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Advanced bale weighing with integrated mass yield system for large square balers

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Advanced bale weighing with integrated mass yield system for large square balers

by

Jeffrey Clark Askey

A dissertation submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Major: Agricultural and Biological Engineering

Program of Study Committee:
Matthew J. Darr, Major Professor
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Phillip Jones
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The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this dissertation. The Graduate College will ensure this dissertation is globally accessible and will not permit alterations after a degree is conferred.

Iowa State University
Ames, Iowa
2018

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ABSTRACT

This research was focused on development of a large square baler mass measurement system. The mass measurement system was designed to provide estimations of mass yield, mass flow, individual flake weights, and bale weights. The developed mass measurement system was evaluated at the same level as the measured ground truth which was defined to be on a bale basis. The mass measurement system utilized experimental force measuring sensors located in the pre-compression chamber to capture the forces associated with crop mass in the pre-compression chamber. Force information coupled with production baler sensor information and geographical information were combined to create estimation of mass flow and mass yield. The developed mass measurement system was evaluated against production scale systems. The performance of the developed mass measurement system was not significantly different at a 95% confidence level when compared to current production bale scale systems and successfully demonstrated mass yield estimations.

Note: Information that is sensitive in nature or proprietary as deemed by the research sponsors has been removed from this dissertation and not released publically.
CHAPTER 1. INTRODUCTION AND REVIEW OF LITERATURE

Precision agriculture has become the focus of improving agriculture practices in order to maximize crop potentials while efficiently and effectively controlling input decisions. Decisions such as fertilizer application, irrigation rate and timing, crop type, and harvest frequencies can be driven from well-informed feedback of current and previous crop yields. On-board yield monitor systems have commonly been utilized in grain, cotton and many other applications to provide real-time and post-harvest feedback on crop yield for a particular crop and harvest. Grain yield monitors have become more common since the first introduction of yield monitoring in the early 1990’s. In 1997, the adoption rate for yield monitors in corn was approximately 17.3%, and by 2010, the adoption rate grew to 61.4% (Hopkins, 2017). By 2016 the adoption rate of yield monitoring systems grew to 63% (Lawton, 2016).

As global population continues to grow there is a continued need to reduce the crop yield gap. A yield gap is described as the difference between what yield is produced and the maximum potential yield a given crop can achieve under perfect conditions. It has been estimated that crops achieve 20% to 80% of their full potential (Lobell, 2009). In order to understand yield gaps of crops, tools and techniques for benchmarking current crop yields need to be developed and made readily available to the agriculture community.

1.1. Yield Estimations

1.1.1. Field Level Yield

Field level yield estimations are common for most crops. After crops are harvested, they are usually weighed when delivered for sale or processing. In order to calculate a field basis yield, total weight of harvested crop and field area are needed (Equation 1.1). This is typically
accomplished by summing various load weights taken from a field with tractor-trailers or grain carts.

\[
Field \ Yield \left(\frac{mt}{ha}\right) = \frac{Field \ Total \ Crop \ Weight \ (mt)}{Field \ Total \ Area \ (ha)} \quad (1.1)
\]

While the above method for average field yield can be utilized for large square bales, oftentimes bales are delivered to locations lacking large truck scales, including on farm for feeding of livestock. A common method for estimating hay and forage yield is to estimate average bale weight. This is achieved by weighing a subset of a field’s bales, or by weighing all bales with a rear tail-board scale system that is mounted to a baler. Total field size is typically known or can be easily found with many widely available geographical information tools, such as Ag Leader’s SMS (Ag Leader Technology, Ames IA). Bale counts for a field are also needed if an average bale weight is utilized rather than total produced mass. Using average bale weight, field size and field bale count, mean field yield can be calculated (Equation 1.2). If a subset of bales are utilized, a randomly distributed sample should be obtained from the field to capture an average bale weight.

\[
Field \ Yield \left(\frac{mt}{ha}\right) = \frac{(Bales) \ \text{Field}}{Field \ Area (ha)} \times AverageBaleWeight (mt) \quad (1.2)
\]

1.1.2. Yield Monitor Systems

Real-time monitoring systems on agricultural harvesters estimate yield based upon several other key calculations. Yield is reported as a mass over a specific area (Equation 1.3). The mass component of yield is estimated by mass-flow sensors, which measure a flow rate or the mass of material over a specific time period. The area portion of yield can be estimated from vehicle forward speed, typically measured by GPS (Global Positioning System) or radar. Speed
is coupled with a working width to get a unit of area over time. At specific time instances yield is calculated, commonly at 1 Hz. GPS coordinates are also captured to map yield.

\[
\text{WetMassYield (} \frac{\text{mt}}{\text{ha}} \text{)} = \left( \frac{\text{WetMassFlow (} \frac{\text{kg}}{\text{s}} \text{)}}{\text{VehicleSpeed (} \frac{\text{km}}{\text{hr}} \text{)} * \text{WorkingWidth (m)}} \right) * 36 \quad (1.3)
\]

Several components are needed in order to develop a mass-yield system. These include a GPS receiver, mass-flow sensors, an ECU (Electronic Control Unit) to process and integrate sensor signals, and typically a display to relay information to the operator (Figure 1.1). GPS information such as Latitude, Longitude, and Vehicle Speed are broadcasted from the GPS receiver on a CAN-bus (Controller Area Network) at common rates of 1 Hz or 5 Hz. Signals broadcasted are based upon a standard message definition defined by SAE J1939 standards (SAE International, Warrendale PA). An ECU which resides on the machine, is connected to a network capable of receiving the GPS signals as well as signals from the mass-flow sensors. The ECU uses data from mass-flow sensors and GPS signals to estimate mass-yield. Estimated mass-yield is then broadcasted on CAN to a display, which displays yield and/or stores the yield data for post-harvest analysis.

![Cotton mass-yield system diagram](image)

**Figure 1.1:** Cotton mass-yield system is comprised of mass-flow sensors, GPS receiver, ECU, and monitor for display and storage of information
In late 1990’s, several commercial yield monitoring systems were available for cotton harvesters. Cotton mass-yield sensors utilize microwave technology to detect the flow of cotton through ducting (Figure 1.2). Adoption rates of cotton yield systems were slow. In 2000, adoption rates were 1.2%. By 2007, rates increased to 4.7% (Hopkins, 2017).

![Figure 1.2: Mass-flow sensors installed on a Cotton Picker (Deere, 2010)](image)

The most common method of measuring mass flow/yield on grain platforms utilizes a single impact plate in the clean grain elevator. This sensor measures the impact force of grain as the grain is projected from elevator paddles (Figure 1.3, Grisso et. al, 2002).

![Figure 1.3: Grain mass-flow impact sensor measures forces due to grain impact (Grisso et. al, 2002)](image)

Several mass flow and mass yield sensing studies have been completed for hay and forage crops on mower conditioners, round balers, and large square balers. Infrared and ultrasonic sensors were tested on a mower to estimate wet mass flow by measuring crop height
directly before cutting. Absolute errors ranged from approximately 7.5% to 18% in various crops when two sensors were utilized (Ramsey, 2015). Ramsey concluded that infrared and ultrasonic sensors were not statistically different in terms of accuracy of performance; however, functionally ultrasonic sensors were more reliable and less susceptible to crop conditions. Ramsey also concluded that calibrations for a mass flow system such as this would be challenging on a mower as there are other steps after the hay has been mowed and direct mass calibrations would be difficult to achieve. Ultrasonic sensors have also been researched to measure windrow height to calculate a volumetric flow rate and correlate to a mass-flow rate on a round baler. A study completed in 2015 from two different fields with a total of 41 round bales showed yield estimation errors around 10% (Ramsey, 2015).

1.1.3. Large Square Baler Yield Systems

Mass yield and mass flow systems that are integrated into large square balers are capable of estimating real-time information by utilizing volumetric measurements. Specifically, this concept captures the rate at which bales grow. Star wheels with digital encoders are placed on bale chamber walls with star fingers protruding into the crop, the star wheel rotates as crop moves through the bale chamber (Figure 1.4).

![Figure 1.4: Top and side view of a bale with star-wheels for measuring bale growth rate](image-url)
Bale growth is coupled with bale width and height to capture a volume. Recording bale growth over time allows for estimation of volumetric flow rate. A study completed in alfalfa (26 bales) and straw (57 bales), utilized star wheel mass-flow measurements found correlations of 88-96% to measured ground truth mass-flow (Shinners et. al, 2000). Volumetric-yield was estimated from the volumetric-flow, time and area where material was collected from. Volumetric estimations and average bale weight were used to estimate mass-flow and mass-yield.

A commercial solution is currently offered by Harvest Tec with the HayBoss G2. Which utilizes a volumetric estimation of mass flow and mass yield, similar to Shinners research (Harvest Tec, Hudson WI). The system is comprised of several sensors that measure bale moisture and displacement. An operator must enter an average bale weight, bale length, and swath width in the setup page. On some models, the baler is equipped with a tail-board bale scale which produces updated bale weights to correct the average bale weight.

