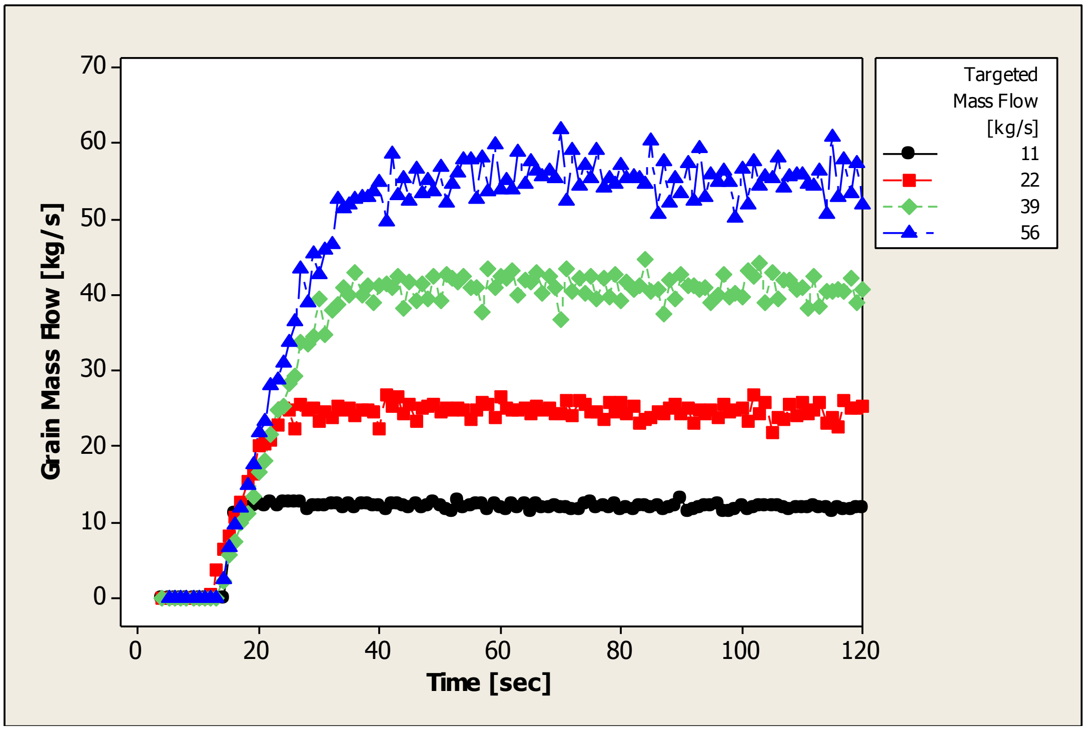


Figure 5.6: Plot of CAN grain mass flow values vs time across four discrete levels of grain mass flow

The previous conclusions were made using visual observations between different test runs, with test repetitions of varying mass flow rates plotted against one another. To evaluate this trend statistically, the data across these different flow rates were plotted and analyzed by their variance to support visual observations. To perform this analysis, the null hypothesis that the variances across all ranges of grain mass flow tested, as a percentage of actual mass flow, are equal, a 95% level of confidence was tested. The results from this analysis are shown in Figure 5.7. From the results, it is shown that a majority of the confidence intervals overlap one another and are equal. But because the results of the analysis produced a P-value that was less than 0.05, the null hypothesis can be rejected and it can be concluded that there is a difference between the variances at different levels of grain mass flow. These results show that, while at most levels of grain mass flow the variance in the yield measured are equal, at lower levels of grain mass flow the variance is statistically different than other levels. This is likely due to the fact that the impact plate does not follow a linear response, and at low levels of grain mass flow the response is less sensitive to slight changes in mass flow.

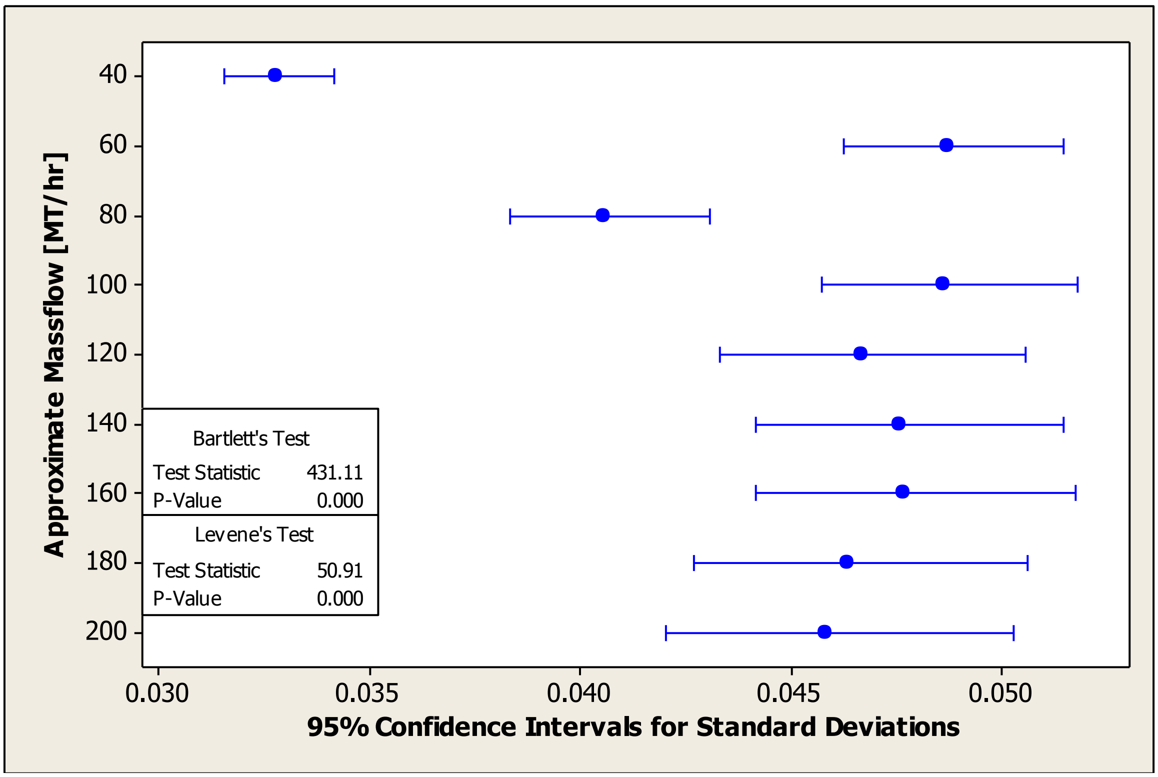


Figure 5.7: Statistical Comparison across different levels of grain mass flow tested for equal variance as a percentage of actual grain mass flow

The results from the entire range of grain mass flow rates are displayed in Table 5.5. Over the nine discrete flow rates tested, as the average steady state mass flow rate increases, the standard deviation also increased in all but one case. In this case, the standard deviation remained pretty constant, only decreasing but a value of .01 kilograms per second. Aside from that one instance, it was shown that as the grain mass flow rate increased, the variance of the measured values of the combine yield monitoring system also increased.

