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Performance benchmark of yield monitors for mechanical and environmental influences

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ABSTRACT. *Crop yield data and maps from previous years are a primary source of information from which crop management recommendations and decisions are based upon. Yield data is a useful tool for making crop management decisions, but becomes irrelevant when it is not accurate or reliable. The objectives of this research were to benchmark commercial yield monitoring systems to better understand performance and to assess limitations of measurement methods from mechanical and environmental influences. Two commercial yield monitors that measured mass and volumetric flow for yield estimation were selected for benchmarking. Each system was calibrated using manufacturer procedures and evaluated in a yield monitor test stand compliant with standards. Clean grain elevator paddle type and machine orientation were selected as treatment factors to evaluate accumulated load accuracy at different grain flow rates. There was no significant difference in mean estimation error for different paddle types for the impact-based mass flow yield monitor. There were significant differences in mean estimation error for different paddle types for the volumetric flow yield monitor. This was attributed to presentation of grain to the sensor between flat and misshapen paddles. Rolled and pitched machine orientations were shown to have significant influence on estimation accuracy for the volumetric flow yield monitor. However, the volumetric flow system maintained lower variability across flow ranges than the impact-based mass flow yield monitor because of a fundamental measurement system that does not rely entirely upon calibration. A fundamental measurement system and known machine properties may be able to overcome the challenges of a harvesting environment. Maintenance of yield monitor accuracy with less calibration will contribute to increased uptime and better basis for crop management decisions.*

Keywords. *Accuracy, Combine harvesters, precision agriculture, yield monitor.*

Introduction

Over the last 20 years, sensing mass flow of grain has become the most common method for determining crop yield. Crop producers must perform a rigorous calibration procedure with their crop harvesters to ensure accuracy of yield estimation, requiring several combine tank loads of grain (Shearer, Fulton, McNeill, Higgins, & Mueller, 1999). Yield monitor accuracy is highly dependent upon the crop properties, harvest conditions, and harvester set-speed for which the calibration was performed (Grisso, Jasa, Schroeder, & Wilcox, 2002). While current yield monitoring systems may provide adequate post-calibration accuracy, it does not support accurate harvesting of multiple crop types without intensive sensor recalibration. Little research has been conducted on alternatives to the current yield monitoring system that maintains accuracy while reducing calibration.

The most common method used to monitor the flow of grain is impact-based sensing. Grain is lifted up the clean grain elevators on paddles and expelled from them at the top of the elevator by centrifugal force as the paddles rotate 180° (Shearer, et al., 1999). Grain is subjected to projectile motion until it contacts the impact sensor positioned across from the clean grain elevator. The impact sensor measures the quantity of grain using a strain gage load cell attached to the impact plate. Grain deflecting off of the impact plate causes deformation in the structural components of the load cell and can be measured using a strain gage in a Wheatstone bridge configuration. Varying amounts of grain flow induce different amounts of strain on the impact sensor, which alter the electrical output signal of the sensor. This electrical signal can be calibrated to correspond to different mass flow rates of grain and adjusted to account for changes in elevator speed. Impact-based mass flow yield monitors are susceptible to error for flow rates that are outside of the calibrated range (Burks, Shearer, Fulton, & Sobolik, 2004).

Another common method of yield measurement is through the use of beam sensors. These sensors function in pairs as an emitter and detector. Therefore, the detector has a binary response to the measurement of the emitted light beam. When the detector measures light transmitted from the emitter a high voltage response is outputted. Alternatively, once the light beam is broken and emittance is no longer detected, a low voltage response is outputted. The timing of light being interrupted can be correlated to the amount of grain being conveyed during that period. A calibration procedure is necessary to determine the frequency of dead band in sensor response due to the clean grain elevator paddles breaking the beam. For this application, it is common to mount these pairs of sensors opposite each other on the clean grain elevator. Since the area of the paddle is fixed, higher crop yields translate to an increased height of the grain pile per paddle. The volume of grain harvested is calculated using the area of a paddle and the height of the grain piled per paddle. Since grain is traded on a mass basis the volumetric estimation is converted using the density, or test weight of the harvested grain. Test weight must be corrected for volumetric yield systems several times per day to maintain accuracy in changing conditions and crop varieties (Blackmore & Moore, 1999).

Objectives

There are several yield monitoring solutions commercially available to producers that claim increased accuracy of yield data, simplified calibration, and ease of use. The long-term goal of this research is to provide users with method of yield monitoring that will maintain accuracy across a variety of harvesting conditions with reduced calibration requirements than what is required currently. Benchmarking available yield monitoring systems was necessary in order to define performance goals, as well as identify advantages and disadvantages of each system. Crop harvesters experience a wide-variety of conditions throughout the harvest season. The focus of this research was the identification of the mechanical and environmental influences on yield estimation and quantifying the induced error of each factor. Independently observing these factors in a test environment allows for insight into opportunities for reduction of yield error.

Materials and Methods

Combine Test Stand

Experiments were completed using a yield monitor test stand. A class 7 combine was positioned so that grain could be precisely metered into the auger bed at set mass flow rates (Figure 1). Corn purchased from a local elevator was metered through the gates of a scaled axle grain wagon. Corn could be recycled from the combine back into the grain wagon for repetitive testing using the unloading auger. Corn mass flow rates were implemented through remote control of linear actuated doors on the grain wagon. Maximum achievable mass flow rate exceeded 50 kg s^{-1}. The test stand had been previously evaluated and proven to provide an accurate ground truth mass flow rate to compare commercially available yield monitor systems (Risius, 2014).

Figure 1: Yield monitor test stand

Corn used for experimental testing was consistently at 15% moisture content and ranged in test weight from 56 to 58 lb bu^{-1}. Preliminary testing revealed that as grain was repetitively recycled through the test stand it would deteriorate over time. The degree of deterioration and the effect on yield monitor estimation accuracy was unknown. Samples were collected throughout testing using a 6 slot grain probe that allowed a sample depth of 1 m in the grain tank. A single sample was composed of five to six grain probes randomly collected from the grain wagon. Samples were mixed in a one-gallon bag and weighed. Measurement of the percentage broken corn and foreign material (BCFM) was performed using a Carter-Day XT7 Dockage Tester. No foreign material was introduced between replicates, BCFM could be directly correlated to deterioration due to grain recycling.

