A Non-Contact Volumetric Based Approach Using a Stereo Camera for Measuring Yield on Sugarcane Harvesters

John Just

Iowa State University

Follow this and additional works at: https://lib.dr.iastate.edu/etd

Part of the Agriculture Commons, and the Bioresource and Agricultural Engineering Commons

Recommended Citation

Just, John, "A Non-Contact Volumetric Based Approach Using a Stereo Camera for Measuring Yield on Sugarcane Harvesters" (2014). Graduate Theses and Dissertations. 17711. https://lib.dr.iastate.edu/etd/17711

This Thesis is brought to you for free and open access by the Iowa State University Capstones, Theses and Dissertations at Iowa State University Digital Repository. It has been accepted for inclusion in Graduate Theses and Dissertations by an authorized administrator of Iowa State University Digital Repository. For more information, please contact digirep@iastate.edu.
A non-contact volumetric based approach using a stereo camera for measuring yield on sugarcane harvesters

by

John Just

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

MASTER OF SCIENCE

Major: Agricultural Engineering

Program of Study Committee:
Matthew Darr, Major Professor
Steven Hoff
Lie Tang

Iowa State University
Ames, Iowa

2014

Copyright © John Just, 2014. All rights reserved
TABLE OF CONTENTS

LIST OF TABLES ........................................................................................................................................ VI

LIST OF FIGURES ................................................................................................................................... VII

LIST OF EQUATIONS ............................................................................................................................. X

ABSTRACT ............................................................................................................................................... XI

CHAPTER 1: INTRODUCTION AND LITERATURE REVIEW ................................................................. 1

Background of Yield Monitors and Sugar Industry .............................................................................. 1

Literature Review ................................................................................................................................. 2

Description of Harvester and Crop Conditions .................................................................................. 3

Methods of Measurement .................................................................................................................... 7

Previous Research and Existing Technologies ................................................................................... 8

Chopper Hydraulic Pressure (By Mass – Indirect) .............................................................................. 8

Elevator Hydraulic Pressure (By Mass – Indirect) .............................................................................. 10

Weigh plate with load cells in floor of elevator (several versions) ..................................................... 11

Under Elevator Optical Sensor Array ................................................................................................ 12

Feed Roller Separation (By Volume – Contact Method) .................................................................... 14

Laser Profiler (By Volume – Non-Contact, for citrus harvester) ......................................................... 16

Project Objectives/System Goals ....................................................................................................... 17

Author’s Role ....................................................................................................................................... 18
CHAPTER 2: ACQUIRING AND INTERPRETING SENSOR DATA

Introduction

Research Objectives

Materials

Methods and Results

Three Slat Testing

Volume and Density Calculations

Full System Lab Testing

Conclusions

CHAPTER 3: FIELD EVALUATION AND REFINEMENT OF YIELD PREDICTION

Introduction

Research Objectives

Materials

Methods

Field Testing Data

Factors Affecting Density

Results (Evaluation of Density Variation)

Green Cane

Analysis of Density Variation within Fields
# Analysis of Variation Between Fields

Nonlinear Transformation of Volume

Analysis of Transformed Density Variation Within Fields

Bias Error and Calibration Frequency Requirements

Analysis of Transformed Density Variation Between Fields

Opportunities for Improvement in Green Cane Yield Predictions

Burnt Cane

**Density Changes within Fields**

**Density Changes between Fields**

**Nonlinear Transformation of Volume**

**Variation Within Fields after SQRT Transform**

**Variation between Fields after SQRT Transform**

**Geo-Correction of Yield Data for Measurement Delay**

**Yield Plots**

**Equations**

**Mean Error, Standard Deviation, and Field Weight Error**

**Comparisons of Agronomic Decisions**

**Field M3**

**Field M4**

**Field TX3**

**Field TX4**

**Conclusions**

**CHAPTER 4: GENERAL CONCLUSIONS**

**System Goals**
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuing Development</td>
<td>71</td>
</tr>
<tr>
<td>Volume Flow Ranges</td>
<td>71</td>
</tr>
<tr>
<td>Field Conditions</td>
<td>72</td>
</tr>
<tr>
<td>Precise Density Shift Data</td>
<td>72</td>
</tr>
<tr>
<td>Future Advancements</td>
<td>72</td>
</tr>
</tbody>
</table>
LIST OF TABLES

TABLE 1: LIST OF CONTRIBUTORS

TABLE 2: SUMMARY OF FIT FOR CAMERA SIGNAL VS WEIGHT PLOT

TABLE 3: STATISTICAL SUMMARY FOR FULL SYSTEM BAMBOO TESTING

TABLE 4: FIELD DATA SUMMARY

TABLE 5: COMPONENTS OF DENSITY

TABLE 6: SPECIFIC FACTORS AFFECTING DENSITY

TABLE 7: MEANS, STD DEV, AND CV FOR EACH FIELD

TABLE 8: CONNECTING LETTERS REPORT (ANOVA) FOR MEAN FIELD DENSITIES (GREEN CANE)