Table 5.5: Table of grain yield monitor stats across nine discrete flow levels of grain mass flow

Mass Flow Variation Test Results		
Target Flow Rate [MT/hr]	Average Measured Mass Flow Rate [kg/s]	Standard Deviation [kg/s]
40	11.92	0.460
60	18.07	0.948
80	24.53	1.078
100	27.75	1.405
120	33.22	1.707
140	40.03	2.063
160	46.21	2.359
180	50.23	2.345
200	54.69	2.833

The testing across different steady state grain mass flows levels developed an understanding of the combine yield monitoring system's response over different ranges of grain mass flow. From the testing, it could be concluded that as the measured value of grain mass flow increases, the variance in response also increases. This important because it shows the physical limitations of the system and the increased levels in variance are something that cannot be corrected for using the current sensor. It is also important to acknowledge that the distribution of measured grain mass flow values at a single flow rate was normally distributed about the average. Because it is normally distributed, given an adequate number of measured values, an accurate calibration should produce fairly accurate results, with the average being fairly representative of the actual yield.

Response to Crop Moisture

The next variable evaluated to determine the effect of its properties on combine yield monitoring performance was crop moisture. Crop moisture is a variable that can impact the ability of the system to measure mass flow because it can affect the response of the grain yield monitor, as it can impact the physical characteristics of the system. Throughout the season a combine may be subject to a wide range of crop moisture levels. In order to understand the effects of moisture on yield monitor performance, testing was performed with low moisture corn obtained from an elevator and high moisture corn consisting of corn greater than 20 percent moisture content.

The tests conducted to examine the effects of crop moisture on combine yield monitor performance were performed across three different flow rates. The results of response in error of the yield monitoring system are shown in Figure 5.8. Visually looking at the results, it appears that at a high moisture level, there is an increase in error in the response of the grain yield monitor. To statistically analyze whether crop moisture is a driving factor in yield monitor error, a hypothesis stating that the means of low moisture corn and high moisture corn are not equal was tested. If, in fact, $\mu_{14.6\%} \neq \mu_{22.6\%}$ it can be concluded that there is a statistical difference in the results across the two variables, it provides evidence that crop moisture is a driving factor in yield monitor error.

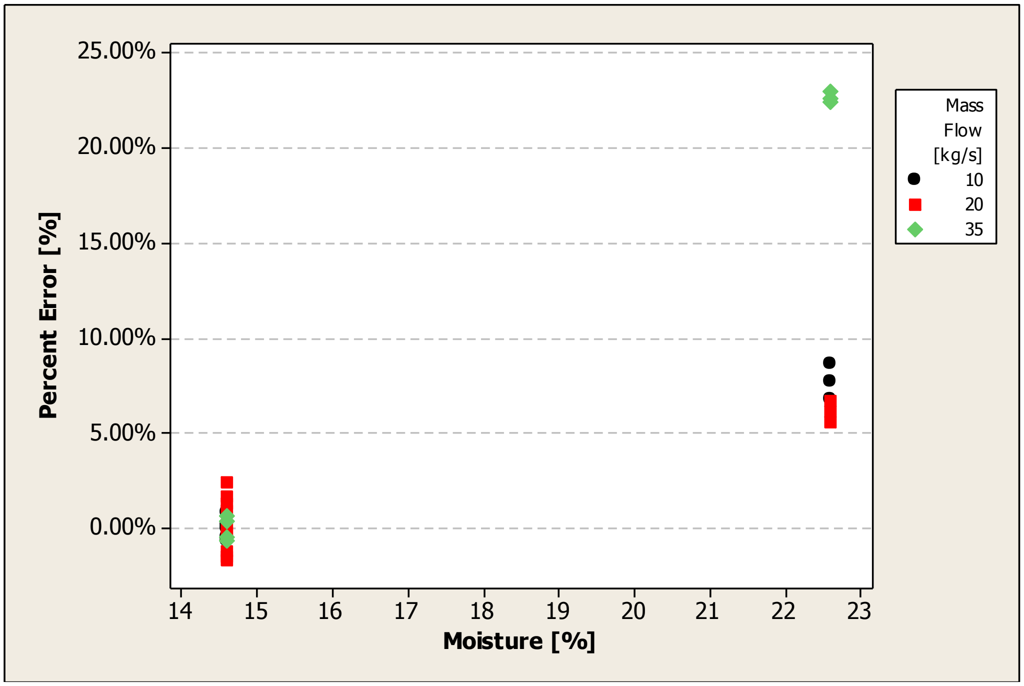
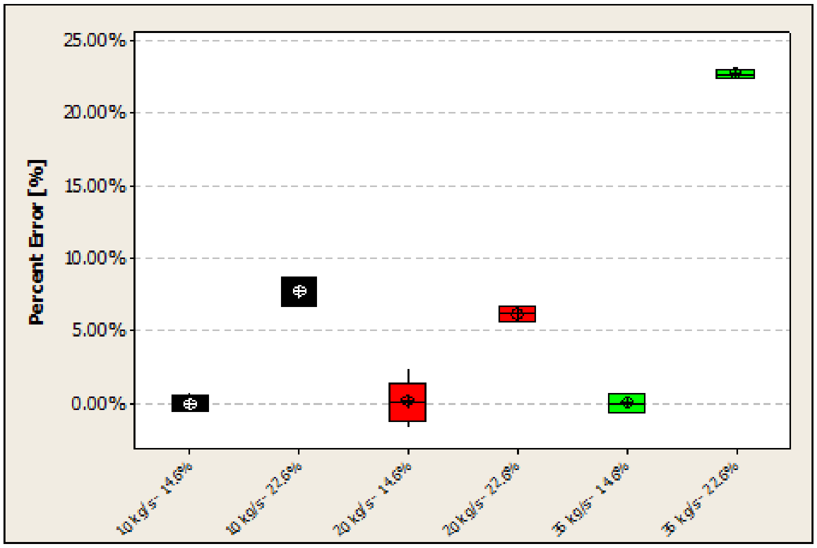


Figure 5.8: Plot of yield monitor error against different levels of moisture.

To evaluate the effect of crop moisture on yield monitor error, the data set was divided up into the different ranges of grain mass flow rates tested, and the yield monitor error was compared between low moisture corn and high moisture corn. The results from this analysis are displayed in Figure 5.9. To examine the difference in error between low and high moisture corn, an analysis of variance (ANOVA) of the data obtained at a 95 percent confidence level was performed. At grain mass flow rate of 10 kilograms per second, the Tukey's group of the low moisture corn was group C, while the Tukey's group of the high moisture corn was group B. Because there is no overlap in groups of high and low moisture corn, it indicates that $\mu_{14.6\%,10kg/s} \neq \mu_{22.6\%,10kg/s}$ and therefore the values are statistically different at a grain mass flow rate of 10 kilograms per second.