Yield Monitors

In this section, the two yield monitoring systems under evaluation are presented. Each system differs in sensing method and location on the machine. Both yield monitors were evaluated simultaneously using the test stand.

Impact-Based Mass Flow Yield Monitor

The mass flow based system under evaluation was an Ag Leader yield monitor. The yield monitor system consisted of several components including the impact-based mass flow sensor, grain moisture sensor, and internal software in the John Deere display. The system came preinstalled from the factory with the mass flow sensor mounted at the top of the clean grain elevator.

Beam-Based Volumetric Flow Yield Monitor

The volumetric flow based system under evaluation was a SmartYield™ Pro yield monitor manufactured by Raven Industries. The system was comprised of a beam-based volumetric flow sensor, grain moisture sensor, processing controller, and external display that allowed aftermarket installation on any combine.

The beam-based volumetric flow sensor was installed on the upper region of the clean grain elevator above the grain moisture sensor. The controller module was mounted to the side of the combine. Since experiments were conducted on a stationary combine, a program was used to simulate the dynamic GPS signal required by the controller. The external display was installed in the cab next to the John Deere display so that accumulated load weight estimations could be compared between the two yield monitors (Figure 2).

Figure 2: SmartYield Pro yield monitor beam-based volumetric flow sensor and display, respectively

Pre-Testing Calibration

Several calibrations were performed on the yield monitors prior to the experiment. Clean grain elevator speed was set to 450 RPM at zero-flow conditions and monitored on the CAN bus throughout testing. Both yield systems were calibrated for machine orientation by following the manufacturer recommended procedures. Static, level position was maintained until calibration was completed. A vibration calibration was performed for the impact-based mass flow yield monitor to reduce systematic error at zero-flow conditions. Vibration calibration was performed through the John Deere display with the separator and feeder house engaged at full engine RPM. Similarly, a zero-flow calibration was performed for the volumetric flow yield monitor to record the sensor response from empty elevator paddles. Both vibration and zero-flow calibrations record the sensor response at no flow conditions so that it could be internally processed out of the final signal in real-time. Calibration of the mass flow sensor was performed in adherence to standard operating procedure (Deere & Company, 2013). Five grain mass flow rates were selected from field observed flow rates to collect calibration loads and evaluate yield monitor performance. Three of these five were selected to also be collected as a calibration load for the volumetric flow yield monitor. Per manufacturer recommendation, one of the three represented either low, medium, or high mass flow rate from the distribution. Accumulated load size target for calibration and evaluation testing was 2,500 kg. The calibration curve of the volumetric yield monitor was updated immediately after a calibration load was collected, which differs from the impact-based mass flow yield monitor that updates the curve after all loads have been collected. Following flow sensor calibration, both systems were ready for evaluation.

Mass Flow Rate of Grain

Mass flow rate of grain was selected as a treatment factor to evaluate the yield monitor performance. Mass flow was measurable using the scaled axle grain wagon and metering system previously described. To select treatment levels of mass flow rate, analysis was conducted into the distribution of mass flow rate on combines. The normal distributions were observed from nearly 2,000 hours of mass flow sensor data recorded from the Controller Area Network (CAN) bus on combine harvesters in a harvest operation. The distribution of mass flow rate was much broader for corn than it was for other crops. Emphasis was placed on flow rates for small grains when selecting treatment levels to evaluate yield monitor performance. Impact-based mass flow yield monitor performance in corn at higher flow rates has already been well documented (McNaull, 2016). Treatment levels spanning two standard deviations for small grains and one standard deviation for corn were targeted (Table 1).

Table 1: Mass flow rate treatment levels for yield monitor evaluation

	Treatment levels: mass flow rate (kg s^{-1})	
Flow rate CDF target	**Small grains**	**Large grains**
-2-sigma	2	5
-1-sigma	4	10
Mean	5	15
+1-sigma	8	20
+2-sigma	10	25

Clean Grain Elevator Paddle Type

The presentation of grain to the sensors for both mass and volumetric flow yield monitors is controlled by the clean grain elevator. Several different configurations of paddle shape and type are commercially available. Clean grain elevator paddle type was selected as a treatment factor to identify how grain presentation to the yield monitors may impact performance. The paddle chain, elevator drive sprocket, and elevator assembly remained unchanged between different paddle types. The paddle material and shape were the only variables altered that define a different type of paddle and corresponding data set (Table 2).

Table 2: Paddle type matrix

Paddle ID no.	Material	Material stiffness	Estimated previous separator run time (h)	Paddle shape
1	Recycled tire carcass	Flexible	250	Cupped
2	Recycled tire carcass	Flexible	616	Flat
3	HDPE plastic	Rigid	5	Flat
4	Belt conveyor rubber	Flexible	0	Flat

Paddle sets 1 and 2 were taken from two John Deere combines that had several harvest seasons of use. They were commercially available paddles made of flexible, rubber ply from recycled tires. Consistency in shape from paddle-to-paddle was poor with several paddles deformed from normal wear and tear. The shape of paddle set 1 was cupped, concave upward that allowed grain to pile in the center of the paddle when the clean grain elevator was running. Paddle set 2 featured a mostly flat shape with some inconsistencies per paddle. Paddle set 3 was a rigid plastic paddle that was consistently flat. The mounting to the elevator chain was the same for all paddle sets. Unlike the rubber paddles, paddle set 3 did not flex when contact was made with the clean grain auger. Instead, the elevator chain would pull slightly away from the elevator drive sprocket. Paddle set 4 was a different type of rubber than paddle sets 1 and 2. Layers of belted rubber kept the paddle shape consistent and flat. The flexible material allowed for the paddles to bend when rotating around the drive sprocket and clean grain auger. The different paddle sets formed four treatment levels to evaluate the yield monitor systems at different mass flow rates (Figure 3). Eight tests were completed on the four different elevator paddle configurations (). Each data set defines a unique calibration for each yield monitor system.