TABLE 9: MEANS, STDDEV, CV PER FIELD AFTER SQRT TRANSFORM

TABLE 10: MEANS PLOT OF DENSITIES BY FIELD AFTER SQRT TRANSFORM

TABLE 11: VARIATION PER FIELD FOR BURNT CANE

TABLE 12: CONNECTING LETTERS REPORT FOR MEAN DENSITY BY FIELD FOR BURNT CANE

TABLE 13: COEFFICIENT OF VARIATION IN BURNT CANE AFTER SQRT TRANSFORM ON VOLUME

TABLE 14: CONNECTING LETTER REPORT FOR BURNT CANE AFTER SQRT TRANSFORM (95% CI)

TABLE 15: FIELD WEIGHT PREDICTION ERROR (%) USING LR DENSITY VALUE
LIST OF FIGURES

FIGURE 1: JOHN DEERE 3510 SUGARCANE CHOPPER HARVESTER ................................................................. 3
FIGURE 2: SUGARCANE HARVESTER AND TRACTOR DURING HARVEST OF GREEN CANE .................... 4
FIGURE 3: SUGARCANE HARVESTER AND TRACTOR DURING HARVEST OF GREEN CANE .................... 5
FIGURE 4: BURNING OF A SUGARCANE FIELD .......................................................................................... 6
FIGURE 5: BURNT STALKS OF CANE IN FIELD ............................................................................................ 6
FIGURE 6: VIEW INSIDE ELEVATOR ON HARVESTER .................................................................................. 7
FIGURE 7: CAMERA AND LIGHTS ON MOUNT ............................................................................................ 22
FIGURE 8: CAMERA VIEW OF ELEVATOR ................................................................................................... 23
FIGURE 9: PROBOX AND WEIGHT SCALE ................................................................................................. 23
FIGURE 10: BAMBOO CONVEYOR INTO ELEVATOR ..................................................................................... 24
FIGURE 11: HARDWARE & INSTRUMENTATION SYSTEM DIAGRAM ......................................................... 25
FIGURE 12: THREE SLATS LOADED WITH BAMBOO .................................................................................... 26
FIGURE 13: CAMERA SIGNAL VS WEIGHT PLOT ......................................................................................... 27
FIGURE 14: FULL SYSTEM TEST (BAMBOO) LINEAR REGRESSION VOLUME FLOW VS MASS FLOW .......... 29
FIGURE 15: FULL SYSTEM TEST (BAMBOO) DENSITY HISTOGRAM .......................................................... 29
FIGURE 16: HISTOGRAM SUMMARIES OF FIELD & MACHINE/OPERATING CONDITIONS ..................... 35
FIGURE 17: TRASH IS A SIGNIFICANT PART OF THE VOLUME BUT CONTRIBUTES LITTLE WEIGHT ............. 37
FIGURE 18: GROUP PLOT OF DENSITIES BY FIELD ................................................................................... 38
FIGURE 19: MEANS PLOT FOR AVERAGE FIELD DENSITIES (GREEN CANE) ............................................. 40
FIGURE 20: DENSITY OF EACH WAGON GRAPHED AGAINST AVERAGED VOLUME FLOW PER WAGON LOAD. COLORS DENOTE REGIONS, SHAPES DENOTE FIELDS .......................................................... 41
FIGURE 21: SQUARE ROOT FIT TO FIELDS B1, B2, M1, M2, M3, M4 ....................................................... 42
FIGURE 22: SQUARE ROOT FIT TO FIELD TX1 ........................................................................................... 43
FIGURE 23: SQUARE ROOT FIT TO FIELD TX3 ........................................................................................... 43
FIGURE 24: GROUP PLOT OF DENSITIES BY FIELD AFTER SQRT TRANSFORM OF STEREO VOLUME ....... 44
FIGURE 25: DENSITY BY VOLUME FLOW AFTER SQRT TRANSFORMATION .................................................................45
FIGURE 26: PLOT OF STANDARD ERROR OF THE MEAN DENSITY WITH INCREASING # OF CALIBRATIONS USING
STDEV OF 5.6% ..................................................................................................................................................46
FIGURE 27: PLOT OF 95% CI OF STANDARD ERROR OF THE MEAN DENSITY WITH INCREASING # OF CALIBRATIONS
USING STDEV OF 5.6% ........................................................................................................................................47
FIGURE 28: MEANS PLOT OF DENSITIES BY FIELD AFTER SQRT TRANSFORM .......................................................48
FIGURE 29: FAN SPEED CHANGES AND PROJECTED CORRESPONDING DENSITY CHANGE ................................50
FIGURE 30: FAN SPEED CHANGES AND PROJECTED CORRESPONDING DENSITY CHANGE ................................51
FIGURE 31: IMPERFECT FIT OF SQRT TRANSFORMATION AT HIGH VOLUME FLOWS .............................................51
FIGURE 32: GROUP PLOT OF LINEAR DENSITIES BY FIELD FOR BURNT CANE ..........................................................52
FIGURE 33: MEANS PLOT BY FIELD FOR BURNT CANE DATA .......................................................................................53
FIGURE 34: BURNT CANE DENSITY PLOTTED AGAINST VOLUME FLOW .................................................................55
FIGURE 35: SQRT CURVE FIT TO FIELD R2 ............................................................................................................55
FIGURE 36: SQRT CURVE FIT TO FIELD R3 ............................................................................................................56
FIGURE 37: SQRT CURVE FIT TO FIELD R4 ............................................................................................................56
FIGURE 38: GROUP PLOT SQRT DENSITIES BY FIELD FOR BURNT CANE .................................................................58
FIGURE 39: SQRT DENSITY BY VOLUME FLOW FOR BURNT CANE ..............................................................................58
FIGURE 40: MEANS PLOT FOR BURNT CANE AFTER SQRT TRANSFORM ...............................................................59
FIGURE 41: PLOTS OF TIME DELAY FROM WHEN MACHINE HARVESTS CANE AND SAME CANE IS MEASURED BY
SENSOR .............................................................................................................................................................61
FIGURE 42: LOW RESOLUTION, MEDIUM RESOLUTION, AND HIGH RESOLUTION YIELD PLOTS OF FIELD M3........64
FIGURE 43: ERROR PLOTS FOR LR AND MR YIELDS SUBTRACTED FROM HR YIELD FOR FIELD M3 .................64
FIGURE 44): LOW RESOLUTION, MEDIUM RESOLUTION, AND HIGH RESOLUTION YIELD PLOTS OF FIELD M4 ....65
FIGURE 45: ERROR PLOTS FOR LR AND MR YIELDS SUBTRACTED FROM HR YIELD FOR FIELD M4 .................66
FIGURE 46 (TOP TO BOTTOM): LOW RESOLUTION, MEDIUM RESOLUTION, AND HIGH RESOLUTION YIELD PLOTS OF
FIELD TX3 ............................................................................................................................................................67
FIGURE 47: ERROR PLOTS FOR LR AND MR YIELDS SUBTRACTED FROM HR YIELD FOR FIELD TX3 .................67
FIGURE 48 (LEFT TO RIGHT): LOW RESOLUTION, MEDIUM RESOLUTION, AND HIGH RESOLUTION YIELD PLOTS OF FIELD TX4 ..............................................................69