Mass Flow [kg/s]	Moisture [%]	Tukey Analysis
10	14.6%	C
20	14.6%	C
35	14.6%	C
10	22.6%	B
20	22.6%	B
35	22.6%	A

Figure 5.9: Box plot and Tukey Analysis of the mean percent error at varying moisture at 10, 20, and 35 kg/s

The same analysis was then performed at grain mass flow rate of 20 kilograms per second. The Tukey's group of low moisture corn was group C, while the Tukey's group of the high moisture corn was group B. Because, again, there is not any overlap in the Tukey groups between high and low moisture corn, it can be said that $\mu_{14.6\%,20kg/s} \neq \mu_{22.6\%,20kg/s}$ and the values are statistically different at a grain mass flow rate of 20 kilograms per second, just as was seen at mass flow rate of 10 kilograms per second.

The final analysis was performed at grain mass flow rate of 35 kilograms per second. The Tukey's group of the low moisture corn was group C, while the Tukey's group of the high moisture corn was group. Because there is also not any overlap in the Tukey groups of high and low moisture corn, $\mu_{14.6\%,35kg/s} \neq \mu_{22.6\%,35kg/s}$, and the values are statistically different across all levels of mass flow rate that were evaluated during the testing procedure.

Testing across different crop moisture levels allowed for the testing of the hypothesis which stated that the means of low moisture corn and high moisture corn are not equal, $\mu_{14.6\%} \neq \mu_{22.6\%}$ (95% confidence level). The results of the testing supported the claim made by the hypothesis, and showed that there was a statistical difference between the combine yield monitor responses at the different crop moisture levels. These results identify that crop moisture is a driving factor in grain yield monitor error, and is a variable that should be considered when trying to understand the accuracy of a given calibration.

Response to Combine Roll

Another variable examined when evaluating the performance of a combine grain yield monitor is the effect that combine roll has on the system. With varying terrains, the combine is subject to a change the trajectory at which grain impacts the yield monitor impact plate and, in turn, alters the response. The purpose of this evaluation is to understand how a change in the combine's level of roll affects performance throughout a harvest season.

The testing procedure, to determine how combine roll effects yield monitor performance, consisted of testing with different combine orientations across different ranges of grain mass flow. The results of response in error of the combine's yield monitoring system are shown in Figure 5.10. Visually looking at the graph, the response of the combine yield monitor seems to change as the roll of the combine is changed. To evaluate whether this is actually true, the hypothesis that was tested states that the means of the yield monitor error across different ranges of combine roll are all equal, $\mu_{(-3)\ \text{degrees}} = \mu_{0\ \text{degrees}} = \mu_{3\ \text{degrees}} = \mu_{6\ \text{degrees}}$. If the statistical analysis of the data disproves the hypothesis, it will support the idea that varying combine roll is a driving factor in yield monitor error.

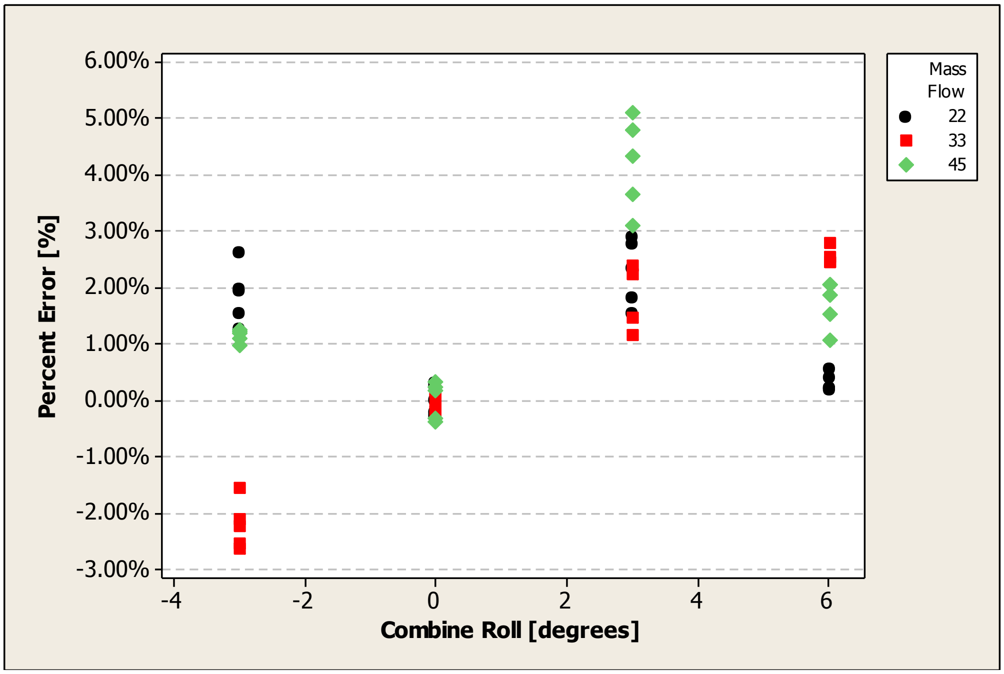
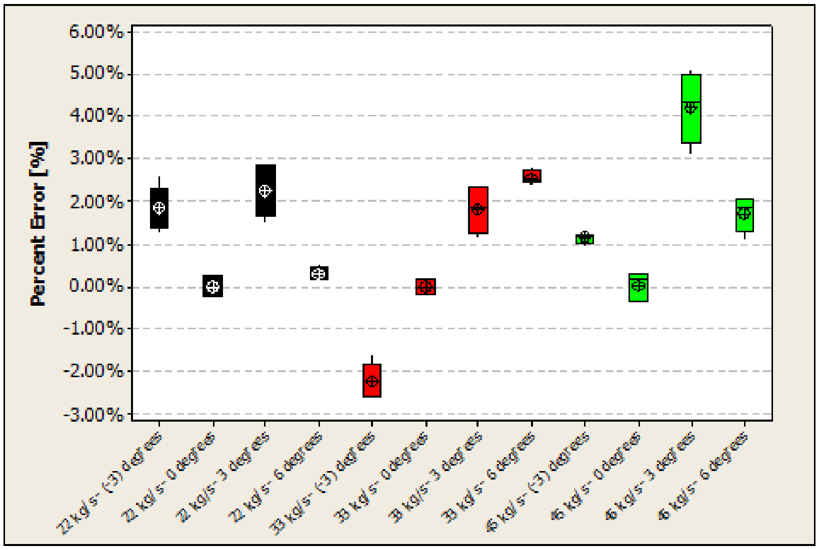


Figure 5.10: Plot of grain yield monitor error across varying levels combine pitch

To evaluate the effect that combine roll has on yield monitor error, the data set of different combine orientations was divided up into the different degrees of roll that the combine was subject to, and the yield error was compared across them. The results of the data at a steady state mass rate of 22 kilograms per second are shown in Figure 5.11. To examine the difference in error an ANOVA was performed to obtain a statistical comparison of the data. The first data set evaluated was a grain mass flow rate of 22 kilograms per second. The Tukey groupings at zero degrees and six degrees overlap one another, and the Tukey groupings for three degrees and negative three degrees also overlap one another, but there is no overlap between all four ranges of combine roll. A likely reason that there is some overlap in the Tukey groups at some levels of roll, but not all levels of roll, is likely due to fact that, while roll impacts accuracy, its effect on accuracy is not a linear relationship; because of this, certain levels of combine roll may show similar results in yield monitor error. Even though there is overlap between some of the means the hypothesis is not supported by the data and in turn support the idea that combine roll is a driving factor yield monitor error.