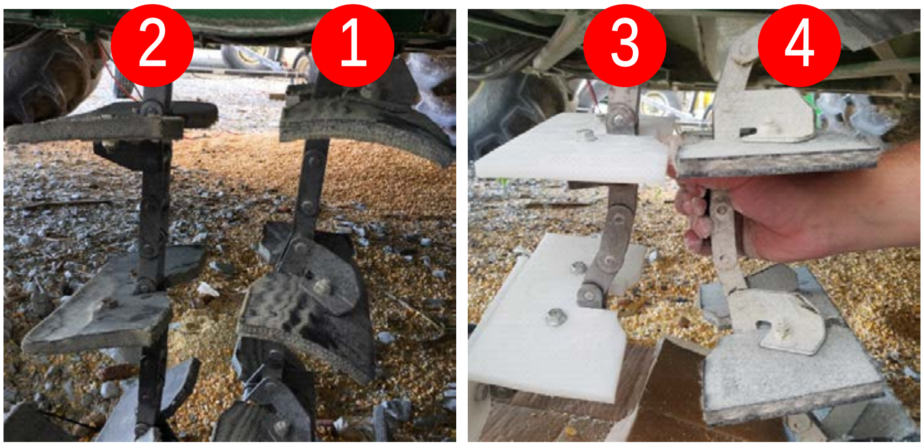

Figure 3: Paddle set configurations and respective ID numbers

Table 3: Data set description for yield monitor evaluation of paddle type

Data set	Paddle set ID no.	Mass flow rate (kg s^{-1})	Replicates
A	1	5	5
		10	5
		15	5
		20	5
		25	5
B	1	5 [a]	3
		10	3
		15	3
		20	3
		25	3
C	2	10	2
		15	2
		20	4
		25	2
D	2	10	4
		15	4
		25	4
E	3	5 [a]	4
		10	4
		15	4
		20	4
F	3	2 [a]	2
		4	4
		8	4
		10	4
G	4	5 [a]	4
		10	4
		15	4
		20	4
		25	4
H	4	5 [a]	4
		10	4
		15	4
		25	4

[a] *Mass flow rate was not characterized in yield monitor calibration*

Machine Orientation

Combine orientation affects how grain piles in the clean grain elevator and induces gravitation effects on the projectile motion of grain leaving the paddle. Machine orientation was selected as a treatment factor to gain a better understanding of the implication of pitch and roll on yield monitor performance. Machine pitch referred to the axial orientation of the combine. The fore position was represented by the crop head or the front of the combine. The aft position was represented by the rear of the combine. Pitch was defined as positive for downward rotation of the head. Machine roll refers to the transverse orientation of the combine. A clockwise transverse rotation of the combine was defined as a positive angle rotation (Figure 4).

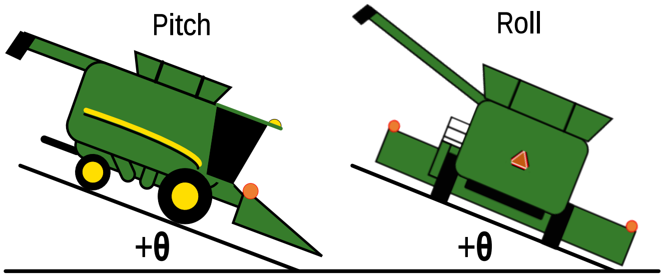

Figure 4: Combine pitch and roll orientation

Data analysis of combine orientation during harvest conditions was used as a basis of determination of pitch and roll angle for testing. Again utilizing the harvester CAN bus database, the mean angle for combine pitch and roll during harvest was nearly zero with similar standard deviation sizes of 2.1° and 2.3°, respectively. Analysis included common crop types from both small and large grains across a range of flow rates. Based on these results, a combine pitch and roll angle of 3 degrees was deemed ideal to test at because it encompassed 86% of orientation distributions. Level, 3 degree pitch, and 3 degree roll treatment levels were tested at different mass flow rates to observe the effect of machine orientation on yield monitor performance (). Both yield systems were calibrated on level terrain at mass flow rates spread across the distribution of interest. The combine was then reoriented to the outlined treatment levels with no recalibration to observe accuracy shift. Yield monitors were evaluated at the same mass flow rates that calibration was completed at. Data sets E and J included one mass flow rate below the calibration range to observe performance shifts. Paddle set 3 was used for all machine orientation replicates because it was the most consistent, flat paddle set. Using the same paddle set for all treatment levels ensured validity regarding accuracy shifts between orientations.

Table 4: Data set description for yield monitor evaluation of machine orientation

Data set	Pitch Angle (°)	Roll Angle (°)	Mass flow rate (kg s^{-1})	Replicates
E	0	0	5 [a]	4
			10	4
			15	4
			20	4
I	0	3	10	4
			15	4
			20	4
J	3	0	5 [a]	4
			10	4
			15	4
			20	4

[a] *Mass flow rate was not characterized in yield monitor calibration*

Methodology for Yield Monitor Evaluation

The instantaneous response from the impact-based mass flow yield monitor and corresponding grain wagon weight were recorded at 1 Hz frequency. Instantaneous output from the volumetric flow yield monitor was not available, as the system was completely self-contained. Grain conveyance and the location of grain entry into the combine induced approximately a 10 second delay for grain to leave the wagon and reach the mass flow sensor at the top of the clean grain elevator. For these two reasons, estimated load weight of the respective yield monitoring systems was compared against the displaced load weight measured by the grain wagon scale. Analysis of accumulated load weight mitigated the effect of time delay and allowed for direct comparison of the two yield systems. Three specific metrics were used to evaluate the accumulated load estimation performance of calibrated mass flow and volumetric flow yield monitors:

- The overall mean error per data set.
- Variability of error per data set.
- True mean error of flow rate ranges within a data set.