1.1.4. Crop Moisture

Moisture is important when analyzing yield information across varying crop conditions. Wet mass measurements of a crop are directly affected by the moisture content within that crop. Most often, mass yield systems are coupled with moisture systems to accurately equate a dry or standard mass for more accurate data (Equation 1.4). In the United States, corn yield is often reported as bushels per acre, where a bushel is classified as 25.4kgs (56lbs) at 15.5% moisture content.

\[
StandardMass(kg) = \frac{1 - WetBasisMoisture(decimal) \times WetMass(kg)}{1 - StandardMoisture(decimal)} \tag{1.4}
\]

In crops such as alfalfa where moisture can range from 5% up to 80%, mass yields can be greatly misinterpreted when comparing cuttings or fields with significantly different moisteres.
For instance, in two fields with wet mass yield of 5 mt/ha, field moistures of 10% and 40%, results in dry mass yields of 4.5 mt/ha and 3.0 mt/ha, respectively.

Moisture measurement systems for hay and forage crops exist and have been widely adopted to measure moisture in real-time on balers. Moisture measurement methods utilize conductance, microwaves, capacitive, and infrared waves. A microwave moisture measuring system in corn stover produced a coefficient of determination ($R^2$) value of 87% in baled crop with moistures between 10-29% (Webster et. al, 2013). In a study completed by Webster, the maximum moisture range for a commercial large square bale microwave sensor was 28.9%.

1.2. Hay and Forage Crop and Machine Operations

In 2017, approximately 21.65 million hectares (53.5 million acres) of hay crop were harvested in the United States for a combined total of 119.7 million metric tons (131.9 million tons) resulting in an average of 5.6 metric tons per hectare (2.5 tons per acre) harvested (USDA, 2017). Hay is the third most harvested crop on an area basis, behind only corn and soybeans at 33.6 million hectares (83.1 million) and 36.2 million hectares (89.5 million), respectively in 2017 (USDA, 2017). Common baled crops are alfalfa, grasses, grain-straw, and corn stover.

Several operations typically precede baling, which can vary depending on crop and customer preference. In a crop such as alfalfa, the standing crop may be cut with machines ranging from sickle mowers to self-propelled disc mowers. The crop is left in field for a duration of time that ranges from a few hours to a few days until a desired moisture content is achieved by natural drying. A second operation involves windrowing the material into rows for the baler with equipment referred to as a rake or merger. Windrowing helps to increase baling efficiencies by providing more material to the baler in a single pass (Figure 1.5).
Crops such as straw and corn stover are residual products that result after a combine has harvested the grain. Residue is commonly spread back on the field and then merged into windrows using a rake or combination shredder-windrower. The windrowed material is then baled, and the bales are moved from field to storage locations (Figure 1.6).
1.3. Large Square Baler Operation and Components

Large square balers are common among commercial and large farms, and provide a method of densifying bulky material into manageable packages. Large square balers have common bale chamber size width and height of 90x90cm, 120x90cm, and 120x120cm, however other sizes do exist. Bale lengths vary based on customer preference, but most balers are capable of producing bales between 60cm and 300cm (Figure 1.7).

![Figure 1.7: Common commercial baler, bale dimensions (120x90cm)](image)

Commercial large square balers consist of seven main machine functions which include: pickup, pre-compression chamber, bale chamber, plunger, tension panels, knotter and needles, and tail-board (Figure 1.8). A baler pickup is the first system to come in contact with the material and provides a means of lifting the crop from the ground into the baler. The pickup consists of several rows of pickup teeth, which rotate about a central axis, the pickup teeth bring material upwards to the top of the pickup at which point crop interacts with augers and pack-fingers or rotors which help transition crop into a pre-compression chamber. A rotor system may also consist of knives to provide cutting of the crop as the crop moves through the rotor system, the knives are commonly engaged in higher moisture crop.
The pre-compression chamber, is a chamber which provides collection of crop material to build uniform flakes and holds material until a set timing is triggered. During the collection of material, material is pre-compressed by means of fingers or forks which pack material into the chamber, this is commonly referred to as a pack-cycle. At set timing instances if the pre-compression chamber is full, a stuff-cycle occurs where material is lifted from the pre-compression chamber into the bale chamber, at this point the material being lifted into the bale chamber is commonly referred to as a flake. A stuff-cycle is timed with the plunger position so that when the plunger is retracted an opening in the bale chamber floor allows the material to enter the bale-chamber.

The bale-chamber is where a bale is built and additional densification takes place, a bale consists of several flakes that are compressed together and securely packaged by means of twine. The bale chamber houses the plunger and tension panels which control and monitor machine loading as well as provide density. The plunger system in a baler is comprised of similar components to a piston in an engine, where the plunger is connected to a set of connecting rods which connect to a crank arm. The crank arm is rotated in a circular motion by a gearbox, the
gear box is driven through the power take off (PTO). The plunger travels down the bale-chamber and back, when the plunger is completely retracted this is commonly called “home-position” (0 degrees), when the plunger is fully extended the plunger is at end of stroke (180 degrees). As the plunger nears end of stroke coming into contact with new crop, crop is compressed between the plunger and existing material in the bale-chamber. Tension panels are controlled by hydraulic cylinders which exert force between the baler frame and tension panels. Tension panels are in contact with the sides and top of the bale. A normal force is exerted on the bale to increase effects of force due to friction and to resist bale movement out of the bale chamber (Equation 1.5). The bale will begin to move outwards once force due to friction is overcome by force being exerted through the plunger.

\[ F_p > (F_s = \mu_s N) \]  

(1.5)

Where:
\[ F_p = \text{Plunger force} \]
\[ F_s = \text{Static friction force} \]
\[ \mu_s = \text{Static coefficient of friction} \]
\[ N = \text{Normal force} \]

Once enough flakes have been compressed together in the bale-chamber and the bale length has reached the desired set length, a set of needles under the baler trip and carry twine from the bottom of the bale up to the top of the baler where the knotters are located. Twine carried by needles is tied together with a twine that runs along the top of the bale in a double over hand knot. Knotters tie two knots in a row, the first knot finishes off the bale just formed and the second knot provides the starting twine for the next bale to be formed. While some balers do have single knotting systems, a double knotter system is common among large-square balers to eliminate the need for knotters to hold an open-end of twine during bale formation. Most commercial large-square balers have six strands of twine which bind the bales together along the length of the bale, however eight strands of twine also exist in some baler models.
As bales are formed in the bale-chamber and move backwards toward the end of the bale-chamber the bales reach a tail-board. Tail-boards provide a system which allow a bale to transition to the ground, twine surrounding a bale is under tension to contain compressed material. If a bale is handled roughly or twine is damaged it can cause twine to break. Once bales are on the ground, stackers or loaders are utilized to collect bales in-field and transport them to tractor-trailers for hauling or to storage locations nearby until bales are needed for feed.

### 1.4. Large Square Baler - Bale Weighing Technology

Accuracy of bale weights calculated real-time on balers is crucial if the average bale weight or total bale weights will be utilized to calculate field mass totals and yields. As bales are produced the bale weights are captured and then average bale weight is updated to more recent information in order to better estimate average bale weight and total mass harvested. The most common method for capturing bale weight is by mounting two differential beam load cells between the bale chamber and rear tailboard (Figure 1.9). Other market solutions install beam load cells between the tailboard and a sub-frame on the tailboard which typically measure 4 points of force.

![Figure 1.9: Large-square baler tail board and baling weighing system, tail board pivots near load cell and is held at an angle by chain or straps (dashed line)](image)

Very little data is available which benchmarks the production bale weighing system on baler tailboards. Bale weight average field level errors of 1-3% have been documented with
commercial available systems operating in corn stover (Webster et. al, 2013). A study of 255 bales, ranging from 200 kgs to 500 kgs, showed a mean error of 2.68% and a 1-sigma of 3.28%, with 86% of the bales having error of less than ± 5% (Maguire et. al, 2007). Maguire’s approach utilized transducers at bale tailboard pivot location along with transducers in bale tailboard chains measuring tension forces.

1.5. Objectives of Research

Yield-systems have become increasingly important to understand and reduce the yield gap of crops. Farm manager’s desire yield feedback to make informed decisions to produce high yielding crops throughout a field and is evident among the adoption rate of current yield technology systems. Large square baler yield systems are fairly new to the agricultural community compared to grain yield systems, and very few solutions currently exist which provide yield estimations on large square balers. Current yield systems for large square balers are based on volumetric flow-rates which assume consistent density within a bale as well as bale to bale. Further research is needed to develop and define mass flow and mass yield through a large square baler which de-couples the reliance on constant density with volumetric flow estimations.

Hay production by area is the third largest crop, however very little commercial systems exist to estimate yield. The key objective of this research was to develop, analyze and verify a mass-yield monitoring system for large square balers, which are common among commercial hay producers. Yield monitoring on balers presents many challenges due to the unique dynamics, crop conditions and baling methodology. Current production bale yield systems which measure volumetric flow estimations assume consistent density throughout a bale. This research defines key parameters needed to estimate mass yield and evaluates the approach. The following objectives are required to accomplish the main objective of this research:
1. Analyze key machine parameters along with the responses of dedicated mass force sensors used to estimate flake weight, mass flow and mass yield at a flake resolution.

2. Evaluate the performance of flake weight estimation and bale weight estimation with integrated mass yield and mass flow system for large square balers.

1.6. Dissertation Organization

This dissertation consists of four unique chapters. Chapter 1 provides an overall introduction and review of literature for mass yield monitoring systems. Yield monitor systems and bale weighing technology for large-square balers is discussed. Baler components and operation are discussed to provide detailed functionality and interaction of complex subsystems.

Chapter 2 of this dissertation discusses research associated with the first objective of analyzing key signals and developing a model algorithm around those signals to produce estimation parameters. This chapter outlines estimation parameters of interest to estimate flake weight, theory of the algorithm and preliminary results.