FIGURE 49: ERROR PLOTS FOR LR AND MR YIELDS SUBTRACTED FROM HR YIELD FOR FIELD TX4 ...............................69
LIST OF EQUATIONS

EQUATION 1: VOLUME AND DENSITY .................................................................................................................. 28

EQUATION 2: DENSITY CHANGE WITH VOLUME FIT LINE ................................................................................. 42

EQUATION 3: SQRT VOLUME AND SQRT DENSITY .............................................................................................. 42
ABSTRACT

This paper describes an approach to measuring sugarcane yield on a sugarcane chopper harvester using a volumetric flow-based measurement of the harvested product on the elevator, and then converting to mass flow using a density that was found by calibration. Initial proof of concept testing on a stationary setup with a John Deere 3520 sugarcane chopper harvester was carried out using bamboo as a surrogate material due to concerns of spoilage with sugarcane billets. Results showed a strong correlation between the detected volume flow and mass flow, with an R-squared of 97%, and a 4.6% coefficient of variation of measured density values. These positive results led to further field testing in Brazil and Louisiana during 2013, and Texas during the 2014 harvest season. Data was gathered in a wide range of field and operating conditions to identify the full predictive capabilities of the system, as well as identify limitations. Analysis of the data collected from field experiments revealed an interesting and useful relationship between volume flow and bulk density, in which bulk density of material on the elevator decreases along a curve that has the same characteristic shape as $\sqrt{x}$. The decrease in density is likely due to less cleaning/removal of trash at higher volume flows through the machine, as well as changes in the way the billets pack in the slats (more loosely packed at larger volume flows). This trend was used by applying a square-root transformation on the measured volume values, which in turn linearized the relationship between volume flow and mass flow such that a simple linear calibration factor (density) could be used to convert measured volume flows to predicted mass flows. After applying the transformation, the average coefficient of variation of measured density values with a given field was about 5.6% for green cane, with indications that extreme variations in machine operating settings, such as fan speed, that were induced during testing caused the average coefficient of variation to be slightly higher than would be expected during typical harvesting. Burnt cane also benefited from transformation of the volume values, albeit not quite as much, and had an average coefficient of variation of roughly 6.1%
in density values. However, at least some of the variation can be attributed to the fact that burnt cane can tend to have a large variation in trash content (pockets of trashy burnt cane mixed in with clean burnt, and vice versa), which in turn causes large fluctuations in measured density values. Yield plots of several fields that compare actual to predicted show very little difference, as long as an appropriate calibration scheme is enacted to ensure a reasonable estimation of the density value for a given field. The research shows great potential for commercialization as a yield monitor for the sugarcane industry, which has not yet seen one of suitable accuracy.
CHAPTER 1: INTRODUCTION AND LITERATURE REVIEW