Harvest conditions fluctuate throughout a crop field and cause changes in grain flow rate, moisture, and test weight. The performance impact of moisture and test weight were reduced by using dry, consistent corn. Therefore, flow rate of grain was combined with other treatment factors of elevator paddle configuration and machine orientation to observe the effect on yield monitor estimation accuracy. Analysis of the overall mean error was used to compare yield monitor performance for each level of elevator paddle configuration and machine orientation across all levels of mass flow rate. This method isolated the shift in performance between paddle type and orientation direction.

The analysis of the variability of all error per data set focused on the repeatability and accuracy of yield monitors evaluated at mass flow rates that they were calibrated for. This method exposed error induced by levels of paddle configuration and machine orientation across all levels of mass flow rate. Lower overall variability was desired more than lower overall mean error, as the former indicated repeatability and was less susceptible to random error. Bias error in a sensor is easier to correct for than inherit, random error.

The true mean error of flow rate ranges was analyzed to evaluate performance impact of each level of mass flow rate on levels of elevator paddle configuration and machine orientation. Confidence intervals evaluated the range of the true mean yield monitor error per mass flow rate set point. Preliminary testing with the test stand revealed that it was not possible to replicate a precise mass flow rate every time. As a result, true mean error would be evaluated for a range of flow rates rather than a specific flow rate setting. Flow rate ranges were determined post-testing by appropriately dividing the observed flow rates (Figure 4.7). Flow rate ranges were divided at natural breaks and included calibration points: 3 to 9, 9 to 15, 15 to 21, and 21 to 27 kg/s.

Results

Performance Impact of Paddle Configuration

The analysis of mean error focused on percent difference between the yield monitor estimated mass of grain metered into the combine and the mass displaced from the scaled axle grain wagon. Ideally, a yield monitor would produce a mean error of zero for grain flow rates within the calibrated range. Analysis of mean error was completed for paddle configuration data sets using flow rates that the yield monitors were calibrated for. Examination of the calibrated flow rate range allowed for statistical comparisons between treatment levels.

The paddle configuration had little effect on the estimation error for the impact-based mass flow yield monitor. Estimation error of data set F using poly paddles was found to be statistically significant to the estimation error, however this can be attributed to evaluation at exceptionally lower mass flow rates than other data sets (Table 5). Impact-based mass flow yield monitor performance was poorer for mass flow rates less than 5 kg s-1 compared to the higher rates. Calibration was difficult for lower mass flow rates due to sensor response limitations. Absolute estimation error for data sets other than F ranged from 0% to 4% and is in agreement with previous research. It was inferred that impact-based mass flow yield monitors are less susceptible to performance error due to clean grain elevator paddle configuration. Paddles project grain across a volume to the sensor, which may explain some reasoning for the lack of influence on impact-based mass flow yield monitor performance.

Table 5: Statistical difference by paddle configuration data set for the impact-based mass flow yield monitor

			Estimation Error			
Data set	**Paddle set ID**	**Replicates**	**Mean**	**Std. Dev.**	**Tukey Grouping**	
A	1	25	2.1%	2.4%	A	
B	1	12	3.8%	4.3%	A	
C	2	10	0.3%	2.6%	A	
D	2	12	-0.3%	4.9%	A	
E	3	12	1.1%	6.8%	A	
F	3	12	-52%	42%		B
G	4	16	3.4%	8.8%	A	
H	4	12	0.5%	5.3%	A	

Influence of paddle configuration was evident for the volumetric flow yield monitor. The paddle configuration was found to be statistically significant to the estimation error (Table 6). Paddle set 2 (data sets C and D), 3 (data sets E and F), and 4 (data sets G and H) were found to not be statistically different from each other, however they were found to be different from paddle set 1 (data sets A and B). The inclusion of data set F in Tukey group B could be attributed the lower flow rates at which the data set was performed.

Table 6: Statistical difference by paddle configuration data set for volumetric flow yield monitor

			Estimation Error				
Data set	**Paddle set ID**	**Replicates**	**Mean**	**Std. Dev.**	**Tukey Grouping**		
A	1	25	-9.1%	6.5%			C
B	1	12	-8.9%	9.6%		B	C
C	2	10	-3.0%	3.0%	A	B	C
D	2	12	1.2%	3.3%	A		
E	3	12	-0.2%	1.8%	A		
F	3	12	-2.6%	7.8%	A	B	
G	4	16	3.7%	4.1%	A		
H	4	12	2.2%	2.4%	A		

Paddle set 1 was found to be statistically different from other paddle configurations for volumetric flow yield monitors. Outlined in Table 4.4, these paddles were cupped upward so that grain collected in the center of the paddle. Individual paddle shape and consistency throughout the paddle set effected performance of volumetric flow yield monitors greater than impact-based mass flow yield monitors. The cause of this came from the presentation of grain to the sensor and the sensing technology. For the impact-based mass flow yield monitor, grain is propelled across the top of the clean grain elevator and into an impact sensor. Impact-based sensors correlate the force of the grain impact to a mass flow rate through calibration and regression. All paddle configurations tested allowed grain to leave the paddle and impact the sensor in a similar way, resulting in comparable yield estimation performance. When mass flow rate was diminished exceptionally in data set F, performance was reduced. It was hypothesized that this was the threshold where the grain trajectory and relationship with the sensor changed. The beam sensor of the volumetric flow yield monitor, positioned on the side of the clean grain elevator, was more susceptible to changes in paddle configuration because the sensing method relies upon the characteristics of grain delivery. Calibration characterized the beam breakage time to volumetric flow rates of grain. The yield monitor operated under the assumption that when the beam breaks, grain loading across the entire paddle is uniform. Misshaped paddles and poor paddle-to-paddle consistency changed the grain profile and loading on the paddle, resulting in increased estimation error for data sets A and B. The estimation error was negative because the yield monitor was underestimating the amount of grain displaced. Misshaped paddles allowed grain to hide from the beam sensor, compared to paddle ID no. 3 which uniformly displayed on the paddle. Paddle loading visual aids were created using the elevator rotational speed and the number of paddles per chain (Figure 5). For the standard elevator configuration, approximately 17 paddles passed the sensing regions of the yield monitors per second. Calibration does not correct paddle sensitivity for the volumetric flow yield monitor if the presentation of grain to the sensor is flawed.