Mass Flow [kg/s]	Roll [degrees]	Tukey Analysis
22	-3	BC
33	-3	F
45	-3	CD
22	0	E
33	0	E
45	0	E
22	3	B
33	3	BC
45	3	A
22	6	DE
33	6	B
45	6	BC

Figure 5.11: Box plot and Tukey Analysis of the mean percent error at varying combine roll at 10, 20, and 35 kg/s

The same analysis was then performed at a steady state grain mass flow rate of 33 kilograms per second. The Tukey groupings at three degrees and six degrees have some overlap, but there is no overlap of the Tukey groups at any other level of combine roll. Similar to the instance of the data at 22 kilograms per second, since all Tukey groups don't overlap one another, the hypothesis is not supported by the data.

The last analysis performed over different variations in combine roll occurred at a steady state grain mass flow of 45 kilograms per second. The results show that there is only a slight overlap between the Tukey groupings at negative three degrees and six degrees, but there is not commonality among any of the other levels of combine roll. These results go along with the results from the data from testing at 22 kilograms per second and 33 kilograms per second and show that the hypothesis is not supported by testing results. The data set analyzed leads to the conclusion that combine roll is a driving factor in yield monitor error. This makes sense because variation in roll is likely going to alter the location on the impact plate that grain strikes. Because of this, it is likely to change the output based on this. Results across different grain mass flow rates looked similar, but there were some slight differences. This is likely, in large part, because as flow changes the physical flow of grain will change due to change quantity of grain over a constant volume.

The results from testing multiple different combine orientations to simulate different levels of roll that may be experienced during the harvest season allowed for the testing of the null hypothesis, $\mu_{(-3)\ deg} = \mu_{0\ degrees} = \mu_{3\ degrees} = \mu_{6\ degrees}$ (95% confidence level). The results of the testing disagree with the hypothesis stating that these are all equal, and instead, in favor of the idea that there is a difference in the error seen across the varying ranges of roll. Those results lead to the conclusion that combine roll is a driving factor in yield monitor error. In this, it should be understood that pass-to-pass loads measured in a field with high variations in terrain may experience a change in yield monitor performance due to constant changes in the combine orientation while harvesting. This is something that cannot currently be corrected for, because pass-to-pass results are different from one another and can't be calibrated for over an entire field.

Response to Combine Pitch

Similar to examining the effects that combine roll has on the response of a combine grain yield monitor, the effect of variations in combine pitch on the system was also evaluated. As with roll, varying terrains that may be experienced by a combine throughout a harvest season can alter the way grain impacts the yield monitor impact plate. This evaluation is important in understanding if a yield monitor is subject to increased levels of error due to the terrain experienced during a harvest season.

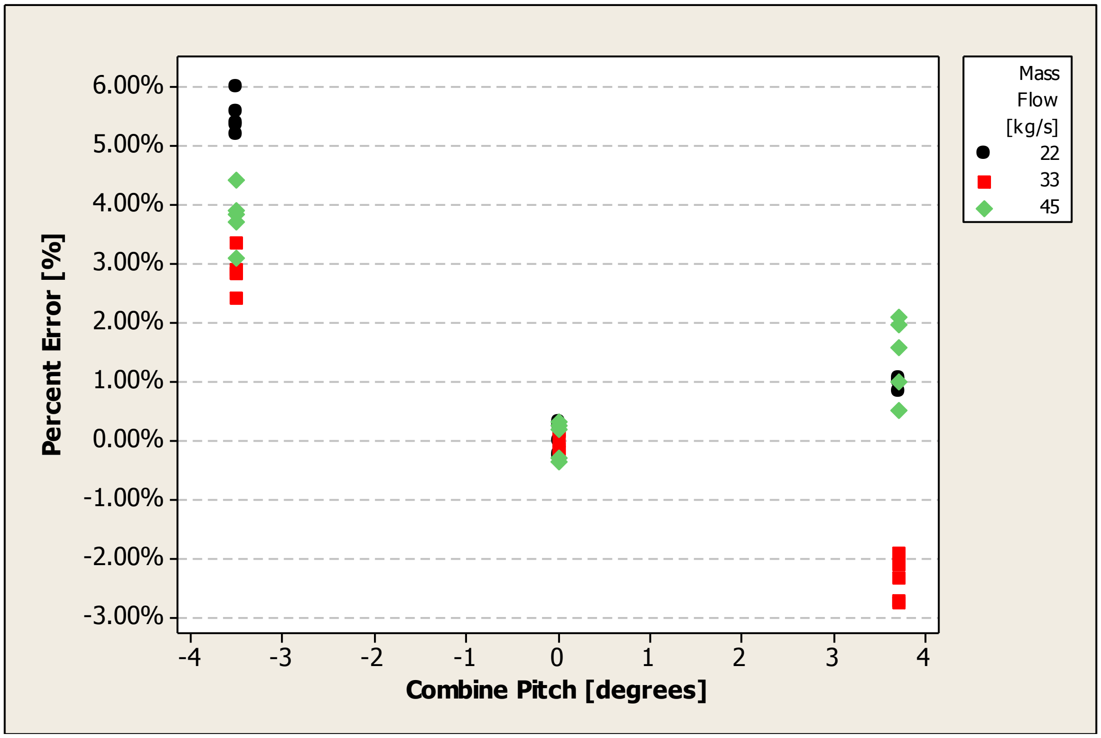
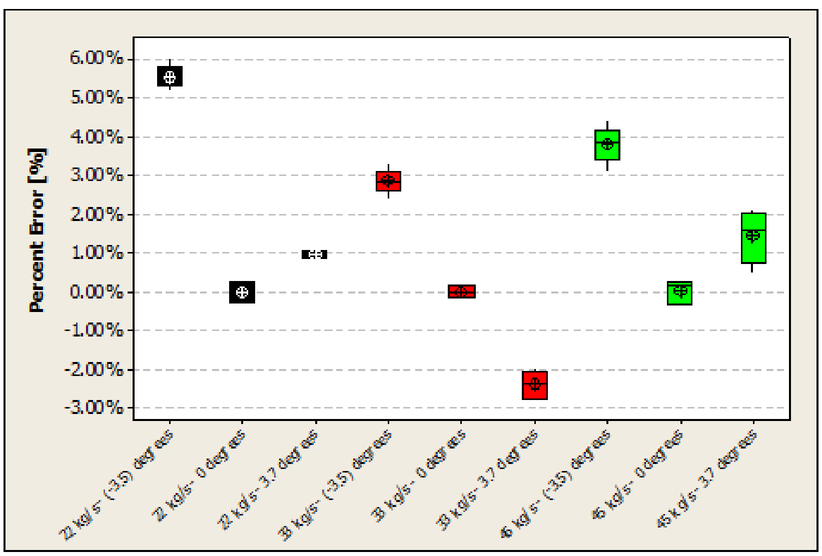