BACKGROUND OF YIELD MONITORS AND SUGAR INDUSTRY

A yield monitor is an automated system designed to capture spatial agronomic information while a crop is harvested at specific points in a field. It is a type of geographic information system that falls under the more general category of geographic information science. More specifically, there are two primary pieces of information to be obtained from a yield monitor:

1. Differential Mass yield (Mass per unit area, e.g. tons/acre)
   1. Characterizes the productivity of the land
2. Harvest Rate/Operation Efficiency (Mass flow, e.g. tons/hr)
   1. Characterizes the productivity of the operator/machine

While many other industries currently have yield monitors, e.g., they have been available for roughly 25 years for grain crops, there has yet to be one invented for the sugar industry that has acceptable accuracy, robustness, and calibration requirements. The shape and consistency of the harvested product (sugarcane billets) is as unique as the sugarcane chopper harvester itself, which contributes to the difficulty of a solution, and requires a design that is specifically engineered for this application. Inventions that work well in other crops have been applied to sugarcane in an attempt to repeat the same results, but never commercialized. Another contributing factor that a yield monitor solution for sugarcane has been slow to market may be due to the delay in industry transition to mechanical harvesting from hand-harvesting, when compared with grain crops. The U.S. sugar industry made a rapid conversion to mechanized harvesting around the same time that yield monitors for grain were first becoming commercially available.

Whatever the reason for the delay in a commercial yield monitor solution for sugarcane, the demand for one is only increasing. Sugarcane is a high impact crop, measuring as the fourth largest crop in the world by acres planted, and sixth largest crop by gross production value. With the widespread
use of mechanical harvesters in the sugarcane industry, and growers looking for ways to increase production and decrease costs, a yield monitor with acceptable accuracy and maintenance requirements is highly desired. The specific advantages of a yield monitor for the sugar industry include the following:

1. More precise crop science applications through GIS data that identifies spatial yield of field
2. Facilitating more precise loading of trucks, and
   a. Minimize transportation costs
   b. Minimize risk of overloading semis and losing money at the mill
3. Providing a means to measure operator efficiency and productivity with mass harvested/time information

Due to similarities between the sugarcane chopper harvester and other vegetable and citrus harvesters, the method discussed in this paper could have a further reaching impact than just the sugar industry. Some examples include root crops (potatoes, beets, onions, and carrots), citrus crops (such as oranges, grapefruits) and tomatoes.

LITERATURE REVIEW

There have been several techniques attempted over the last 20 years while trying to measure sugarcane yield on a machine during harvesting. Some examples are an impact/deflection plate similar to what is ubiquitously used in grain crops, weigh plate in the elevator floor that trigger a reading as each slat passes by, optical sensors that measure the proportion of the elevator floor covered with material, and several others that attempt to use measurements of the machine work performed and translate it to a mass flow. The more recent attempts of most of these methods are summarized below in the “Previous Research and Existing Technologies” section. In addition, a plausible method with a laser profiler that was tested with citrus fruits is briefly reviewed.
DESCRIPTION OF HARVESTER AND CROP CONDITIONS

As a reference for terms used throughout this paper, some diagrams and pictures below will help the unfamiliar reader to better visualize the relevant parts of a sugarcane chopper harvester, as well as the two conditions under which sugarcane is harvested (green and burnt).

*Figure 1: John Deere 3510 Sugarcane Chopper Harvester*
Figure 2: Sugarcane Harvester and Tractor during Harvest of Green Cane
Up until the mechanization of sugarcane harvesting, sugarcane fields had to be burned before harvesting them, as detailed in figures 4 and 5. Without mechanical harvesters, it is necessary to burn the fields to greatly reduce the effort of hand harvesting, as well as reduce the risk of encountering animals such as snakes. Even then, a worldwide shift to harvesting sugarcane without first burning the field, otherwise known as “green cane”, is something that has only recently occurred due to public and environmental concerns with pollution, and the use of sugarcane trash as a biomass. Mechanically harvesting the cane “green” is still a slower process, and requires more fuel, than if the cane is first burnt. Wear on the machine is also increased. At the factory, processing the green cane is more taxing on the equipment and tends to produce lower sugar juice purity, which is ultimately the standard by which the quality of the cane is measured. In regards to yield monitors,
the difference in physical characteristics of green and burnt cane, especially bulk density, has a large effect on the prediction accuracy of certain methods for measuring yield.