Figure 5: Grain pile loading on paddle sets 1 and 3 for 5 kg s^{-1} mass flow rate, respectively

The overall standard deviation across all flow rates was compared between data sets to evaluate the effect of paddle configuration on the repeatability of the yield monitoring systems. The variability of the impact-based mass flow yield monitor estimation error was between 2% and 9% for all paddle configurations, excluding data set F (Figure 4.11). The variability increased substantially to a 1-sigma standard deviation of 42% for data set F. This concurred with analysis of overall mean error that the estimation performance was reduced due to low flow rate calibration. Data sets G and H had larger variability than data sets A, B, C, and D although the mean estimation errors were comparable. Further research would need to be conducted to determine root cause.

Data sets A, B, and F had the largest variability for the volumetric flow yield monitor. Increased variability for data set F was likely the result of low flow calibration and presentation of grain to the sensor. Exceptionally low flow rates were tested within data set F. If the grain mass flow rate was low enough that a paddle was not completely filled with grain, the yield monitor would overestimate yield under the assumption that paddles are completely filled with grain to the measured height. Research showed that the mass flow rate threshold of complete coverage of paddle area with corn was 2 kg s-1. This was a level that data set F was evaluated at. Increased variability for data sets A and B was a result of misshaped and inconsistent paddles. All other data sets contained a 1-sigma standard deviation less than 5%.

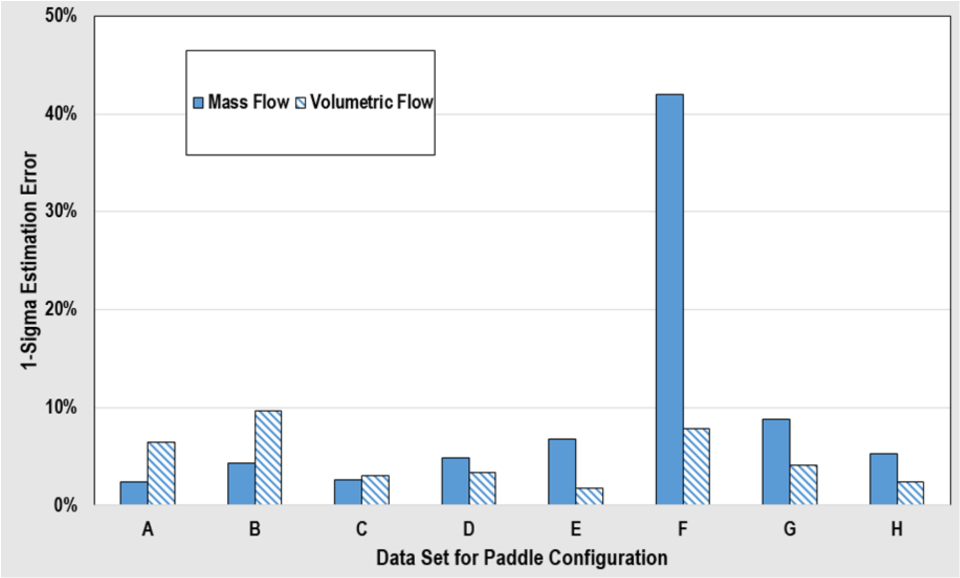

Figure 6: Standard deviation of yield monitor estimation error across all flow rates.

The true mean error for four flow rate ranges was analyzed for each paddle configuration. As described, each paddle configuration was used in two data sets (Table 3). True mean error for the impact-based mass flow yield monitor ranged from -8% to +7% across all flow ranges and paddle configurations (Table 7). Paddle set 1 had three flow ranges that were found to not be statistically different from one another. Paddle sets 2, 3, and 4 had comparable flat shaped paddles and had at least two flow rate ranges that were found not to be statistically different. Paddle sets 3 and 4 had two groups of paired flow rates and showed poorer estimation accuracy at higher mass flow rate. The impact-based mass flow yield monitor demonstrated comparable performance across all paddle types, however statistical difference was found between flow rates. Repeatable results across the entire calibrated flow range is fundamental in obtaining accurate yield measurement. Bias error that offsets the yield estimation across all flow rates is easier to correct than random error and variability between flow ranges.

Table 7: Statistical differences by specific flow rate range and paddle set for impact-based mass flow yield monitor

Paddle set ID	Flow Range (kg s^{-1})	Estimation Error		Tukey Grouping						
		Mean	Std. Dev.							
1	5-9	-1.0%	1.3%			C	D	E	F	
	9-15	3.9%	2.6%	A	B	C				
	15-21	5.7%	3.1%	A	B					
	21-27	2.3%	1.5%	A	B	C	D	E		
2	5-9	3.4%	3.2%	A	B	C	D			
	9-15	1.4%	2.8%		B	C	D	E		
	15-21	-2.8%	3.4%					E	F	G
	21-27	-3.5%	1.3%				D	E	F	G
3	5-9	2.0%	4.8%		B	C	D	E		
	9-15	6.0%	0.91%	A	B					
	15-21	-8.1%	0.64%							G
	21-27	NA	NA							
4	5-9	5.5%	5.4%	A	B					
	9-15	7.3%	1.65	A						
	15-21	-6.5%	1.9%						F	G
	21-27	-8.1%	2.6%						F	G

True mean error for the volumetric flow yield monitor ranged -18% to 5% across all flow ranges and paddle set configurations (Table 8). True mean error for flat paddle sets 2, 3, and 4 ranged from -5% to +5%. Paddle set 1 had the largest error range with nearly zero yield estimation error at lower flow rates and the largest error at the higher flow rates. Flow ranges 15-21 and 21-27 kg s-1 were found to be significantly different from flow ranges for all paddle configurations. This was attributed to the shape and consistency of the paddles. Misshaped paddles allowed grain to settle in areas of the paddle where the sensor could not accurately measure. Consistency of each paddle affected the zero flow tare and resulting accumulated load estimations. At least two flow ranges from paddle sets 2, 3, and 4 were found to not be significantly different from each other within the same paddle set. Similar results as the impact-based mass flow yield monitor of two groups of statistical significance per paddle configuration were found. Three of the four paddle configurations are were found to not be statistically different for the 5-9, 9-15, and 15-21 kg s-1 ranges.