Figure 5.12: Plot of yield monitor across varying levels combine pitch

Testing of how combine pitch effects yield monitor performance consisted of testing with the combine positioned in three different orientations to simulate change pitch during harvest conditions, across three different ranges of grain mass flow. The response of the error measured by the grain yield monitor experienced in this range of testing is shown in Figure 5.12. Visual observations of the plot indicate that, as the combine pitch is changed during harvest conditions, the error experienced by the grain yield monitor is also affected. To statistically evaluate this claim, the hypothesis stating that the mean error across different levels of combine pitch, $\mu_{(-3.5)\ deg} = \mu_{0\ degrees} = \mu_{3.7\ degrees}$, was evaluated. If the statistical analysis contradicts this hypothesis, it will support the idea that varying combine pitch is a driving factor in combine grain yield monitor error.

In examining the impact that pitch has on yield monitor error, the data set from different combine orientations was divided up based on the different degrees of pitch that the combine was subject to during testing, and the resulting errors were compared against one another. To compare whether or not the errors varied across different levels of pitch, an ANOVA was performed to obtain a statistical analysis of the, and is displayed in Figure 5.13. The results of this analysis were plotted at a grain mass flow rate of 22 kilograms per second. At this particular flow rate, there is no overlap between Tukey groups of yield monitor error at any variation of combine pitch. Because of this, it can be concluded that the data does not support the hypothesis that they are all equal, and instead, favors the idea that pitch is a driving factor in yield monitor error.



Mass Flow [kg/s]	Pitch [degrees]	Tukey Analysis
22	-3.5	A
33	-3.5	C
45	-3.5	B
22	0	E
33	0	E
45	0	E
22	3.7	D
33	3.7	F
45	3.7	D

Figure 5.13: Box plot and Tukey Analysis of the mean percent error at varying combine pitch at 10, 20, and 35 kg/s

The data set compiled from the data collected at a grain mass flow rate of 33 kilograms per second was then analyzed. Similar to the data examined at a grain mass flow rate of 22 kilograms per second, there is no overlap among the Tukey groupings from any of the three discrete levels of pitch. Again, the data shows that the hypothesis claiming that yield monitor error is constant across varying degrees of combine pitch is not supported.

Lastly, the data set from testing at a steady state grain mass flow rate of 45 kilograms per second was analyzed. Again there was no overlap in the Tukey groups of the error in the combine yield monitoring system, indicating that the null hypothesis should be rejected. Therefore, it can be concluded that, across different levels, combine pitch yield monitor error is different. The effect caused by variations in combine pitch make sense because, as it changes, it likely to affect the location at which it strikes the impact plate, similar to what was experienced in varied combine roll. Similar trends were seen across different levels of grain mass flow, though there were slight differences, likely due to changes in flow properties likely to be seen by denser mass flow rates.

The results obtained from simulating various levels of pitch that a combine may be subject to during the harvest season allowed for the conclusion that the null hypothesis, $\mu_{0\ degrees} = \mu_{3\ degrees} = \mu_{6\ degrees}$ (95% confidence level), could be rejected. Instead, the results display that as combine pitch is varied, the error in the combine yield monitoring system is also variable. Because of this, it can be concluded that combine pitch is a driving factor in yield monitor error.

5.4.2 Harvest Season Data Analysis

Over the course of the 2013 fall harvest season, extensive quantities of yield monitor data was collected across a total of 846.5 acres, compromised of fields of either corn or soybeans. The data was collected on the same combine that was used in simulating field conditions on the test stand. The data collected was used in the following section to examine how changes in different parameters affect the performance of the combine yield monitoring system. The data sets analyzed consisted of CAN logs, recorded ground truth scale weights, and grain samples.

After processing the harvest data, the full range of average mass flow rates was able to be obtained. From knowing the full range of data, the set can be broken up into different subsets of data based on mass flow. These different subsets, in turn, can be seen as representative as different points along a yield monitor calibration curve. Across each range, the data is normalized in order to have the data representative of a well calibrated yield monitor that is not subject to any biasing.

The full range of average mass flow rates for each grain tank load is shown in Figure 5.4 on page 62. Over the entire harvest season the average grain mass flow rate was 15.33 kilograms per second and the entire data set ranged from 2.5 to 27.5 kilograms per second. In order to evaluate the data set across different levels of grain mass flow, the data set was broken up into five equally spaced regions centered around 5, 10, 15, 20, and 25 kilograms per second in order to include all data points from the harvest season. In the following evaluations, different field metrics will be evaluated over each of the discrete ranges of grain mass flow.

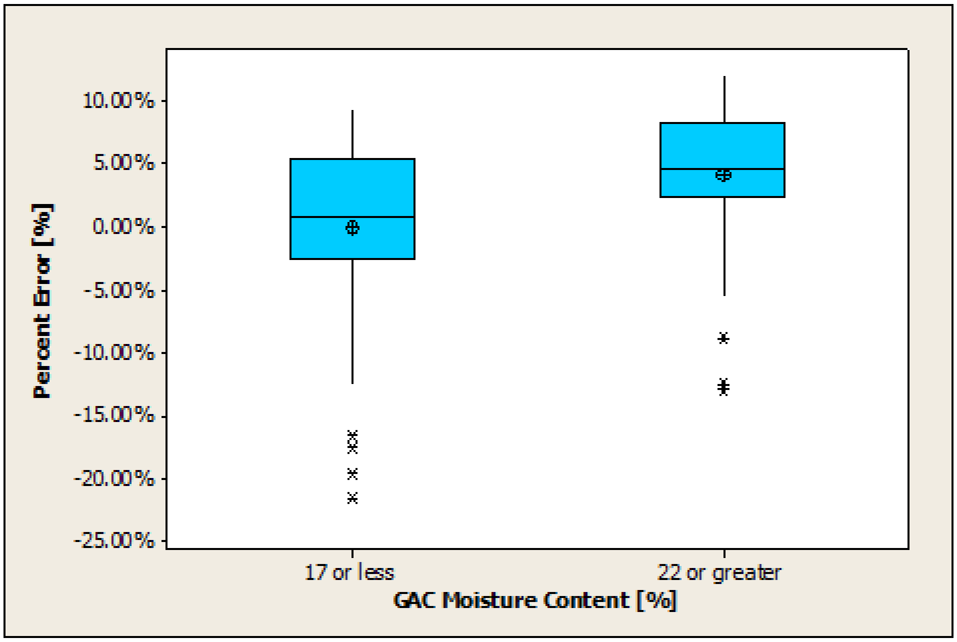
The same data for soybeans obtained during the 2013 harvest season was evaluated and the ranges of grain mass flow can be seen in Figure 5.5 on page 63. Over the course of the season, the average grain mass flow rate was 5.44 kilograms per second, and the entire data set ranged from 2.25 to 7.75 kilograms per second. To evaluate the data set across various levels of grain mass flow, the data was divided up into three equally space regions centered around 3, 5, and 7 kilograms per second in order to include all data points collected during the season.