Figure 4: Burning of a Sugarcane Field

Figure 5: Burnt Stalks of Cane in Field
METHODS OF MEASUREMENT

There are two categories under which any method to measure yield on a harvester will fall, and 2 subcategories under each of these methods. These are listed below and briefly described.

1. Mass Flow
   a. Directly by using load cells
b. Indirectly by measuring a machine work function and using a developed algorithm/model that relates the work function to mass flow. This requires performing some type of calibration to fit the model.

1. Volume Flow
   i. Displacement (contact) by measuring the area of a movable opening with the material flowing through. The opening must be in direct contact with the material and change area in proportion with the physical amount of material flowing through it.
   ii. Volume (non-contact) by means of a sensor that can accurately measure the physical dimensions of a quantity (pile) of material.

PREVIOUS RESEARCH AND EXISTING TECHNOLOGIES

CHOPPER HYDRAULIC PRESSURE (BY MASS — INDIRECT)


System Description:

This system measured pressure across the chopper and feed roller motors and employs a Hall Effect sensor to measure motor speed. This value is then used to calculate power exerted by the motors, which is assumed to have a direct correlation to mass flow through the machine. This system requires a calibration to fit a model that can use the measured machine work to predict mass flow.

Advantages:

- Simple, robust, inexpensive, and requires very little changes to machine.

Disadvantages:
Model that translates machine work to mass flow likely to change as machine components wear (blades dull, friction in moving parts changes) and different crop conditions experienced (wet/dry, green/burnt, general toughness/fiber content).

Extent of Environment/Test Conditions:

   - Tested over 3 days, Two different varieties, varying ground speeds (3 km/hr to 9 km/hr)
   - Mostly burnt cane (small amount of green cane)
   - Roughly 30 runs total, averaging 45 seconds per run (using a 4 ton wagon)

   - Two trials conducted (2008, 2009)
   - 2008 Trial:
     i. Data collected on one field over two days, with constant ground speed during each test.
     ii. Data consists of small loads (50m harvesting from a row) and large loads (full weigh bin – size in tons not stated)
   - 2009 Trial:
     i. Data collected over two days, on a different field each day (most data from day 2 due to loss of data from day 1)
     ii. Tests conducted at two different speeds to induce varying flow rates
     iii. Data consists of small and large loads similar to 2008

Published results:

1. Cox (2002) reports an $R^2$ fit of 84% for the calibration line. This is a straight line fit between measured mass flow for each run against the averaged power measured for each run.

**ELEVATOR HYDRAULIC PRESSURE (BY MASS – INDIRECT)**

*Graeme J Cox (2002), AgGuide Unit (previously commercially available) - small assessment done by Jensen, T. (2010)*

System Description:

Pressure is measured across the elevator motor, and speed measured by Hall Effect sensor similar to chopper and feed roller method. Also similar to the chopper/feed roller method, power exerted by the motor is assumed to be proportional to the mass flow, and so a calibration is performed and a model generated to relate motor power to mass flow.

Advantages:

- Simple, robust, inexpensive, and requires very little changes to machine.

Disadvantages:

- Power required will change as machine parts wear or change tolerance (friction on metal components, chain loosens), as the elevator incline changes, and in different crop conditiongs (wet/dry, green/burnt)

Extent of Environment/Test conditions:

   - Tested over 3 days, Two different varieties, varying ground speeds (3 km/hr to 9 km/hr)
   - Mostly burnt cane (small amount of green cane)
   - Roughly 30 runs total, averaging 45 seconds per run (using a 4 ton wagon)

• Two trials conducted (2008, 2009)

• 2008 Trial:
  i. Data collected on one field over two days, with constant ground speed during each test.
  ii. Data points represent small loads (50m harvesting from a row) and large loads (full weigh bin – size in tons not stated)

• 2009 Trial:
  i. Data collected over two days, on a different field each day
  ii. Tests conducted at two different speeds to induce varying flow rates
  iii. Data points same as 2008

Published results:

1. Cox (2002) reports an $R^2$ fit of 86% for the calibration line. This is a straight line fit between measured mass flow for each run against the averaged power measured for each run.


Weigh plate with load cells in floor of elevator (several versions)


System Description:

A section of the elevator floor is removed and replaced with a section supported on a load cell. A multi axis accelerometer is used to measure and correct the incline of the elevator since this affects the magnitude of force the load cell experiences when a mass is resting on it. The accelerometer may
also be used to adjust for low frequency movements of elevator that can affect weight readings.

Weight measurements are taken as each slat or step on the elevator passes by (using a magnetic proximity sensor for positioning), similar to a catch-and-weigh system. Calibrations can be performed at any time by placing a known weight on the weigh pad.