Chapter 3 of this dissertation discusses research associated with the second objective of evaluating the performance of the developed mass yield system for large square balers. Chapter 3 builds upon Chapter 2 in an effort to further evaluate and verify the developed system.

The fourth and final chapter provides a summary of the key findings of this dissertation research. Future research opportunities are discussed along with knowledge gaps of the integrated mass-yield system for large square balers.
1.7. References


Deere. 2014. New John Deere Large Square Balers. Screenshot taken at time 0:10. https://www.youtube.com/watch?v=F1AQ41vpBVA


Ramsey, H. 2015. Development and implementation of hay yield monitoring technology. MS thesis. Clemson University, Plan and Environmental Sciences, Clemson (South Carolina)


CHAPTER 2. DEVELOPMENT OF ADVANCED BALE WEIGHING SYSTEM WITH INTEGRATED MASS YIELD

2.1. Introduction

Typical production yield monitoring systems utilize only one sensor to estimate incoming flow of material. Some systems such as the Cotton mass-flow sensors, utilize multiple sensors of the same type across different incoming flow paths, but the estimation of mass-flow is restricted to one sensor technology. A machine virtual sensing system was developed to estimate mass flow and yield through a large square baler utilizing a combination of sensors to quantify key algorithm estimation parameters and the current state of the baler. The algorithm developed was based on field collected data from two balers over a 1-year period in 2015 baling alfalfa and grass mix. The integrated algorithm was designed to calibrate for sensor and machine discrepancies to improve the robustness of the approach.

This research direction was slightly different compared to prior approaches. Specifically, the system under development was a direct mass algorithm calculation rather than a volumetric calculation that is converted to mass through a density transfer function. The developed system calculates mass yield on an individual flake basis at the most forward point where the baler first engages with the crop. Through the direct measurement of force exerted by lifting the crop into the bale chamber, the dependency on bale density with volumetric flow measurements no longer existed. This approach was also designed to capture forces within the baler and was less susceptible to outside interference and variability, such as vehicle pitch, roll, or acceleration. This approach brings together several on-board sensors that have direct contact with crop to build robustness and accuracy across a variety of crop conditions.

System performance targets were based on previous studies of bale weight scale technology for large square balers along with research of volumetric flow measurements.
Technology utilizing load cells on the rear tailboard to obtain bale weights have been demonstrated with 86% of bales (n = 255) having error of ± 5%, with bale weights ranging from 200 kgs to 500 kgs (Maguire et. al, 2007). Volumetric flow rate technology has previously been demonstrated with correlations between 88-96% (Shinners et. al, 2000).

2.2. Materials and Methods

2.2.1. Feed System Components

Baler feed system comprise of various components and functions which transitions the crop from loose material into compressed material. Components of the feed-system include: pre-compression chamber, feeder forks, locking mechanism, tripping mechanism and various drive system components (Figure 2.1). The pre-compression chamber is a curved rectangular structure which houses crop material and provides a transition from the pickup system into the bale chamber.

Figure 2.1: Screenshot of John Deere's large-square baler feed-system with major components called out, feeder forks rotate counter-clockwise in orientation above (Deere, 2014)
On the bottom side of the pre-compression chamber a drop door, or commonly referred to as “feed pan”, is secured in place with pins during normal baling conditions, however in the event of a plugged pre-compression chamber the feed pan can be un-pinned and rotated down for clean-out. Feeder forks provide a mechanical means of moving crop from the lower pre-compression chamber to the upper pre-compression chamber, these forks rotate about an elliptical path inside and out of the pre-compression chamber. The path of forks are dictated by a locking mechanism being locked or unlocked, which is controlled by a triggering mechanism. In the locked state the rocker arm is restricted backwards by a mechanical latch, which allows the feeder forks to travel along a longer elliptical path (stuff cycle). During a stuff cycle, shown on Figure 2.1, point A is latched backwards by the locking mechanism. Upon rotation this causes point C to de-couple and feeder forks rotation to occur at point B. In the unlocked state the rocker arm is free to swing back and forth as the crank-arm rotates the feeder forks, resulting in a smaller elliptical path (pack cycle). During the pack-cycle rotation occurs at point A while point C is coupled and the feeder forks don’t rotate about point B.

The mechanical trip system is comprised of pressure sensing plates, linkage cable, and a latch, once enough material is added to the pre-compression chamber, sensing plates are pushed out of the pre-compression chamber which pulls a cable and activates a latch to catch the rocker arm (locking mechanism). The locking mechanism is on a roller-cam design, which allows proper timing of a stuff-cycle to occur avoiding interference with the plunger components. The mechanical driven component is the feeder crank arm which is driven from a gear-box and provides power to rotate the feeder forks (Figure 2.2).
Figure 2.2: Screenshot of John Deere’s feed system with drive and motion components, power is provided to the crank arm and the rockshaft arm is free to rotate if not locked (John Deere, 2014)

Forces exerted due to crop can be broken down into four main force components. Force due to mass of the crop (weight), force exerted on the crop for compression and lifting, force normal to the pre-compression walls, and the reaction force from friction (Figure 2.3). Normal force is exerted on the pre-compression walls, floor and top which is 90-degrees or perpendicular to the wall. The normal force is comprised of two components, the first component is exerted due to the weight of the crop while the second force is due to the compression of the crop. The crop when compressed can be thought of as a complex spring and damper system, as crop is compressed and packed into the pre-compression chamber the material is pushing outwards resisting deformation, which results in a normal force exerted outwards. A frictional force resists movement and is exerted on the pre-compression frame. The frictional force is a result of the normal force exerted on the pre-compression and the coefficient of friction. The lift force is comprised of the force to overcome frictional forces and crop mass force.
As compressed material is lifted into the bale chamber, these forces and their interactions change. In the initial stages of lifting where the flake is lower in the pre-compression chamber, the normal force is comprised of the mass force as well as the force to resist compression. As crop is lifted upwards the force magnitude and vectors change. The normal force exerted on the pre-compression walls is reduced and becomes a reaction force of the compressed material and less from the crop mass. The crop weight force is exerted more directly on the feeder forks as the forks approach the top of the pre-compression chamber.

Solving for the force produced by the crop mass, provides the needed metric for estimating the flake mass. The frictional coefficient during the compression and lifting of the crop is unknown. The force generated to lift and compress the crop can be captured by instrumenting feed system components. The normal force can be captured by measuring crop pressure exerted on areas of the pre-compression chamber wall.
Sensors were also installed on the bottom feed pan drop floor to capture normal forces of the crop as material was packed into the pre-compression chamber and then lifted into the bale chamber.

The feed pan sensor response was expected to increase as the feeder forks compressed material into the pre-compression chamber. When the forks were not in contact with the crop the force measured was expected to be representative of the crop in the pre-compression chamber. The feed pan sensor was expected to have a stair-step response, when no crop is in the chamber the sensor is near zero. Upon the first pack-cycle the response would be at some value higher than that of zero, and each additional pack-cycle would continue to increase sensor response until a stuff cycle occurred. After a stuff cycle event the sensor was expected to return to the original empty reading.

2.2.2. Plunger Load and Tension Panel Pressure

Measuring and monitoring plunger load and tension panel pressure is common on large square balers. The combination of load pins and pressure sensors along with a control system manages bale densification resulting in varying bale weights. The system is self-controlled with a feedback loop to limit the plunger load within design constraints. Two main control systems exist to control bale density, pressure control and plunger load control.

In pressure control mode tension panel hydraulic pressure is set to a constant pressure by an operator and the system attempts to maintain the set pressure allowing for plunger load to fluctuate. Plunger load is still monitored in this control system and will automatically adjust pressure if load is too great, which could result in component failure or machine destruction. Manufacturers recommend set point ranges for tension pressure control mode in typical baling conditions. This includes cases such as high moisture silage crops where the pressure is reduced.
compared to drier hay crop or straw where pressure can be even higher than dry hay crops. The second control system used on balers is plunger load based control, which monitors plunger load every plunger stroke. Plunger load is typically defined as 0-100% and is incremented in 1% or 5% points. Plunger load is typically defined as the percentage of load being utilized compared to the maximum load the plunger system is designed for. There is a force measuring sensor on each of the two plunger connecting rods to measure total force exerted during compression of material. If the actual plunger load is different from the operator set point the control system regulates and increases/decreases pressure in the tension panel hydraulic pressure circuit to move plunger load closer to the set-point.

Plunger load can vary due to a number of factors that are related to crop, such as moisture, crop type, and resulting flake thickness. Operators also vary plunger load based on preference and the target market for the baled material. If bales are transported offsite, operators increase plunger load to produce the highest density bales. Adverse effects of increasing plunger load for particular crops can result in twine failure and broken bales.

2.2.3. Feeder Pan Force Sensor

The feed pan on the bottom of the pre-compression chamber was instrumented for analysis. Under normal operating the feed-pan is in direct contact with crop being fed into the pre-compression chamber. Feed pan normal force was measured with two beam load cells near the bottom front of the feed pan. A sensor was mounted on each side, with maximum loading capacity of 2200 Newton’s per load cell (Figure 2.4, Appendix A). The bottom of the feed pan was held in place with a set of pins, which mount through the pre-compression frame and feed pan. These pins were removed once beam load cells were added in order to capture normal
forces exerted on the feed pan as material was fed into the pre-compression chamber by the rotor and moved with the feeder forks.