These discrete ranges will be used in evaluating the performance of the combine grain yield monitoring system across different harvest conditions.

Field Moisture Content Analysis

One variable, whose impact on the combine yield monitoring system was examined, was crop moisture. Crop moisture has the ability to affect the performance of the grain yield monitoring system because it impacts the physical characteristic of the grain being measured. Over the course of the harvest season a wide variety of crop moistures were experienced, ranging from 13.5% moisture to 27.5% moisture. The average crop moisture in corn was 18.87%; the complete distribution is shown in Figure 5.2 on page 59.

In order to evaluate the effect moisture content has on combine yield monitor performance, the impact of moisture content was compared across different ranges of grain mass flow. To determine whether or not moisture content has an effect on yield monitor performance, the hypothesis that yield monitor was different between high and low moisture corn, $\mu_{low\ moisture} \neq \mu_{high\ moisture}$, was evaluated. For analysis purpose, grain moisture contents less than or equal 17% were considered as low moisture corn, while grain moisture contents greater than or equal 22% where as high moisture corn.



Moisture [%]	Tukey Analysis
> 22%	A
< 17%	B

Figure 5.14: Box plot with Tukey analysis of yield monitor error by moisture content

When evaluating the data from the harvest season, the data ranging from 12.5 kilograms per second to 17.5 kilograms per second, which consisted of 126 data points, was used in developing an understanding of the effect of moisture content. Because yield monitor performance varies across different levels of grain mass flow, dividing individual loads into ranges of closely related grain mass flow rates was necessary to avoid any biasing from widely distributed mass flow rates. The data range selected was 12.5 kilograms per second to 17.5 kilograms per second because it consisted of a high range of data points, specifically in the high and low moisture regions. To evaluate how moisture content affected yield monitor performance in this range of grain mass flow, an ANOVA test was performed of the mean yield monitor error to obtain a statistical comparison of the data. From the data, displayed in Figure 5.14, it is shown that there is no overlap among the Tukey groups, indicating that there is a difference in yield monitor error between low moisture corn to high moisture corn. From this, it can be concluded that the data set supports the hypothesis and also the claim that crop moisture is a driving factor in yield monitor error.

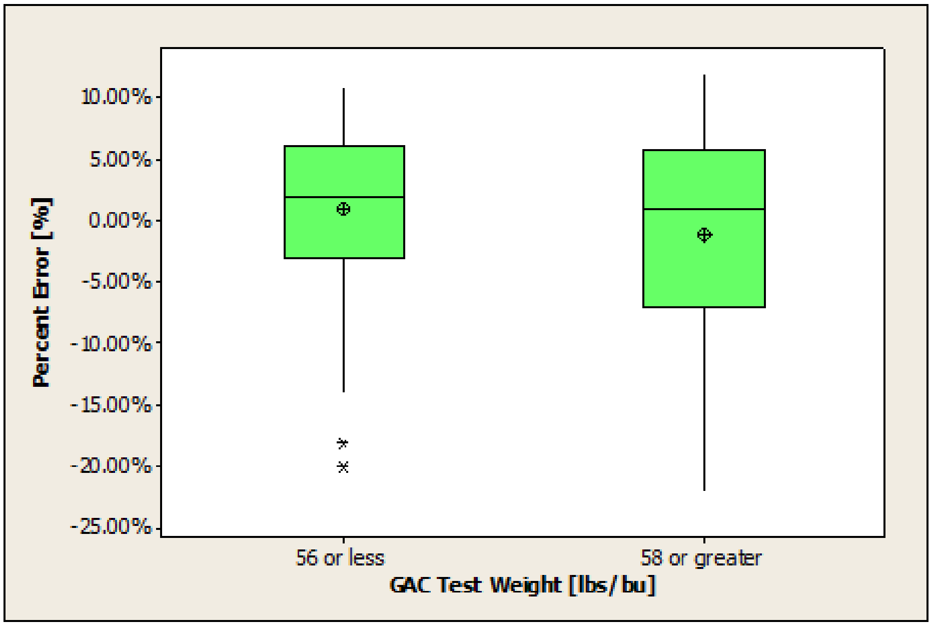
Crop Test Weight Analysis

Another variable examined, based on its impact to the accuracy of the combine grain yield monitoring system, was test weight. Test weight is also a physical characteristic of the grain and, because of that, is likely to impact yield monitor error as it is varied. Over the course of the 2013 harvest season, test weight varied from 50.5 to 62.5 pounds per bushel, which can be seen in Figure 5.3 on page 60. The average test weight recorded for corn was 56.71 pounds per bushel.

When evaluating the impact the test weight of harvested grain has on yield monitor performance, the error in yield monitor response was compared across different ranges of grain mass flow. In determining whether varying test weights impacted the performance of the yield monitor, the null hypothesis stating that yield monitor error was different across different discrete test weights, $\mu_{l<56lbs/bu} \neq \mu_{>58lbs/bu}$, was evaluated.

Similar to the analysis of moisture content, the data ranging from 12.5 kilograms per second to 17.5 kilograms per second was used in evaluating the effect of test weight on combine grain yield monitor error. In order to test the stated hypothesis, an ANOVA test was performed of the mean yield monitor error to obtain a statistical comparison of the data, at a test weight less than 56 pounds per bushel and greater than 58 pounds per bushel; this is shown in Figure 5.15. The results show that there is overlap of the Tukey groups of the mean, error and therefore there is not enough evidence to prove that they are statistically different.

From this, it can be concluded that there is not data to support the null hypothesis, and the claim that test weight can alter yield monitor performance is not backed by the data.



Test Weight [lbs/bu]	Tukey Analysis
> 58	AB
< 56	B

Figure 5.15: Box plot with Tukey analysis of yield monitor error by test weight

As with corn, the test weight of soybeans was also evaluated over the course of the harvest season. Over the course of 85 grain tank loads, the test weight of soybeans ranged from 52.75 to 58.25 pounds per bushel and averaged 56.12 pounds per bushel. The full distribution of tests weights can be seen in Figure 5.16.