Advantages:

- Direct mass measurement
- Load cell output curve may be easily calibrated by placing known weights on plate

Disadvantages:

- Requires significant changes to machine, and several instruments working together (more costly, complex)
- Susceptibility to mechanical noise during operation
- Load cell baseline (zero) drift
- Physical contact with material risks buildup of debris and dirt that can bias readings

Published results:

1. Price (2011)
   - 15 small loads (< 8,000 lb) with average error of 11% (SD 8.4%)
   - 14 truckloads (roughly 50,000 lb) with average error of 3.7% (SD 3.5%)

UNDER ELEVATOR OPTICAL SENSOR ARRAY

Randy Price et al (2010)

System Description:
A row of digital (on/off) optical sensors is mounted “looking” up through the holes of the elevator floor to determine presence of material. The measurement is then interpreted by using the duty cycle of the signal as each slat passes, and assuming it corresponds to a certain volume of material, which can then be summed and translated to weight by a calibration value (density).

Advantages:

- Inexpensive, simple, and relatively robust

Disadvantages:

- Dependent on ambient light (nighttime and early morning operations affected)
- Not measuring depth, so, could be highly affected by trash laying in the elevator since it blocks out light but doesn’t have volume
- Requires a calibration, and will be highly affected by changes in material density
- Not available commercially despite strong reported results

Extend of Environment/Test Conditions:

- 2008
  - Green Cane, One test field, 50 data points
  - Three different run distances (18.3m, 76.8m, 146.3m)
- 2009
  - Green Cane, Five days, 28 truckloads (ranging 22 ton to 25 ton)

Results:

- 2008 - Average error of 7.5% (SD 6.3%)
- 2009 – Average error of 2.53% (SD 2.55%)
FEED ROLLER SEPARATION (BY VOLUME – CONTACT METHOD)


System Description:

The feed roller section of the machine consists of several pairs of rollers located between the base-cutter and drum chopper, with a stationary bottom roller and floating/pivoting top roller forming a pair. These rollers are rotated by hydraulic motors such that they forcibly move the stalks through the machine, while the separation between the rollers moves from fully closed to some maximum distance, depending on the quantity of material flowing through them. A sensor/actuator assembly is attached to one of the floating (top) roller at one end, and fixed at the other end to the machine, such that the change in position of the floating roller can be measured.

Advantages:

- No changes in machine design required
- Relatively inexpensive solution

Disadvantages:

- Requires calibration to find density for conversion to mass
- Roller is solid piece and so independent vertical movement at any point along the roller axis is limited, which therefore limits resolution in volume measurements.
- Accuracy is highly dependent on changes in bulk and particle densities such as:
  - Non uniform feeding of material, Moisture content, Amount of trash present

Extent Environment/Test Conditions:
   - Tested over 3 days, Two different varieties, varying ground speeds (3 km/hr to 9 km/hr)
   - Mostly burnt cane (small amount of green cane)
   - Roughly 30 runs total, averaging 45 seconds per run (using a 4 ton wagon)

   - Two trials conducted (2008, 2009)
   - 2008 Trial:
     i. Data collected on one field over two days, with constant ground speed during each test.
     ii. Data points represent small loads (50m harvesting from a row) and large loads (full weigh bin – size in tons not stated)
   - 2009 Trial:
     i. Data collected over two days, on a different field each day
     ii. Tests conducted at two different speeds to induce varying flow rates
     iii. Data points same as 2008

Published results:

   - Straight line fit to average feed roller separation (mm) against average mass flow rate (kg/s) per run resulted in a 91% $R^2$ fit.

   - Results notably less optimistic than Cox (2002)
   - Overall $R^2$ fit of 73.3%
   - Unable to account for changing flows at high throughput
LASER PROFILER (BY VOLUME — NON-CONTACT, FOR CITRUS HARVESTER)

Ujwala Jadhav (2010)

This system is noted due to high potential for success given the results from the system presented in this paper, and similarities in approach.

System Description:

A LIDAR based laser scanner was used to scan the cross section of a conveyor carrying citrus fruits. Angle and distance information from the sensor was translated to Cartesian coordinates (y,z) and the speed of the conveyor used to determine the (x) coordinate. A volume of material on the conveyor was then calculated from this information, and a calibration performed to find density for conversion to mass flow.

Advantages:

- Relatively high accuracy of volume measurement compared to any other volumetric based approaches found in literature for sugarcane yield monitors.
- Can be installed without extensive modifications to the harvester

Disadvantages:

- As with other volumetric based approaches, it requires a calibration to find the density of the material and accuracy is dependent on density changes.
- Accuracy could possibly be affected by dirty/dusty environment
- Instrumentation is very expensive

Extend of Environment/Test Conditions:
• Testing was conducted at conveyors speeds between 0.5 m/s to 1.8 m/s, on flat and incline conveyors.

• For each speed tested, the system was calibrated at several different quantities of material, and the calibration curve determined/evaluated. The calibration (density) was subsequently used to predict mass of several “validation” trials at each speed.