Figure 2.4: Feed pan force load cell mounted near front of feed pan with feed pan pins removed

A statistical analysis was performed (Appendix B) to compare mean empty chamber force response to force responses when material was moving through the pre-compression chamber. When the pre-compression chamber was empty, and that of when the full chamber occurred, there was not enough evidence to suggest that mean signal response are different at a 95% confidence level.

Prior to baling, signal response was checked and if the sensor response had appeared to become noisy, the cabling and/or sensor was replaced. Any bales that appeared to have significant signal noise or a lack of signal response associated with them, were discarded from this study as the response was not truly representative of the material being baled. This included when the sensor response was flat lined at values of 0, -32768 and 32767 (int16 A/D), typically indicating a completely broken wire. There were also instances where the wire had not completely failed.
One component feature of the feed-system which has not been discussed thus far is the protective drive train clutch on the feeder forks. A clutch that is pre-set from mechanical design constraints trips if loading on the feeder forks becomes overly high in order to protect the system from failure. This event is commonly referred to as a “plug”. A plug is a result of too much crop being compressed into the pre-compression chamber and typically occurs in high moisture crops, corn stalk type materials, non-uniform windrow conditions, or at vehicle speeds too high for the material type being baled. Plugs may or may not be self-cleared. If a small plug occurs the next cycle may free the plug, otherwise material has to be cleared out of the chamber by hand. Due to this any data collected where a plug occurred was discarded from this study.

A plug event was identified in the data by utilizing the production sensors and logic that was displayed which alerts an operator of a plug. Plug events were determined with a magnetic pickup sensor installed on the baler, near the feeder crank arm which triggered when the feeder crank arm passed by.

### 2.2.4. Crop Flow Sensing

To accurately trigger estimation calculations for time and area, a crop flow sensing system was needed. A sensor was installed directly above the baler pickup to monitor incoming crop at the most forward point on the machine and located in the center of the pickup from left to right (Figure 2.5). The sensor was an ultra-sonic barrel type sensor with a sensing range of 100-900 mm. The sensor output voltage spanned from 0.5vdc to 4.5vdc with a linear response (Equation 2.1).
An algorithm was developed to determine whether crop was flowing into the machine based on the ultrasonic sensor information (Appendix C). A user calibration was also developed to allow the system to be calibrated using a two point calibration process. The first calibration point corresponded with the pickup in the completely raised position and the second calibration point was associated with the pickup completely lowered and resting on the gauge wheels. Distance measured increased as the pickup was lowered to the ground.

Crop flow sensing logic reduced error associated with inactive baling on mass flow and yield calculations. The method used provided reasonable and responsive feedback on when crop was actively flowing into the pickup. The typical response below shows where the machine was in-actively baling on headland turns.
The crop flow sensing was demonstrated and verified real-time in varying crop conditions, the system was responsive in both light and heavy windrow conditions as well as different crop throughput capacities.

2.2.5. Area, Time and GPS Estimation

To calculate area and time for mass yield and mass flow, a system was needed to ensure accuracy. Both area and time were calculated at 100 Hz. The last known valid vehicle speed was used to interpolate speed between the 5 Hz speed reported measurements. Vehicle speed based on radar was used to estimate distance traveled. Distance can be calculated from latitude and longitude using the haversine formula but this adds complexity when accounting for hill slopes, and error can also be induced in the estimation when GPS signal is limited or obstructed by structures such as trees or buildings. Time was calculated using the known software execution rate of the prediction model. The execution rate was accumulated at each iteration from the start of the flake to the end of the flake when crop flow was active to define the time when the flake was being produced (Equation 2.2).

\[
FlakeTime(\text{secs}) = \sum_{i=1}^{j} ModelRate(\text{secs})
\]  

(2.2)

The area portion was calculated from a user defined windrow width, vehicle speed and software model call rate (Equation 2.3). Effective windrow width can vary depending on practices performed on the crop prior to baling such as cutting and raking, the overlap that each of those processes had can vary by operator if auto-steering was not utilized and by the configuration of the equipment.

\[
Area(m^2) = WindrowWidth(m) \times \frac{VehicleSpeed(kph)}{3.6} \times ModelRate(\text{secs})
\]  

(2.3)
Both the area and time portion were only estimated when crop flow was active to ensure accuracy, upon a flake increase the accumulation values were saved and then the accumulated variables were reset to begin the estimation for the next flake.

In order to accurately link the mass yield and mass flow to geographical locations incoming latitude and longitude needed to be corrected due to the offset between the GPS receiver and mass flow measuring location on the baler. A distance of 2.6 meters was measured from the GPS globe to tractor hitch pin and a distance of 3.0 meters was measured from the tractor hitch pin to pre-compression chamber entrance for a total offset distance of 5.6 meters.

While latitude and longitude at the baler can be estimated using the haversine formula, the coupling of the tractor and baler through a hitch pin caused conditions where the baler wasn’t directly behind the tractor. Distance traveled for GPS latitude and longitude correction was estimated using vehicle radar based speed (Equation 2.4). Distance, latitude and longitude were saved into a 100 element FIFO (first-in-first-out) buffer as the GPS was received at 5 Hz (0.2 seconds), the distances were summed each iteration to estimate total distance moved. A 100 element buffer was chosen due to the 5 Hz GPS rate, this would allow for 20 seconds of buffered GPS information. This provides adequate data storage when the machine was moving faster than 1.0 kmph, if the machine was moving slower than 1.0 kmph for a duration of 20 seconds the buffer size would not be adequate. Baling speeds are typically higher than 1.0 kmph, however vary depending on crop, ground roughness, and operator preference. To accommodate lower baling speeds, the buffer was only updated if the distance moved was greater than 0.06 meters from the first element in the buffer.

\[ \text{Distance}(m) = \left(\frac{\text{VehicleSpeed}(\text{kph})}{3.6}\right) \times \text{ModelRate}(\text{secs}) \]  

(Equation 2.4)
To estimate the GPS point which the mass yield and flow should be linked with, a simple linear interpolation method was utilized. The latitude and longitude on either side of the 5.6 meter distance offset was utilized for interpolation points. It should be noted that as distance between the latitude and longitude interpolation points grows so does the error, at large distances a haversine formula should be used, however at incremental distances error is minimal.

2.2.6. Estimation of Dependent Variable and Model Theory

The approach used in this dissertation to develop a relationship between several independent variables to the dependent variable flake weight, was developed around bale weight. Actual flake weight ground truth measurements are difficult on a large scale. Flakes once compressed are tightly packed and indistinguishable within certainty from one-another. Bales must also be broken apart in order to weigh on a flake basis. Due to complexity of weighing individual flakes an approach was taken to develop a model for flake weights at a bale level. At bale level methods to measure weight were less intrusive and easier to implement on a large-scale data collection.

2.2.7. Model Logic and Operation

Model development and analysis was completed with Mathworks products Matlab and Simulink (Mathworks Inc., Natick MA). Model-based software development (MBSD) is a common software programming method to develop functional models and produce auto generated code for embedded controllers. MBSD is also easy to troubleshoot with model-in-the-loop (MIL) testing. Various Simulink toolboxes were used including Stateflow to develop state charts for model logic and execution.
2.2.8. Ground Truth Data Collection

Bale weight, length and geographical position was recorded with a 3-point load cell system (Figure 2.6). The load weighing system consisted of three differential beam load cells (Digi-Star PN: 143978), a junction box (Digi-Star PN: 404930), and a GT400 scale head (Digi-Star PN: 405559) (Digi-Star, Fort Atkinson WI). Bale length along with relative bale position right to left on the scale was captured with two ultra-sonic sensors with a range of 100mm to 900mm. Analog signals were read into a computer via an analog-to-USB system (National Instruments, USB-6003, Austin TX). Pitch and roll of the scale was captured utilizing a dual-axis tilt sensor (Level Developments, PN: LCH-45, Chicago IL). A Garmin GPS WAAS receiver was utilized to capture location of the weighing tractor at 5 Hz (Garmin International Inc., Olathe KS). Bales were picked up by orienting bale-spears in the middle of the bale, and then driving forward into the bale. Once the spears were as far into the bale as possible and the bale was against the back frame stop, the bale was then picked up off the ground. Having the bale completely back against the frame, helped reduce bale sagging and provided a repeatable measurement procedure.

![Figure 2.6: Bale Weighing Tractor and Equipment Used](image-url)
A computer graphical user interface (GUI) was developed for the operator to interact with the system such as recording information and calibrating, as well as monitoring data. The interface consisted of several key components, a bale table, geo-spatial map, selected bale number, bale weight, bale length, bale position left-hand, bale position right-hand, pitch, and roll. A geospatial map allowed for a 2-dimensional representation of position for each bale produced along with current position of the weighing tractor (Figure 2.7). White-dots represented bales that had yet to be weighed, red-squares represented bales that had already been weighed, a single green-square represented the weighing tractor and blue lines represented the baler’s path. Baler data files were uploaded to the weighing system after baling was completed, containing the following information:

- Bale drop location (Latitude & Longitude)
- Bale drop date and time
- Bale drop number
- Machine
- Machine path (machine location recorded at 1 Hz)

Figure 2.7: Map produced to track bales when dropped in field, white dots are bales not weighed, red boxes are bales weighed, green box is current weighing tractor position, blue line is baler path

All bales prior to weighing were displayed in a bale table which changed as the distance to bales from the weighing tractor changed (Table 2.1). The table consisted of the machine name
which the bale belongs to, machine bale number, and distance to the bale. Bales were displayed in order of distance to the bale, the bale with the least amount of distance was displayed first and defaulted as the selected bale.