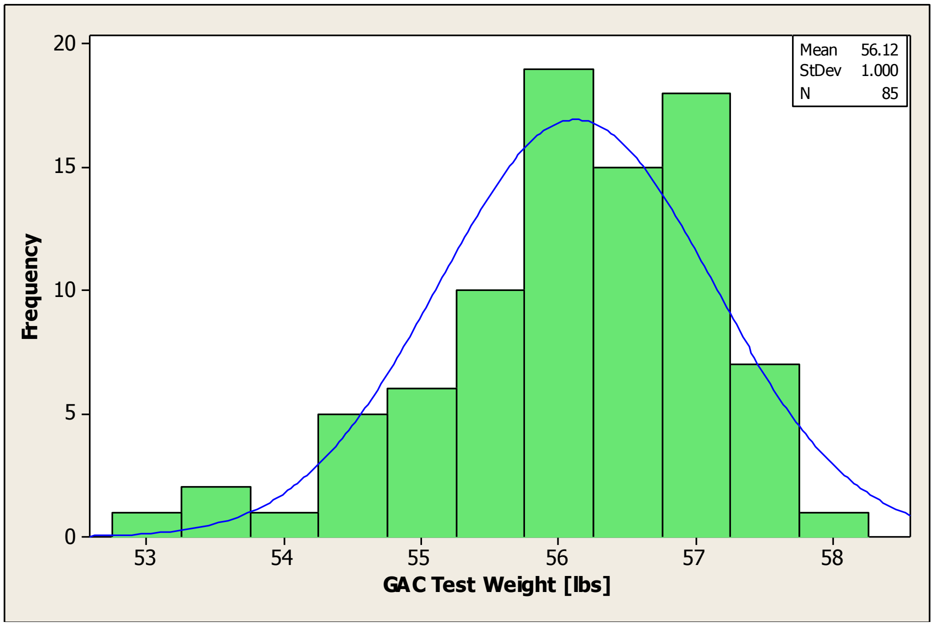


Figure 5.16: Distribution of the test weights recorded in soybeans during the 2013 harvest season

Similar to the results of the evaluation of soybean moisture content, there was not a very wide distribution among the test weight of soybeans to develop any conclusions as to how yield monitor performance responds to variations in the test weight of the harvest crop. In total, 94 percent of the data points fell within a range of three pounds per bushel. Due to this, there was not enough distribution of the data points to develop a hypothesis regarding yield monitor accuracy and test weight, as was done with corn.

Machine Dynamics Analysis

A set of variables that incorporate the machine dynamics in field conditions was another aspect that was considered in evaluating the combine grain yield monitoring system. The variables examined in this analysis were yield monitor error, with respect to combine pitch, combine roll, and vehicle speed. Throughout the harvest season combine pitch, combine roll, and vehicle speed values were captured at all times the machine was harvesting through CAN logs. The results of the data were analyzed to determine if it was possible to conclude that any of these machine dynamics can affect yield monitor performance as they vary. When evaluating these parameters, both the average value obtained from each load and the amount by which the system varied over each load were considered during the data analysis.

CAN data was post-processed to obtain the signal containing combine roll from logs obtained during the harvest season. Using this data, the grain yield monitor error was plotted against the average roll value as well as the standard deviation of the roll, shown in Figure 5.17, to evaluate how combine roll and variance in combine roll both affected system performance. Looking at the graphs, there was not a visible trend in field data that suggests that combine roll or varying combine roll has an impact in yield monitor performance. This is likely due to the fact that, over the course of a load, the average roll value typically falls close or on zero, as evident in Figure 5.17. This can be attributed to the lack of extreme variation in terrain over which the testing was performed.

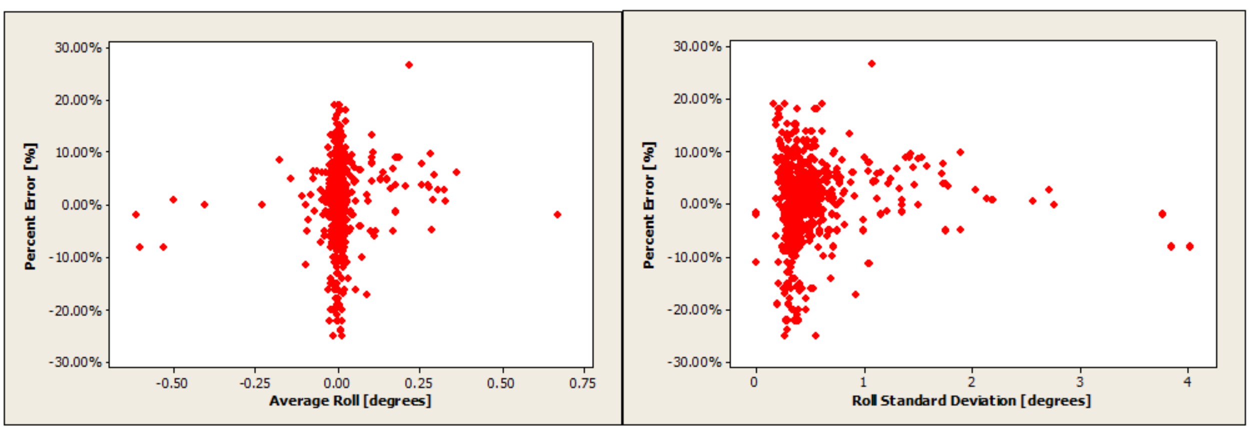


Figure 5.17: Plot of percent error against combine roll (left) and variance in combine roll (right)

Also extracted from CAN data signals, collected over the course of the harvest season, was combine pitch. Figure 5.18 displays all values of grain yield monitor error, with respect to both average combine pitch and variation in average combine pitch experienced over the course of a grain tank load. Similar to what was seen in the evaluation of combine roll on yield monitor performance, the data does not show any evidence that either factor has significant impact on yield monitor error. As with combine roll, the values of pitch are centered around zero, and rarely during a load did the combine experience levels of pitch greater than one degree. Again, this in large part can be attributed to the lack of different levels of terrain experienced over the course of the harvest season.