Results:

• Calibration curves showed $R^2$ fit of around 98% to 99%

• Prediction errors decreased as quantity of material flow increased, with small trials showing < 8% error and larger trials indicating < 5% error in typical harvesting quantities.

PROJECT OBJECTIVES/SYSTEM GOALS

Based on a review of literature and the commercial value of a sugarcane yield monitoring system, the following goals were developed:

1. The standard deviation of error about the bias error by wagon should be no greater than 5%.

2. After a calibration (assuming a calibration may be performed on each field), the bias error of prediction (mean value of a Gaussian distribution of prediction error) should be no greater than 5% by wagon load (10 tons). This, in effect, is the same as the absolute error of total harvested weight of field, assuming the number of wagon loads per field is large and will cluster around the true mean calibration value.

3. Calibrations should be minimal to achieve stated goals above.

The above goals were determined to describe a commercially viable sugarcane yield monitor solution of acceptable accuracy to the average grower.
AUTHOR’S ROLE

In addition to the details listed in Table 2.1, the author’s role consisted of the following:

- Field data collection during testing in Brazil in July of 2013
- Field data collection in Louisiana on December 10th through 12th in 2013
- Data analysis as shown in chapters 2 and 3.

REFERENCES


3. Domingos G. P. Cerri, Paulo Graziano MagalhÃ£es. Sugar Cane Yield Monitor. Paper number 051154, 2005 ASAE Annual Meeting. @2005


13. Agricultural Marketing Resource Center (AgMRC), By Diane Huntrods, AgMRC, Iowa State University, and Vikram Koundinya, graduate student, Iowa State University. Updated May 2012 by Malinda Geisler, AgMRC, Iowa State University. http://www.agmrc.org/commodities_products/grains_oilseeds/sugarcane-profile/


CHAPTER 2: ACQUIRING AND INTERPRETING SENSOR DATA

INTRODUCTION

None of the methods detailed in the literature review have been successfully implemented as a commercial product, which requires meeting the system goals specified in chapter 1 in typical harvesting conditions. Of the categorical methods for measuring yield, the non-contact volume method offers the most potential for new development, since instrumentation and methods exist that can measure volume quite accurately, and have not been attempted. One method, detailed above, is by using a laser profiler. The method described in this paper uses a stereo camera. A stereo camera offers the following advantages/disadvantages:

Advantages:

- A single sample produces a 3-dimensional (x,y,z) coordinate grid of the area of measurement. This is an advantage even over the laser profiler which produces only a 2-dimensional (y,z) coordinate plane with each sample.
- Far more accurate volume measurement achieved than other methods attempted for sugarcane yield monitors using a volumetric based approach.
- Can be installed without modifications to the current harvester design

Disadvantages:

- Like all volumetric-based approaches, requires a calibration to find the density, and accuracy is dependent on density changes in the material being measured.
- Not a commercial/off-the-shelf instrument, and therefore material and development costs are very high
RESEARCH OBJECTIVES

This chapter details the proof-of-concept stage of a sugarcane yield monitoring system using a stereo camera as the primary instrument. The goals of this stage are as follows:

1. Verify the stereo camera produces a signal that correlates with volume, using a material similar to sugarcane.
2. Detail a method to relate the stereo volume signal to mass/weight during harvesting
3. Build a sugarcane harvest simulator for hardware-in-the-loop (HIL) testing using a material similar to sugarcane,

MATERIALS

All materials and labor for this project were funded by John Deere. Deere also directly supplied a Deere 3520 sugarcane chopper harvester for lab testing, GPS receiver on machines for field testing, stereo camera with associated embedded hardware, and 10 ton sugarcane carts with load cells for ground truth measurements during field testing. Software/programming, engineering design, and fabrication support for this project was provided by the following entities and individuals:

<table>
<thead>
<tr>
<th>Equipment/Instrument/Software</th>
<th>Entity</th>
<th>Individual(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stereo Calculation Software</td>
<td>NREC/CMU</td>
<td>Carlos Vellespi</td>
</tr>
<tr>
<td>Stereo Recording Software</td>
<td>NREC/CMU</td>
<td>Carlos Vellespi</td>
</tr>
<tr>
<td>Camera Mount</td>
<td>ISU*</td>
<td>Levi Powell</td>
</tr>
<tr>
<td>Bamboo Test System</td>
<td>ISU*</td>
<td>Levi Powell</td>
</tr>
<tr>
<td>ISOBUS GUI Layout/Design</td>
<td>ISU*</td>
<td>John Just</td>
</tr>
<tr>
<td>ISOBUS GUI programming</td>
<td>John Deere</td>
<td>Bhanu Reddy</td>
</tr>
<tr>
<td>UART/CANbus Message Definitions</td>
<td>ISU*</td>
<td>John Just</td>
</tr>
<tr>
<td>Yield Calculation Software</td>
<td>ISU*</td>
<td>John Just</td>
</tr>
<tr>
<td>Brazil Weigh Scale Telemetry System</td>
<td>ISU*</td>
<td>John Just</td>
</tr>
<tr>
<td>Brazil CANbus data recorder software</td>
<td>ISU*</td>
<td>John just</td>
</tr>
<tr>
<td>U.S. Weigh Scale Telemetry System</td>
<td>ISU*</td>
<td>John Just/Junsu Shin</td>
</tr>
<tr>
<td>U.S. CANbus data recorder software</td>
<td>ISU*</td>
<td>John Just/Junsu Shin</td>
</tr>
</tbody>
</table>
*All work done by ISU commenced under the supervision of Dr. Matt Darr.