Table 2.1: Example of displayed bale table

<table>
<thead>
<tr>
<th>Machine Bale Number</th>
<th>Distance (m)</th>
<th>Machine</th>
</tr>
</thead>
<tbody>
<tr>
<td>10001</td>
<td>10.0</td>
<td>Machine - A</td>
</tr>
<tr>
<td>10002</td>
<td>30.6</td>
<td>Machine - A</td>
</tr>
<tr>
<td>5001</td>
<td>40.1</td>
<td>Machine - B</td>
</tr>
</tbody>
</table>

Once a bale was selected and picked up with the weighing system, the operator waits for the measured weight to stabilize. Once the weight had not changed by 0.5 kgs the weight was recorded if the pitch and roll were within ± 5 degrees of level (0 degrees). If pitch and roll were outside of ± 5 degrees, the operator adjusted pitch and roll by leveling the front 3-point hydraulically or by driving to level ground. Bale data was saved to a file where it could be accessed later for analysis, containing the following information:

- Bale weigh location (Latitude & Longitude)
- Bale weigh date and time
- Bale number
- Machine
- Pitch (degrees)
- Roll (degrees)
- Measured bale length (mm)
- Bale center left to right in relation to bale scale (mm)

In order to maintain scale accuracy throughout the harvesting season, calibration weights were built to calibrate the system on a daily basis prior to weighing bales for a study (Figure 2.8). The calibration weights were built with a steel-frame and 15 tractor suitcase weights weighing approximately 45 kgs. Once the calibration weights were built, painted, and assembled the calibration weight were then weighed on a certified calibration scale to determine the overall
In total four calibration weights were built with overall weights of 723.0 kgs, 726.5 kgs, 727.5 kgs, and 728.0 kgs.

![Figure 2.8: Calibration weight utilized to calibrate the weighing system 723.0 kgs (1594lbs)](image)

### 2.2.8.1. Ground Truth Weight Accuracy Evaluation

Scale repeatability was investigated to understand the error associated with calibration of scales and error associated with measuring a bale. A calibration weight was utilized to understand the error associated with calibration of the system, by weighing the same weight (726.5 kg) 10 times with each scale unit. The calibration weight was lowered to the ground after each measurement so that the weight was not in contact with the scale spears. The scales combined had a mean error of 0.11% with a standard deviation of 0.35% (Table 2.2).

<table>
<thead>
<tr>
<th>Scale</th>
<th>Error % Mean</th>
<th>Error % Standard Deviation</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.06</td>
<td>0.11</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>-0.34</td>
<td>0.40</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>-0.38</td>
<td>0.26</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>0.21</td>
<td>0.14</td>
<td>10</td>
</tr>
</tbody>
</table>

A similar study was done to capture the error associated with weighing a bale. A bale weighing 449.0 kgs was utilized in this testing and was weighed 10 times. After each measurement the bale was lowered back to the ground and the spears were backed out of the
bale. Total mean error for all four scales was 0.15% with a standard deviation of 1.75% (Table 2.3). The standard deviation was higher when weighing a bale compared to that of calibration. The increase in standard deviation was assumed to be caused by compression loading of the load cells during the process of the forks inserting the bale. The load cells were bolted in weldments, which allowed for load cells to be replaced upon failure. Tolerances in the mounting of the load cell could cause the point of action for the moment to slightly shift. Additional variability is likely also caused due to the bale not being lifted in the exact same manner each iteration. During calibration, the calibration weight was the only force exerted on the spears which was perpendicular to the spears, minimal force was exerted about the axis of the spear.

Table 2.3: Scale calibration error mean and standard deviation for a 449.0kg bale

<table>
<thead>
<tr>
<th>Scale</th>
<th>Error % Mean</th>
<th>Error % Standard Deviation</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-2.23</td>
<td>0.74</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>1.45</td>
<td>0.20</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>1.46</td>
<td>1.61</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>-0.08</td>
<td>0.12</td>
<td>10</td>
</tr>
</tbody>
</table>

Effects of scale accuracy due to varying bale orientation, pitch, and roll was investigated to understand the impact on ground truth measurements. A 589.5 kg bale was utilized to study effects of the bale not being centered left-to-right on the scale system. The bale was picked up in varying locations with an offset from the center ranging from -300mm to 300mm with 0mm being center. The error approached 1.0% when the bale was measured 200mm on either side of center. Data captured showed that 76% of bales had an offset from center less than 100 mm while 96% of the bales weighed had an offset less than 200 mm (Figure 2.9). An additional study was also completed to understand the effects of the bale being near the edge of the spears rather than back at the frame, upon completion of this study a mean error of less than 0.75%pts was measured associated with the bale placement. It was concluded that the effect of the bale being
near the end of the forks was negligible along with the center of the bale, as the error associated with these was within the error associated with picking up the bale.

![Figure 2.9: Bale offset from center of scale, 0 mm indicates bale is centered on scale](image)

Pitch data was collected, which revealed that 95% of the bales were within 5 degrees of level. The bale scale system utilized a front 3-pt hydraulic top-link which could be adjusted by the operator to maintain scale pitch to within targeted range of ± 5 degrees. Measured roll data from the scale system was captured and 89% of the bales weighed fell within 5 degrees of level. Due to the system mechanical design, roll was not easily adjustable and could only be changed by driving the machine to level ground. In some fields the targeted range, ± 5 degrees, was difficult to achieve and would add in significant time for the operator to move to level ground.

Due to the possibility of pitch and roll affecting ground truth weight measurement a study was performed to relate error associated with each. Equations were developed and implemented to correct for the magnitude of pitch and roll, based on field testing of the system (Figure 2.10). During pitch and roll analysis the bale being weighed was not removed from the scales, the measured bale weight where the pitch and roll were zero was utilized as the base measurement. The tractor was then moved to achieve varying pitch and roll values. As previously mentioned
the pitch of the scale system is adjustable, however the roll of the scale was not easily adjustable. During manufacturing of the scale the steel components were not exactly the same length, resulting in a bias being observed in the measurements. In order to correct for the bias of pitch & roll, a series of measurements were captured with the scale leveled, verified with a secondary digital angle finder.

![Figure 2.10: Pitch & roll effects on accuracy of ground truth measurement system, (roll & pitch bias corrected for)](image)

Total variability in the measurement system can be defined as the variability associated with the calibration, picking up the bales, bale center with respect to the center of the scale, and the variability in the pitch and roll measurement (Table 2.4 & Equation 2.5). This brings the total standard deviation of the ground truth measurement system to be 1.80% pts.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Error % pts 1-Sigma</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td>Picking bale up</td>
<td>1.75</td>
<td></td>
</tr>
<tr>
<td>Center of bale</td>
<td>-</td>
<td>within variability of picking up bale</td>
</tr>
<tr>
<td>Position of bale</td>
<td>-</td>
<td>within variability of picking up bale</td>
</tr>
<tr>
<td>Pitch &amp; Roll</td>
<td>0.21</td>
<td>0.3° per manufacture</td>
</tr>
</tbody>
</table>
\[ \sigma_{\text{total}} = \sqrt{\sigma_{\text{calibration}}^2 + \sigma_{\text{picking bale up}}^2 + \sigma_{\text{roll pitch}}^2} \] (2.5)

### 2.2.8.2. Bale Moisture Content

Moisture samples were collected during baling to estimate the moisture of baled crop. The moisture ground truth provided knowledge on the influence of moisture on the mass predictions. A sub-sample was taken from the bale end with a coring bit diameter of 6.35 cm and 75 cm in length (Figure 2.11). The sample location was near the center of the bale between the two center twines, and the core was taken across several flakes to capture the best representative sample from the bale. In order to core sample the bales the operator pulled up next to the bale and hydraulically operated the unit from the cab. As the coring bit spins the operator moved the bit into the bale. After the crop material was cut away and entered the bit, the bit was retracted from the bale and the operator pulled forward. To eject the sample a hydraulic ram was actuated with controls on the back of the tractor which allowed the operator to catch the sample in a plastic bag with a barcode for tracking the sample back to the machine bale information.

![Figure 2.11: Equipment used to sample bale for analysis of moisture content](image)
Samples were dried in order to calculate moisture content, the ASABE standard was used for hay and forage materials which advises samples should be dried for 24 hours at 103°C (ASABE, 2012). Moisture content was calculated as a percent wet basis (Equation 2.6).

\[
\text{Moisture Content (\%)}_{\text{wet basis}} = \frac{\text{Wet weight} - \text{dry weight}}{\text{Wet weight}} \times 100
\]  

(2.6)

\[\text{\textit{2.2.9. Field Data Collected}}\]

Data was collected throughout March into December of 2015, from two separate machines baling alfalfa and grass, both being the same model of baler producing bales of 120x90cm. Machines were each outfitted with data acquisition systems and additional sensors to capture desired machine information. Baling of crop was targeted to produce bales over the entire range of bale density within the capabilities of the machine as well as various moisture contents. In total 1584 bales were utilized in this analysis from 2015, with 817 bales from Machine-A and 767 bales from Machine-B (Table 2.5).