Table 8: Statistical differences by specific flow rate range and paddle set for volumetric flow yield monitor

Paddle set ID	Flow Range (kg s^{-1})	Estimation Error Mean	Estimation Error Std. Dev.	Tukey Grouping								
1	5-9	0.61%	0.84%	A	B	C	D	E				
	9-15	-6.0%	5.1%							G		
	15-21	-13%	3.8%								H	
	21-27	-18%	2.9%									I
2	5-9	2.7%	1.8%	A	B	C						
	9-15	1.9%	1.8%	A	B	C	D					
	15-21	-4.2%	1.3%						F	G		
	21-27	-4.7%	2.7%					E	F	G		
3	5-9	-2.9%	1.9%				D	E	F	G		
	9-15	1.8%	1.0%	A	B	C	D	E				
	15-21	0.40%	0.59%		B	C	D	E	F			
	21-27	NA	NA									
4	5-9	4.9%	2.5%	A	B							
	9-15	5.1%	1.3%	A								
	15-21	-1.1%	0.91%			C	D	E	F			
	21-27	-1.3%	1.2%	A	B	C	D	E	F	G		

Performance Impact of Machine Orientation

The overall mean error, variability, and mean error per flow rate range were analyzed to evaluate the impact of machine orientation on yield monitor performance. Estimation error was found to not be statistically different by machine orientation for the impact-based mass flow yield monitor, although overall mean error increased from level to roll and pitch orientation (Table 9). Mean error produced for roll and pitch orientations was 3.2% and 5.0%. Results were in agreement with previously reported results by Fulton et al. (2009).

Table 9: Statistical difference by machine orientation data set for impact-based mass flow yield monitor

Data set	Orientation	Replicates	Estimation Error Mean	Estimation Error Std. Dev.	Tukey Grouping
E	Level	12	1.1%	6.8%	A
I	3° Roll	12	3.2%	6.8%	A
J	3° Pitch	10	5.0%	7.6%	A

Estimation error was found to be statistically different by machine orientation for the volumetric flow yield monitor (Table 10). Yield monitor performance was highly accurate for level orientation with mean error nearly zero. Data set I, rolled orientation, produced the largest mean error of 11%, while pitched orientation was less severe to estimation accuracy.

Table 10: Statistical difference by machine orientation data set for volumetric flow yield monitor

Data set		Replicates	Estimation Error Mean	Estimation Error Std. Dev.	Tukey Grouping		
E	Level	12	-0.2%	1.8%			C
I	3° Roll	12	11%	2.1%	A		
J	3° Pitch	10	6.7%	1.5%		B	

Both rolled and pitched machine orientation caused the volumetric flow yield monitor to overestimate the mass of the accumulated load. Overestimation stems from the measuring method of the sensor. Changes in machine orientation caused uneven loading on elevator paddles and overestimation of grain flow (Figure 7). When the combine was rolled, grain piled to one side of the elevator paddle. The yield system estimated grain flow under the assumption that when the sensing beam was broken, grain pile height was consistent all the way across the elevator paddle. Since grain height varied, overestimation occurred. Similar results were observed for machine pitch, however with lower mean error. The clean grain elevator allowed grain to pile towards the front of the paddle for pitched machine orientation. Beam sensor installation allowed for the approximate center of the pile to be measured and pile height to be averaged between both sides of the pile, resulting in less error for pitched orientation. The severity of grain piling to one side of the paddle is dependent upon the degree of machine pitch or roll and angle of repose of the grain.

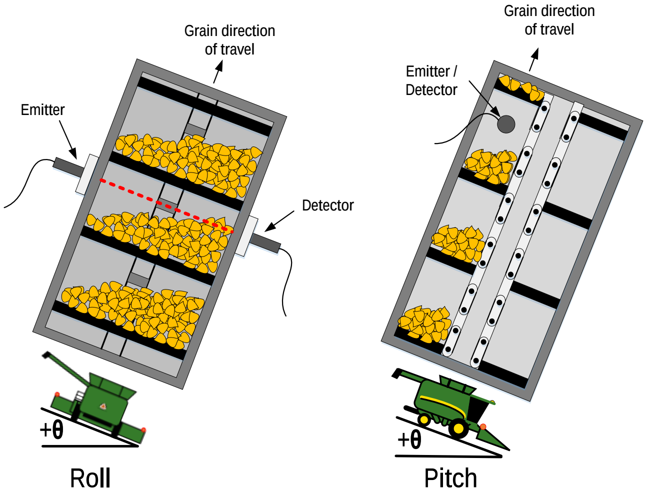

Figure 7: Machine orientation impact on grain pile in the clean grain elevator

The repeatability of the yield systems was analyzed using the overall standard deviation across all flow ranges. Standard deviation was consistent between the data sets for each of the yield monitors, likely because evaluation was completed with the same paddle set. Rigid, flat paddles from paddle set 3 were used for all machine orientation data sets to isolate orientation as the treatment factor. The variability in yield estimation was greater for the impact-based mass flow yield monitor than the volumetric flow yield monitor. Increased variability of the impact-based mass flow yield monitor was expected based on paddle configuration results. Volumetric flow yield monitor results had average error standard deviation less than 2% for the three data sets. Repeatability across all flow ranges is a key metric of yield monitor performance and allows for simple estimation offset adjustment based on machine orientation. The controller module should have corrected yield estimation using the pre-test slope calibration, but it is unclear why the system did not compensate.

Analysis of the true mean error showed that there was significant difference between machine orientation and estimation error for different ranges of flow rates for the impact-based mass flow yield monitor (Table 11). In general, similar performance was achieved at each mass flow rate for the three machine orientations. For all data sets, flow rate range 15-21 kg s-1 was found to be statistically significant to the other two flow ranges. Flow rate ranges 5-9 and 15-21 kg s-1 were found not to be statistically significant between each orientation data sets. It was inferred from similar performance for the three data sets that the impact-based mass flow yield monitor was less susceptible to performance degradation from changes in machine orientation.