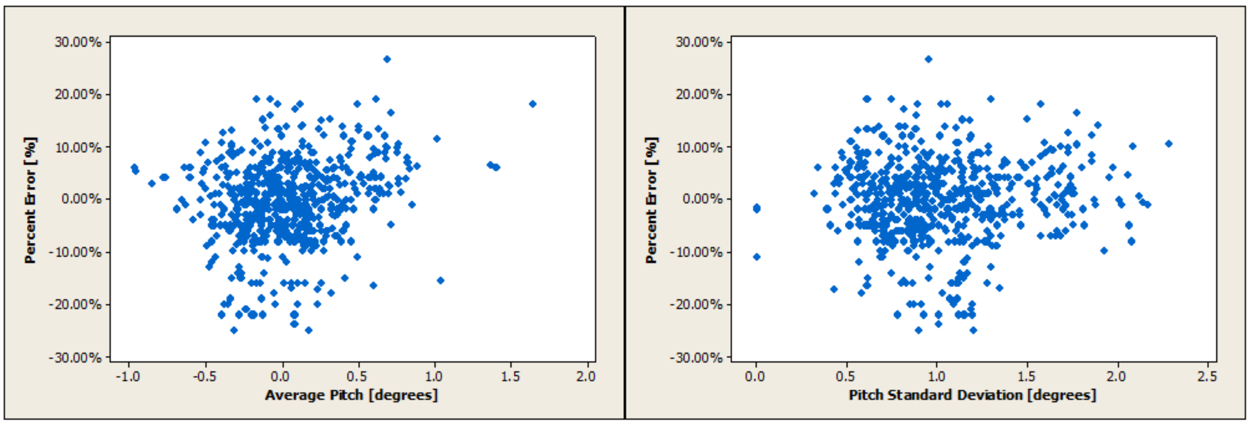


Figure 5.18: Plot of percent error against combine pitch (left) and variance in combine pitch (right)

5.4.3 Summary of Results

From both the results from the test stand and the 2013 harvest season, it is shown that variations in different field metrics have the ability to influence the yield value measured by the combine's yield monitoring system. From the data sets, within a harvest season and a well calibrated monitor with little variations in harvest conditions, a combine yield monitoring system should be able to provide an adequate representation of actual yield of harvested grain. In this scenario, combine yield monitoring systems can provide high levels of data that can be appropriately used in various avenues of farm management, specifically within the area of precision agriculture.

In contrast, unfavorable conditions and improper use could also lead improper management decisions and inaccurate performance evaluations. It is important for producers to understand what may lead to inadequate yield data to help better comprehend what the data they have available actually means. Understanding what issues may drive yield monitor error can help alert them when it may be necessary to recalibrate their system, or to identify possible faulty data. When it comes to yield monitor error, the quality of how well the current system calibration represents the current harvest conditions is the key driving factor. Because of this, levels of yield monitor error can be highly variable based largely on the ability of the producer to calibrate their own system.

The factors most likely to influence error the most are those closely related to the current crop conditions. Significant factors are likely to include crop moisture and crop yield itself. Crop moisture was shown to be a factor that affected yield monitor error, in both the controlled testing and during the actual harvest season. Moisture is a significant factor, largely due to the fact that it changes the physical characteristics of the grain being measured. This is likely a driving factor due to the fact the system uses physical measurements in its estimation of yield. Yield is also a driving factor because it has a strong influence on grain mass flow. Higher yielding areas of a field are likely to result in high levels of instantaneous mass flow assuming vehicle speed remains fairly constant. The inverse is also true with low yielding areas likely to result in lower levels of grain mass flow. From the testing results, yield monitor error was shown to vary across different levels of grain mass flow. Because the system uses a calibration curve in its yield estimation, different points along the curve may be more representative of actual harvest conditions than others while some areas, specifically observed in lower mass flow rates in the data set, may have greater levels of percent error than the actual data.

Considering this, to achieve accurate results, producers should update their system calibrations regularly in order for their calibrations to be representative of the current conditions. Any time a producer notices a significant change in crop conditions, it is highly recommended that the system be recalibrated. This could be from a drastic change in crop moisture, a change in quality of crop, moving from field to field, or combination factors that have occurred over time. To produce accurate results, the harvest conditions of the calibration need to be identical to the actual harvest conditions. To do this, calibrations should be performed at typical harvest speeds in area of the field that provides a good representation of the field as whole. Performing a calibration in a portion that does not well represent the field as a whole, such as the headlands, or at irregular vehicle speeds, won't produce accurate calibration results because calibration point is dissimilar to the portion of the calibration curve that will typically be used while harvesting. Calibrations should be performed multiple times throughout a single season to compensate for conditions that may not be noticed, or have changed slowly over the course of the season. Taking the correct steps in yield monitor calibration can produce more accurate yield that data can be used as a key tool in the decision making process of the overall crop production.

5.5 Conclusions

Over the course of testing, several conclusions were developed as to how different harvest parameters drive yield monitor error. Increasing the understanding of grain yield monitor accuracy is increasingly important, as the data obtained by the system is being used as a tool in more ways than ever before, in the overall management decisions a producer faces. Understanding the impact different conditions have on yield monitor performance will help better develop an idea of the capabilities and limitations of grain yield monitors as they continue to become more popular throughout the entire row crop production industry.

To evaluate the level of accuracy of combine grain yield monitoring systems, testing was performed in both a controlled environment and actual harvesting conditions. Testing in a controlled environment allowed for different test metrics to be identified, and set as an independent variable for testing. With an individual variable being controlled, and all other parameters held constant, the effect of that variable on yield monitor error can be properly evaluated, while also limiting any other biasing effects. Testing in actual harvest conditions gives an actual representation of system performance in real conditions. In actual harvesting conditions, controlling individual variables may be difficult or impossible to do, but with appropriate data collection techniques, the ample amount of data collected produced results from which conclusions could still be made.

From the data produced by the test stand, an overall understanding of how grain mass flow varies across different flow rates was developed. It was shown that, as mass flow rates increased, system variability also increased though the entire run, and was still centered on a single point. Knowing this, an accurate calibration should still produce results, accurately representing the actual value across different ranges of grain mass flow; however higher flow rates will be susceptible to greater variance. The data also identified that combine pitch, combine roll, and crop moisture were all driving factors in yield monitor error. From the results each one these variables produced statistically different values across different ranges of the independent variable. These conclusions, developed from the test stand data help develop an understanding of these different conditions will affect the yield monitor performance in actual field conditions.

The data obtained from testing in actual field conditions also allowed for conclusions to be made about the effect different parameters have on yield monitor error. From harvest data, it was shown that crop moisture is a driving factor in yield monitor error and produced results similar to those produced on the test stand evaluation of moisture content. While yield monitor error was driven by moisture, the data set did not produce any results to show that test weight had a significant impact on error itself. The evaluation of different machine dynamics did not show that there was any statistical differences in yield monitor error across different levels combine pitch and roll, as was seen on the test stand. A possible explanation of these results can likely be attributed to the fact that the data set was collected across fields in central Iowa and were, therefore, not subject to any significant effects of terrain. The conclusions developed will help provide a broader understand of how a yield monitor responds in actual harvest conditions.

Overall, the data sets obtained from testing led to the development of a better understand of how different harvesting conditions affect yield monitor performance and what the capabilities and limitations of the system actually are. These results are important to understand as yield monitoring technology is constantly increasing in usage, capability, and being used for in-field management decisions made by producers. The understanding gained about system performance in respect to variations in harvest conditions, may aide in providing opportunities to identify the capabilities of current yield monitoring systems, develop criteria for system recalibration when field conditions change, and discover potential developmental areas for the improvement of the current system.

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