<table>
<thead>
<tr>
<th>Machine</th>
<th>Bales Weighed</th>
<th>Bale Moisture Samples</th>
<th>Mean Bale Moisture</th>
<th>Bale Moisture Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine - A</td>
<td>817</td>
<td>343</td>
<td>14.6 %</td>
<td>6.3 %</td>
</tr>
<tr>
<td>Machine - B</td>
<td>767</td>
<td>296</td>
<td>11.0 %</td>
<td>4.5 %</td>
</tr>
</tbody>
</table>

\[\text{\textit{2.2.9.1. Field data treatment factors and treatment levels}}\]

Several treatment factors were targeted to ensure that data collected was representative of typical field conditions that vary rather than targeting uniform conditions (Table 2.6). Treatment factors consist of both controllable and observable factors. The controllable factors are influenced by the operator through different methods of implementation and aren’t directly controlled. For instance the mass flow rate can be varied by implementing different forward vehicle speed, however was also dependent on the actual field conditions and yield of the crop.
### Table 2.6: Treatment factors and levels for development of mass system

<table>
<thead>
<tr>
<th>Treatment Factor</th>
<th>Treatment Levels</th>
<th>Implementation</th>
<th>Implementation Targets</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass Flow Rate</td>
<td>Vehicle speed variation</td>
<td>3-18kph</td>
<td>Limited by field conditions and material feeding</td>
<td></td>
</tr>
<tr>
<td>Moisture Content</td>
<td>5-45%</td>
<td>Exposure throughout the year</td>
<td>Field dependent</td>
<td></td>
</tr>
<tr>
<td>Bale Weight</td>
<td>Plunger load set point</td>
<td>60-100%</td>
<td>Field dependent</td>
<td></td>
</tr>
<tr>
<td>Flake Count</td>
<td>Vehicle speed variation</td>
<td>3-18kph</td>
<td>Field dependent</td>
<td></td>
</tr>
<tr>
<td>Uneven material flow</td>
<td>Plunger Load ratio</td>
<td>Multiple field &amp; crop condition exposure</td>
<td>Influenced by operator Windrow uniformity</td>
<td></td>
</tr>
<tr>
<td>Plunger to Flake Ratio</td>
<td>Vehicle speed variation</td>
<td>3-18kph</td>
<td>Two machines</td>
<td></td>
</tr>
<tr>
<td>Machine</td>
<td>Multiple machine exposure</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Mass-flow rate can be controlled given the same crop conditions by varying vehicle speed. As vehicle speed was increased the mass-flow rate was also increased.

Moisture content was an observable property which was field dependent. Baling was targeted throughout the year to capture data in high and low moisture conditions, high moisture baling typically occurs early and late season. Varying moisture content can also be achieved by baling crop that the end-user would like to ensile. Ensiled crop is not allowed to dry down to a dry hay condition and is baled at higher moisture with the intent to ensile and/or add preservative to the crop to prevent spoilage. The moisture content captured in this study ranged from 5-45% (Figure 2.12). Only a subset of bales were sampled for moisture analysis to reduce the time
needed to collect samples and additional resources to dry samples, in total 640 bales were sampled for moisture.

Figure 2.12: Distribution of bale moisture collected during 2015, moisture ranging from 5% to 45%

Bale weights can be controlled within some range but are also dependent on crop and field conditions. Plunger loads were varied between 60-100% of full plunger load. Loads less than 60% were not studied as they are outside of the normal use range for large square bales.

Flake count cannot be directly controlled but could be influenced by the operation of the machine and was also observable. Flake count varies due to a wide range of factors such as crop condition, bale density, bale length, and machine throughput. Flake counts ranged from 20-100 flakes per bale in this study.

Uneven material flow cannot be directly controlled and was an observed treatment factor. Material flow can vary from side-to-side due to windrowing practices, operator driving, and crop feeding into the baler. Uneven material flow into the baler was influenced by weaving side-to-side in the windrow causing more material to be feed into one side versus the other. Uneven material flow was typically measured by the plunger load ratio from the right-hand and left-hand
load cells. If the right-hand load cell is higher than the left this indicates the operator need to move right in order to bring more material into the left side of the baler.

Plunger to flake ratio was a measurement that indicated how many plunger strokes occur per flake feeding event. For a machine to operate at maximum throughput a ratio of 1:1 was desired. This ratio could be controlled by vehicle speed changes, given the same crop conditions if a machine was slowed down the ratio would increase, if vehicle speed increased the ratio would decrease. If vehicle speed was increased above which crop conditions would allow for and the machine was running in 1:1 this could cause machine plugs and poor crop feeding. Plunger to flake ratios were observed from 1:1 to 3:1 in normal baling conditions excluding headland turns.

Two machines were utilized in the study to understand the effects of mechanical differences such as component wear and sensor mounting tolerances. The influence of mechanical differences were not directly studied and are out of the scope of this project, it was expected that the mass calibration was capable of overcoming these affects. The machines also allowed for multiple machine exposure to ensure that the mass system was not developed to only one machine and to build confidence in the system working on other machines of similar model.

2.2.10. Instrumentation

Several forms of signal communication was recorded to collect data for this project. The main data acquisition platform was a National Instruments CompactRIO (National Instrument, Austin Tx). A cRIO-9082 was utilized to capture data at 500 Hz from digital, analog, strain and controller area network (CAN) channels (Figure 2.13). The baler used in this study had a standard speed of 45 plunger strokes per minute at a nominal PTO speed of 1000 rpm, resulting in one plunger cycle occurring every 1.33 seconds. At 500 Hz this resulted in a resolution of 0.54 degrees of plunger position. The digital and analog signals captured production sensor
information which was normally broadcasted out on CAN, however a latency exists on CAN and the data frequency rate was too high to capture via CAN. This approach allowed the data analysis to mimic the dynamic signal timing of the electronic control unit (ECU) that would ultimately implement this algorithm. The strain signals corresponded to the four unique experimental sensors. Non-critical machine information was recorded via CAN, including flake and bale count. GPS was also captured from the implement CAN bus to provide current machine location.

Meta-data was captured via a real-time LabVIEW graphical user interface (GUI) and recorded with each data log file. Meta-data included information such as machine, crop type, farm, field, cutting, crop notes, and date.

![Image of System instrumentation diagram](image-url)
2.3. Results and Discussion

The data set for 2015 was subset into two distinct categories, one for analysis and development of the system model as well as one for the model validation. The dataset used for analysis and development will be referred to as the “Calibration” dataset while the data used for validation of the model will be referred to as “Validation”. During model development only the calibration data was utilized to develop the model, the model was then applied to the validation data set. To distinguish subsets of data into calibration and validation categories, the 1584 bales were randomly assigned a numerical value between 0 and 1 utilizing a random number generator with a uniform distribution. The goal of the random number generator was to split the data 50/50 into the subsets of validation and calibration. Values less than or equal to 0.5 were assigned into the calibration data set, while values greater than 0.5 were assigned into the validation data set. This approach resulted in approximately 50.4% of the data being assigned to the calibration data set and 49.6% assigned to the validation data set. The calibration data set consisted of 799 bales and the validation data set consisted of 785 bales.

All weights, densities, mass-yield, and mass-flow are reported as wet basis and not corrected for moisture content, while moisture content does need to be corrected for in order for an accurate comparison this research was focused on a method to obtain wet basis mass.

2.3.1. Bale Weight Estimation Parameters

The calibration data set was utilized to develop a relationship between the estimation parameters and the measured bale weight. The sixteen terms were analyzed as a potential estimation parameter for the mass estimation model. An initial model was developed to include all sixteen terms in the estimation
of bale weight. A main effects analysis was studied to understand which terms influenced bale weight estimation (Figure 2.14). The main effects plot compared the mean bale weight to the fitted means of the developed model utilizing all sixteen terms. A more horizontal relationship suggests that the term does not have a main effect. Varying slopes represent different magnitudes of main effects. Term F1 and F4 are relatively horizontal with a slight slope suggesting that these terms don’t have a main effect on the bale weight estimation and provide little use for the estimation model. Terms F6, F7, F10, and F13 appear to have a small main effect on bale weight, but further statistical analysis should be completed to verify the significance of these terms. The remaining terms appeared to have varying magnitudes of effects on the estimation model. F2, F9, F11, F12, F15, and F16 appeared to have a negative main effect relationship with the estimation of bale weight, as bale weight increased the main effect decreased. Likewise F3, F5, F8, and F14 appeared to have a positive main effect relationship with the estimation of bale weight.

![Figure 2.14: Term main effects for bale weight utilizing full term developed model](image)

A step-wise regression was utilized to develop a model that described the bale weight with limited terms. A statistical package, Minitab, was utilized to analyze a regression fit which
was based on the least square method (Minitab Inc, State College, PA). Minitab’s bidirectional elimination stepwise regression was utilized as an automatic procedure for considering potential terms. A term was only selected if it was significant at an alpha level of 0.05. The procedure added a term if the term was significant at an alpha level of 0.05 and removed terms that were not significant at an alpha level of 0.05.

Overall the developed mass system demonstrated a technique which estimated mass weight.

The calibration model was applied to the validation data set to ensure that the model was not fit to calibration data and would hold true when applied to data that was not used to develop the model. The validation and calibration data set were compared throughout the entire bale weight. An ANOVA was completed based on bale weight % error by data set (Calibration vs Validation). The ANOVA showed that at an alpha level of 0.05 to fail to reject the null hypothesis that the means were equal (p-value 0.32), meaning there was not significant evidence which suggested the calibration mean error is different from that of the validation mean error (Appendix D).

The calibration and validation data consisted of two unique machines, the same developed model was applied to both machines without calibrating for machine differences. It was assumed that all else being equal the same model should hold true across various machines of the same model. At a 95% confidence interval, mean error of machines were not significantly different, with a p-value of 0.9 the null hypotheses was not rejected (Appendix D).