Table 11: Statistical difference by specific flow rate range and machine orientation for impact-based mass flow yield monitor

			Estimation Error		
Data set	**Orientation**	**Flow Range ($kg\ s^{-1}$)**	**Mean**	**Std. Dev.**	**Tukey Grouping**
		5-9	5.4%	0.21%	B
E	Level	9-15	6.0%	0.91%	B
		15-21	-8.1%	0.64%	C
		5-9	5.5%	4.7%	B
I	3° Roll	9-15	9.9%	0.89%	A B
		15-21	-4.8%	0.57%	C
		5-9	6.8%	2.2%	B
J	3° Pitch	9-15	13%	0.53%	A
		15-21	-4.6%	0.38%	C

Volumetric flow yield monitor estimation error was found to be statistically significant for different machine orientations, but not for flow rate within the same orientation data set (Table 12). Although different orientations shifted mean performance, variability of error within flow rate ranges was less than 3%. The volumetric yield monitor performed more uniformly across flow rates than the impact-based mass flow yield monitor.

Table 12: Statistical difference by specific flow rate range and machine orientation for volumetric flow yield monitor

			Estimation Error		
Data set	**Orientation**	**Flow Range ($kg\ s^{-1}$)**	**Mean**	**Std. Dev.**	**Tukey Grouping**
E	Level	5-9	-1.9%	0.96%	D
		9-15	1.8%	1.0%	C
		15-21	-0.40%	0.59%	C D
I	3° Roll	5-9	10.8%	3.3%	A
		9-15	12.3%	0.50%	A
		15-21	10.9%	0.87%	A
J	3° Pitch	5-9	5.8%	0.35%	B
		9-15	8.6%	0.53%	A B
		15-21	5.6%	0.91%	B

Peformance Impact of Non-Calibrated Flow Ranges

Manufacturers recommend recalibration of yield monitors when crop conditions change and no longer are represented by the current calibration factors. It is difficult to get exposure to all anticipated crop conditions in a single yield monitor calibration, so it is often necessary for a producer to calibrate multiple times throughout a season to maintain accuracy. Even so, a calibration will not encase all of the continuous range of flow rates a field may have. In this section, yield monitor performance was analyzed for flow rates that were below the range of calibration.

Absolute yield estimation error increased significantly for flow rates that were outside of the calibrated range (Figure 8). Estimation error was analyzed across all paddle configurations on level orientation. The impact-based mass flow yield monitor consistently underestimated the mass displaced from the scaled grain wagon. The impact-based mass flow yield monitor estimated the flow rate of grain using regression from the calibration loads. Flow rates evaluated outside of the calibrated range are estimated using extrapolation and subject to error. Extrapolation of flow rates becomes increasingly difficult when a non-linear relationship exists between the yield sensor and flow rate. The dramatic drop-off of estimation accuracy for flow rates outside of the calibrated range suggested a non-linear relationship existed for the impact-based mass flow sensor, which places higher priority in maintaining a calibration suitable to the current harvesting environment. Non-linearity of impact-based yield sensors across a wide flow range has been well-documented by previous research. The impact-based mass flow yield monitor performance declined as flow rate decreased, with a low of -100% error. Presentation quality of grain to the mass flow sensor is drastically reduced at lower flow rates, making it difficult to record grain impulses. Calibration was difficult and time consuming at lower flow rates due to diminished sensor response. Calibration loads were often rejected after target load size had been reached due to estimated accumulated mass not measuring within the manufacturer tolerance range.

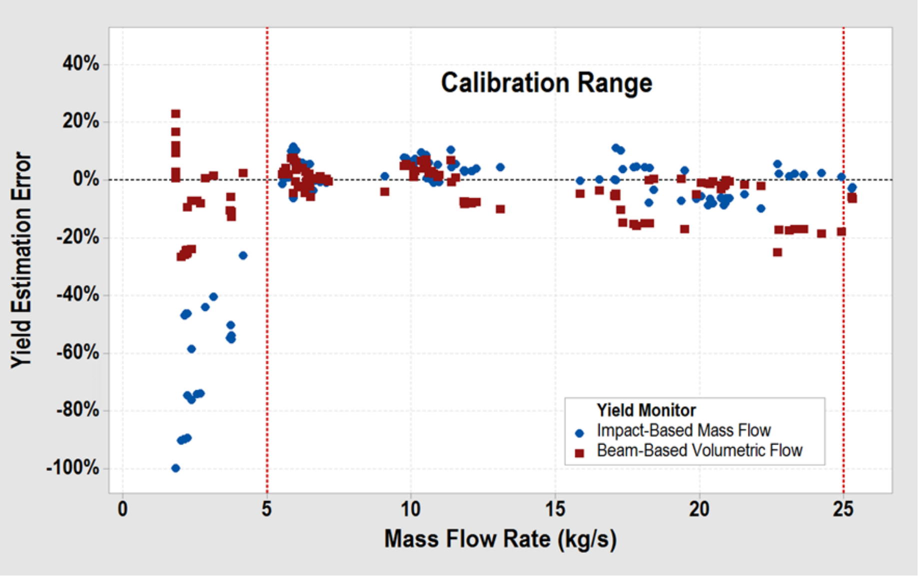

Figure 8: Yield monitor accuracy for flow rates outside of calibration range

The volumetric flow yield monitor performance diminished as uncalibrated flow rates were introduced, although not as significantly as the impact-based mass flow yield monitor. The volumetric flow yield monitor used regression of calibration loads to estimate flow rate, however it also utilized fundamental measurement principles. The beam-based volumetric sensor estimated the volume of grain on a paddle using the beam break time, paddle dimensions, and clean grain elevator speed. A basic yield estimation equation was formed and regression used to correct for bias error, moisture, and grain quality. This translated to decreased mean error for flow rates below the calibrated range compared to the impact-based mass flow yield monitor. The increased variability of positive and negative estimation error came from different paddle configurations. As different paddle configurations were evaluated, accuracy at lower flow rates reflected the presentation quality of grain to the beam-based volumetric sensor and echoed the necessity for consistent grain presentation from the paddle.