Several factors were identified which may have potential to affect the performance of the developed mass system. The factors identified were, bale flake count, bale length, and bale moisture. Flake count did not appear to have any influence on error of the model.
Bale length was identified as a potential source affecting the mass system performance. Bale weights can be influenced by simply making shorter or longer bales. When bale weights were changed by varying bale length in the same crop conditions, this leaves potential to over fit for specific crop conditions. Specifically when bale length was changed significantly, bale weight was not changing as a function of crop properties or moisture. Measured bale length was compared to the calculated bale weight error, there was no apparent trend.

Bale moisture as measured from sampling bales was also a metric identified was a potential source for error variability. Moisture was identified for two reasons, one moisture will obviously directly affect the mass of crop and second reason was that crop properties such as friction were likely to change which would have a direct impact on force measurements. There was no apparent relationship between moisture and bale weight error, a regression analysis revealed.

It should be noted that the algorithm developed was across the entire season and performance has not been corrected for periodic calibrations such as on a daily or field basis.

2.3.2. Flake weight estimation

Flake weights followed a non-normal distribution. Due to the mechanical setup of the system the flake sizes are naturally restricted to a minimum size to ensure bale uniformity and “desired” shaped bales. This minimum size results in a minimum flake weight, while it is possible for flake size to be less than the typical full-filled flake it is uncommon. This resulted in the distribution to be skewed one-side (right-skewed) with minimal weights at the lower end. The upper flake weight was not bounded and can potentially increase further taking on higher mass values. Machine-A on average had slightly higher mean flake weights compared to Machine-B.
In total 84,733 flakes were utilized in the calibration and validation data set to develop a mass system based upon the described forces and validate the model (Table 2.7).

Table 2.7: Estimated flake weight metrics from machines in 2015

<table>
<thead>
<tr>
<th>Machine</th>
<th>Flakes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine - A</td>
<td>46,700</td>
</tr>
<tr>
<td>Machine - B</td>
<td>38,033</td>
</tr>
</tbody>
</table>

Flake weights vary from flake to flake as previously noted the mean flake weight standard deviation per bale. Bale-A had a final estimated weight and consisted of 77 flakes, the flake weights do not appear to follow a pattern and vary from one flake to another, varying as much as from flake to flake. Bale-B had an estimated bale weight and consisted of 58 flakes.

2.3.3. Mass Yield and Mass Flow Estimation

Estimated wet mass yield ranged from 0.0 kg/m² (0.0 tons/acre) to 0.7 kg/m² (3.1 tons/acre) with a mean of 0.24 kg/m² (1.1 tons/acre) (Figure 2.15). Mean wet mass yield is very much aligned with industry standards.

Figure 2.15: Estimated wet mass yield for 2015 data set, average wet mass yield of 0.24kg/m²
Specific fields were set aside to only bale with test balers in this study to help validate the mass-yield system across crop conditions and machine given the same field. One particular field (13.3 hectares) was baled 3 times for mass data collection. For this field the April, June, and July cutting was analyzed to quantify the consistency of mass-yield over multiple cuttings (Figure 2.16). The April cutting had a mean wet yield of 0.20 kg/m² while the June cutting had a mean wet yield of 0.21 kg/m² and the July cutting had mean wet yield of 0.23 kg/m². Moisture was only collected for the April and July cutting, the mean moisture for these cuttings were 13.1% and 7.9%, respectively.

![Figure 2.16: Wet mass yield comparison for the same field over 3 different cuttings](image)

The method used to correct for the distance between the GPS receiver and the baler pickup was most noticeable at the edge of the field where the baler exited out of a windrow and turned to go back into another windrow (Figure 2.17). In Figure 2.65, the white arrows indicate direction of travel, the left image shows the geospatial layout of the yield points prior to correction and the right image shows the same windrows with correction. With no correction for an offset distance the yield points flow out into the headland when coming out of the windrow.
and when entering a windrow the position of data was marked further into the windrow than where it was actually captured. This creates a staggering or saw-tooth type look to the yield data when looking across the field edge. After the offset distance was corrected the staggering or saw-tooth affect was no longer noticeable and the data points were mapped at more representative locations on where the data was actually captured.

![Figure 2.17](image)

**Figure 2.17: GPS points corrected for offset distance from receiver to baler pickup, white dashed arrows indicate direction of travel**

The balers utilized in this study operated at 45 plunger strokes per minute, in a 1:1 ratio this would mean that a new flake cycle occurs every 1.33 seconds. Therefore yield mapping resolution was one flake, which means as the ratio changes from 1:1 or as vehicle speed changes the resolution or distance between yield points will also change. For instance, as vehicle speed decreases but the baler remains in a ratio of 1:1, typical of heavier crop yields, the yield resolution increases (Figure 2.18). If vehicle speed remains the same, however crop yield is decreased resulting in a ratio greater than 1:1, distance between the yield points increases. This was observed in the North-West corner of the field (top-left), where the distance between the red points increased. In other areas of the field where the machine was baling in 1:1 mode in
moderate crop yield the distance between the yield points remained relatively the same. Thus when operating in 1:1 mode the resolution of yield then becomes linked to the actual yield of the crop, as in heavy yield conditions vehicle speed is typically limited by mass-flow rates that the baler is capable of.

![Yield map of one field showing resolution of yield data points](image)

**Figure 2.18: Yield map of one field showing resolution of yield data points**

The test field compared across the three cuttings was also compared at a spatial level, utilizing Ag Leader’s SMS (Ag Leader Technology, Ames IA), to build confidence that the mass system developed was repeatable given the same field and similar crop conditions (Figure 2.19). It was assumed that in the months of testing that the relative yield within the field would remain approximately the same, i.e. low yield spots will be lower yielding among upcoming months and high yield spots will continue to be higher yielding spots. The three yield-maps were observed to have similar areas of the field which had weaker yield numbers, all three cuttings showed the North-West (Site-A) corner of the field had lower yield compared to other areas of the field. Another area of the field that was consistent among the three cuttings was the bottom center of the field and about 2/3 of the way to the right of the field there was a weaker yielding area running North and South (Site-B).
Figure 2.19: Yield map comparisons for the same field over 3 different cuttings, Top-April, Middle-June, and Bottom-July. Green indicates higher yielding areas and Red indicates lower yields. Black outlines denote areas of field with similar field characteristics over the three cuttings.
The three cuttings were statistical analyzed by dividing the field into 128 block sections each containing 0.1 hectares. Through geo-fencing, the individual yield points associated within each block for each year was then averaged for a mean yield within the block. The mean yield within each block was analyzed to statistical compare spatial yield differences between the cuttings.

To accurately compare the yield over the different cuttings the yield was corrected for each cutting based on the mean yield. An ANOVA (α = 0.05) with Tukey’s comparison was completed to observe the differences and then plotted spatially with a color scheme matching the results of the comparison (Figure 2.20, Appendix E). In blocks of the field that showed higher and more consistent yields, the yield difference was not significantly different among the three cuttings. Over 48% of the field was not significantly different among the three cuttings. In blocks of the field where yield was relatively lower, the significant difference varied by cutting. In the top-left corner of the field, the July cutting was dominantly the significantly different cutting. The July cutting was significantly different in 23% of the field. When comparing the April and June cutting, over 88% of the field was not significantly different, while June and July only 60% of the field was not significantly different. Comparing the April and July cutting approximately 64% of the field was not significantly different.
Figure 2.20: Mean yield comparisons of test field over 3 cuttings, Tukey’s test at alpha level of 0.05

2.3.4. Mass Yield Comparisons

While not an objective of this research additional data was captured from the study field shown in the previous section to compare generated yield maps to other field measurements which may help to explain yield variation throughout a field.

NDVI imagery was captured in December 2014 prior to this study to understand vegetative relative differences in a study field and how it may compare to yield (Figure 2.21). While this data was captured at a different time then what yield data, the field had no major changes to it such as tillage, fertilization, spraying or re-seeding, thus it was assumed that the relative differences within the field would remain fairly the same. The only processes that occurred during this time to the field was typical mowing, raking, baling, bale stacking and irrigation of the field. Visually comparing yield and NDVI it was observed that similar areas of
the field where yield and vegetation were lower compared to other areas of the field. Both unique locations in the field, Northwest corner (Site-A) and just east of the center of the field (Site-B), show similar results which suggests that yield data adequately depicts yield variation throughout a field.

![Figure 2.21: NDVI imagery of study field, data captured in December 2014](image)

### 2.4. Conclusions

In summary the method for measuring mass on large-square balers as described in this research was a reasonable solution for estimating mass-yield, mass-flow, and bale weights. This research approach focused on obtaining a direct estimate of mass at a flake level, by utilizing measured and estimated bale weights. The performance of the developed mass system was comparable to previous research on bale scale technology and volumetric mass flow measurements for large square balers. Comparing the accuracy between the two balers used in this study the methods used to correct for biases of sensors and machine uniqueness resulted in similar performance between the machines.
Data in this study resulted in wet mass yield values in the range of 0.0 kg/m² to 0.7 kg/m² which align with industry yield numbers. Upon comparison of a field over several cuttings, unique field characteristics were present in yield-maps over these cuttings showing areas of the field that were lower yielding. The developed yield technology can be utilized to provide information on field productivity to make managerial decisions.

For simplicity and validation of the mass system, effective width was an assumed constant parameter throughout a field, due to effective swath widths of mowers and raking methods, it was likely that swath width varied throughout a field. Additional geospatial analysis or post-processing of yield information would likely allow for analysis of the effective windrow width to vary, further increasing the accuracy of yield estimations. While this was beyond the scope of this research, it was recognized as a potential source of error impacting yield estimations and further work is needed to develop and implement methods to accurately estimate effective swath width.

The next step was to further validate the developed mass system to determine if this approach was repeatable in varying field conditions and among other machines. Additionally the developed mass system should be implemented real-time to demonstrate the response of the mass flow and mass yield system.
2.5. References

American Society of Agricultural and Biosystems Engineers (ASABE). 2012. Moisture measurement – forages. ASABE Standard Procedure S358.3

Deere. 2014. New John Deere Large Square Balers. Screenshot taken at time 0:53. https://www.youtube.com/watch?v=F1AQ41vpBVA


CHAPTER 3. SYSTEM VALIDATION AND FIELD PERFORMANCE OF ADVANCED BALE WEIGHING SYSTEM WITH INTEGRATED MASS YIELD

3.1 Introduction

The system developed in Chapter 2, was further evaluated with exposure to multiple machines and crop conditions outside of the calibration and validation set in 2016. The mass-system was monitored real-time by implementing the execution on a cRIO. Data was also collected for post-processing and comparison to the 2015 data. Testing and evaluation of performance was completed with the focus on the following objectives:

- Quantify the performance of the bale weighing system across varying field and seasonal conditions.
- Evaluate the performance of the developed mass weighing system with current production tailboard bale weighing systems.

Benchmarking of a current bale scale weighing system was established to define the performance of production rear-tail board mass weighing systems. The performance of production bale scales were evaluated to provide a baseline of typical mean errors. The developed mass weighing system was compared to the production bale scales. Performance targets were to be as accurate as production bale scale systems.

3.2. Materials and Methods

3.2.1. Sensor Implementation

Changes were made from the sensor implementation in 2015. In 2015 feed pan sensors were mounted toward the front and lower corner of the pre-compression feed pan, in 2016 the sensor location was changed to the upper pre-compression chamber feed pan pivot location. The sensor location change was made for several reasons, the primary being in 2015 when plugs
occurred additional time was needed to remove the sensors to allow the pre-compression door to swing down, which was inconvenient and slowed down the process of unplugging the pre-compression chamber. A mount was designed and fabricated which would allow the load cell to be mounted at the pivot, while allowing for the feed pan to still pivot.

The sensor physical mounting location change effected the force response of the sensor. The previously described methods from Chapter 2 were implemented to develop new coefficients which would describe the relationship between the estimation parameters and measured bale weight.

3.2.2. Real-Time Implementation and Demonstration of Mass Flow & Yield

The mass system developed and evaluated in Chapter 2 was implemented in real-time for the 2016 baling season. The MBSD developed for the mass system in Chapter 2 was implemented on a National Instruments CompactRIO (National Instrument, Austin Tx). NI’s Model-Interface Toolkit allowed the model to be auto-coded out from the Simulink environment into a DLL (Dynamic-Link Library). A cRIO-9082 was utilized to convert raw sensor voltages to engineering values and execute the mass estimation model at a rate of 100 Hz. The sensor engineering values along with key calculations for mass-yield and mass-flow estimation were displayed for real-time evaluation (Figure 3.1). The mass information was coupled with GPS information and displayed on a tablet for user interaction. Machine and sensor responses were recorded for post-processing analysis.
3.2.3. Field Data Collected

Data was collected during the 2016 harvest season from two machines with a bale chamber of 120x90 cm. Machine-B was the same machine utilized in the study during 2015, and Machine-C was a new introduction.

Field data collected from Machine-B and Machine-C. Bale average moisture ranged from 8% to 40% with a combined mean bale moisture of 15.5% and a standard deviation of 7.1% (Table 3.1).
<table>
<thead>
<tr>
<th>Machine</th>
<th>Bales Weighed</th>
<th>Bales Sampled for Moisture</th>
<th>Mean Bale Moisture</th>
<th>Bale Moisture Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine - B</td>
<td>439</td>
<td>47</td>
<td>19.7 %</td>
<td>7.6 %</td>
</tr>
<tr>
<td>Machine - C</td>
<td>263</td>
<td>56</td>
<td>12.0 %</td>
<td>4.3 %</td>
</tr>
</tbody>
</table>

Bale flake counts ranged from 25 to 70, with a mean of 48 flakes and standard deviation of 9 flakes (Table 3.2). Baler vehicle speeds varied from 5 kmph to 18 kmph with a mean of 13 kmph and a standard deviation of 2 kmph. Plunger load mean was 74.4% with a standard deviation of 9.5%. Tension panel pressure had a mean of 137 bar with a standard deviations of 44 bar.

**Table 3.2: Machine metrics for 2016 data set**

<table>
<thead>
<tr>
<th>Metric</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flake Count</td>
<td>48</td>
<td>9</td>
</tr>
<tr>
<td>Vehicle Speed</td>
<td>13 kmph</td>
<td>2 kmph</td>
</tr>
<tr>
<td>Plunger Load</td>
<td>74.4 %</td>
<td>9.5 %</td>
</tr>
<tr>
<td>Tension Panel Pressure</td>
<td>137 bar</td>
<td>44 bar</td>
</tr>
</tbody>
</table>

### 3.3. Results and Discussion

The system developed in Chapter 2 was applied to data collected in subsequent years to analyze the performance of the system. Ground truth data collected was captured by the same scales and methods used in Chapter 2.

While the system was developed and implemented real-time the data presented in this section was post-processed. Moving the feed pan sensor from the lower pre-compression chamber feed pan up to the pivot on the feed pan resulted in a different system response as previously discussed. The data was divided into calibration and validation sets to calibrate new estimation parameters. In total 752 bales were analyzed in this study with 433 bales in the validation set and 419 bales in the calibration data set.
The feed pan force response was analyzed to understand signal response to bale weight when mounted at the feed pan pivot location.

The change in location of the feed pan force sensor from the lower front mounting location to the upper pivot location effected the estimation parameter response. While the feed pan is a solid steel component the interaction of crop on the door and the location that the interaction occurs results in varying forces measured at the specific sensor locations due to moments affecting response sensitivity.

The estimation parameters utilized in the model had a p-value <0.001. The estimation parameter effort was calculated as the absolute percent contribution of the estimation parameter in the bale weight estimation model (Equation 3.1). Individual estimation parameters were multiplied by the respective coefficients and then divided by the estimated bale weight. The estimation parameter multiplied by the coefficient resulted in a mass (kg) contribution to the model.

\[
Estimation \ Parameter \ Effort \ (\%) = \left| \frac{Estimation \ Parameter \ * \ Coefficient}{Estimated \ Bale \ Weight (kg)} \right| \quad (3.1)
\]

The calculated estimation parameter efforts were plotted against the measured bale weight. Several estimation parameters, F2, F5, F9, and F15 provided a consistent contribution to the estimation of bale weight throughout the bale weight range. The estimation parameter effort for F6, was observed to decrease as a function of bale weight. The estimation parameters F4 and F12, were observed to increase in effort as a function of bale weight.
3.3.1. Performance of Bale Weighing Estimation

Bale flake count was compared to bale weight error. There were no obvious trends observed between bale flake count and bale weight error for both the calibration and validation data set.

The measured bale length was compared to the bale weight error. There were no obvious trends observed between measured bale length and bale weight for Machine-B and Machine-C.

Measured moisture content was compared to the calculated bale weight error. Both Machine-B and Machine-C showed no obvious trends that would suggest the moisture content of a bale impacts the models performance to estimate bale weights.

3.3.1.1. Bale Basis Performance

The performance of the mass system was analyzed on a bale basis to evaluate the mass system.

3.3.2. Bale Scale Comparisons

The developed mass system was compared to production bale scale systems. Only the validation data set was utilized for the developed mass system performance. The production bale scale system was the same model across all three machines.

Overall the developed mass system was comparable to the production mass system.

The percentage of bales captured within each absolute error bin was evaluated on a system basis rather than a machine basis. The total bales within each absolute error bin were summed for this comparison with disregard to the machine which data was collected from but rather the system.
3.4. Conclusions

The developed mass system showed a correlation to the measured bale weights after the feed pan sensor was moved.

The developed mass system when compared to the production mass system was not significantly different. The developed mass system won 4 out of the 5 error bin ranges for accuracy when compared across the systems. The developed mass system was proved to be as accurate as currently available commercial production bale scale systems.
CHAPTER 4. CONCLUSIONS

While yield monitoring technology has been widely used for many years in grain and cotton production systems, very little technology exists for estimating yield for large square balers. New methods and approaches described throughout this dissertation provides implementation of technology to estimate mass on a flake basis unlocking further calculations of mass-flow and mass-yield, as well as bale weights in alfalfa and grass hay. The developed system has proven to be successful in estimation of mass across 2 years and 3 different machines.

Opportunity for research exists with additional improvement to the system performance as well as expanding the technology into other commonly baled crops such as straw and corn stover. The technology could be further expanded and evaluated among varying baler sizes, such as 90cm x 90cm or 120cm x 120cm bale chambers. Furthermore additional yield accuracy can be established by developing an integrated across machine platform which will account for the effective baling width variation or through post-processing techniques. Further development of moisture sensors would allow for crop moisture to be coupled with mass to provide dry basis estimations.