Conclusion

The accuracy and variability of two commercial yield monitors that utilize different measurement principles were evaluated using a combine test stand. Accumulated grain weights were compared between the systems, as the unprocessed signals were unavailable. The mean error and variability across all flow rates and mean error between flow ranges were used as performance metrics for evaluation.

The impact-based mass flow yield monitor used a mass flow sensor installed at the top of the clean grain elevator to measure impulses as grain is projected from the clean grain elevator paddles. Yield estimation accuracy was reliant upon calibration for the different treatment levels. Clean grain elevator paddle configuration and machine orientation were not statistically significant to yield estimation error. The impact-based mass flow yield monitor performance was found to have higher variability across all flow ranges during testing. Average variability was 5% for flow rates expected of large grains. Performance was dramatically reduced for flow rates typical of small grains and flow rates that were outside of the calibrated range. Absolute errors ranging from 30% to 100% were observed for flow rates less than 5 kg s-1. Improper calibration and load rejection were common for low flow rates. Poor performance at low flow rates was caused by the diminished sensor response and inability to measure small grain impulses. Reliance solely on regression of calibration loads allows for error influence for crop conditions that are beyond the scope of the most recent calibration. The impact-based mass flow yield monitor performed well when the system experienced conditions for which it was calibrated for, but accuracy deteriorated when evaluation stepped outside of those conditions. In a sensing environment where crop conditions vary continuously, there is a calibration paradox for the most widely used yield monitoring system.

The volumetric flow yield monitor used a beam-based volumetric flow sensor installed on the side of the clean grain elevator to measure grain fill height per paddle. Volumetric grain flow rate was determined using a fundamental equation with inputs of paddle dimension, fill height, and clean grain elevator speed. Grain test weight was used for conversion between accumulated grain volume and mass and was controlled in the test stand using consistent bulk grain. Both clean grain elevator paddle configuration and machine orientation were found to be statistically significant to yield estimation error. Cupped, misshaped paddles had mean estimation error of 9% and mean standard deviation of 8%. All other data sets featuring flat, consistent paddles had a mean estimation error of 0.2% and mean standard deviation of 4%. Yield estimation performance for level, rolled, and pitched machine orientations were found to be statistically different from each other. Absolute mean error for each of the orientations was 0.2%, 11%, and 7%, respectively with a standard deviation of 2%.

Influence of paddle configuration and machine orientation on yield estimation accuracy highlighted the sensitivity of grain presentation to beam-based volumetric sensors. Grain shifting, exceptionally low flow rates, and non-level piling in the clean grain elevator created a difficult sensing environment. The volumetric flow yield monitor was more accurate than the impact-based mass flow yield monitor at flow rates typical of small grains and conditions not covered by calibration. The use of the fundamental measurement method and equation allows for less dependency on calibration, but is still required to correct for crop and machine specific parameters.

Each yield monitoring system exemplified qualities that are ideal for maintenance of yield estimation accuracy. Compliance across machine parameters and crop conditions, reduced variability between flow ranges, and the move towards a fundamental measurement method of yield estimation will allow for increased performance for a larger crop matrix. Although the impact-based mass flow rate was less susceptible to errors induced by paddle type and machine orientation than the volumetric flow yield monitor, it was subject to more inherit error across the flow rate range. Random error and variability across flow rate ranges reinforces the need for regular re-calibration of the sensor, which adds inefficiency during harvest. Additionally, the estimation error skyrocketed when flow rates outside of the calibrated range and less than 5 kg s-1 were experienced. This becomes a problem with field exposure where conditions cannot be controlled. Small grains such as wheat, soybean, canola, and barley regularly contain flow rates within this area of concern. The volumetric flow yield monitor was more susceptible to error induced from changes of the machine rather than inherit error, giving it an advantage if design changes can be made to control those aspects. Design control of the presentation characteristics of grain to the sensor and inherit linearity in sensor response allow potential for predictability of sensor performance in different crop environments. The next generation of yield monitoring technology has the potential for wide market adoption through increased accuracy, less calibration dependency, and maintenance of performance.

References

Blackmore, S., & Moore, M. (1999). Remedial correction of yield map data. *Precision Agriculture*, 53-66.

Burks, T. F., Shearer, S. A., Fulton, J. P., & Sobolik, C. J. (2004). Effects of Time-Varying Inflow Rates on Combine Yield Monitor Accuracy. *Applied Engineering in Agriculture*, 269-275.

Deere & Company. (2013, December). *S-Series Combine Calibration Guide.* Retrieved from Sloan Implement Company: http://www.sloans.com/wp-content/uploads/2013/12/S-Series-Calibration-Guide3.pdf

Fulton, J. P., Sobolik, C. J., Shearer, S. A., Higgins, S. F., & Burks, T. F. (2009). Grain yield monitor flow sensor accuracy for simulated varying field slopes. *Applied Engineering in Agriculture*, 15-21.

Grisso, R. D., Jasa, P. J., Schroeder, M. A., & Wilcox, J. C. (2002). Yield Monitor Accuracy: Successful Farming Magazine Case Study. *Applied Engineering in Agriculture*, 147-151.

McNaull, R. P. (2016). Development of a real-time algorithm for automation of the grain yield monitor calibration. *PhD diss*. Ames, IA: Iowa State University, Department of Agricultural and Biosystems Engineering.

Risius, N. W. (2014). Analysis of a combine grain yield monitoring. *MS thesis*. Ames, IA: Iowa State University, Department of Agricultural and Biosystems Engineering.

Shearer, S. A., Fulton, J. P., McNeill, S. G., Higgins, S. F., & Mueller, T. G. (1999). Elements of Precision Agriculture: Basics of Yield Monitor Installation and Operation. *University of Kentucky Coopertive Extension Service*.