Table 1: List of Contributors

<table>
<thead>
<tr>
<th>Hardware Description</th>
<th>ISU*</th>
<th>Contributors</th>
</tr>
</thead>
<tbody>
<tr>
<td>U.S. CANbus data logging hardware</td>
<td>ISU*</td>
<td>John Just/Edson Vendrusculo</td>
</tr>
<tr>
<td>Elevator speed sensor level shifter</td>
<td>ISU*</td>
<td>John Just/Edson Vendrusculo</td>
</tr>
</tbody>
</table>

The camera mount was located at a point on the elevator to avoid hitting the primary extractor shield as the elevator rotates from one side of the machine to the other. LED lights on the mount allow for night time operation and ensure minimum lighting levels in all conditions since stereo volume calculation is highly dependent on ambient light.

Figure 7: Camera and Lights on Mount
The test system facilitated controlled simulation of harvesting for regression testing of the system prior to deployment to field testing. Bamboo was used as a surrogate to sugarcane since sugarcane billets would rot very quickly due to being filled with sugar and moisture.
Data logging entailed capturing information from three different sources: stereo camera, weigh scales on carts, and CANbus.

- **Weigh Scales:** Weigh scales were retrofitted onto 10 ton carts, and the weigh scale data was transmitted wirelessly from the tractor to the harvester for data logging. In the U.S. it was also rebroadcast onto the CANbus for logging on a secondary laptop (using Vector CANalyzer) as well as display on the ISOBUS display GUI. For Brazil, a Microautobox was used as a hardware interface and data logged directly to a laptop.

- **Stereo camera:** Data from the stereo camera was logged on a laptop that was connected by Ethernet to the hardware interface of the camera.

- **CANbus:** For U.S. testing, CAN data was recorded on a flash drive using an embedded logging system that operated when the machine was on. When combined with the telemetry system on the weigh carts, this facilitated gathering data throughout the harvest season without ISU staff present. In addition, Vector Canalyzer was used for logging to a laptop during visits by ISU staff to the field. For Brazil testing, CAN data was logged similar to the weigh scale data through a Microautobox.
An ISOBUS GUI was used for feedback and simple controls during field testing. Some of the indicators/controls are listed below:

- Cart weight from weigh scale
- Predicted yield (both instantaneous and accumulated)
- Yield prediction calibration related controls and feedback
- Calibration of hardware (stereo camera)
- Status feedback for hardware/software/instrumentation
- Elevator speed

Elevator speed was detected using proximity sensors mounted in the side of the elevator. These also allowed for position detection, although position was determined to be unnecessary. The sensors were wired into the Microautobox during lab testing, and to camera hardware module during field testing. A level shifter was designed to drop the voltage of the signal from the sensor from 12V to TTL for hardware compatibility.

*Figure 11: Hardware & Instrumentation System Diagram*
METHODS AND RESULTS

A controlled setup at Iowa State University using a John Deere 3520 sugarcane harvester and bamboo as a surrogate to sugarcane was used for initial proof of concept as well as further system engineering and development prior to field testing.

THREE SLAT TESTING

First stages of proof of concept was performed through repeated testing by identically loading three slats with a controlled weight of bamboo (Figure 12), and running the loaded slats by the camera and recording the output. The camera was mounted above the elevator (similar to Figure 7) and recorded measurements at 7.5Hz (7.5Hz approaches the limit that the hardware/software can process the stereo images and perform other functions in real-time). Nine different weights were used, and the results of the testing are shown in Figure 13 and Table 2. The data points were obtained by taking the average of the three highest stereo signal measurements from each test. From these results there is strong evidence of a trend (two-sided P-value < .0001) and no evidence of a nonzero intercept (two-sided P-value of 0.26), with a straight line fit of 90.6%.

![Three Slats Loaded with Bamboo](image)

*Figure 12: Three Slats Loaded with Bamboo*
Figure 13: Camera Signal VS Weight Plot

Summary of Fit

| Parameter          | Estimate | Std Error | t Ratio | Prob>|t| |
|--------------------|----------|-----------|---------|------|
| Intercept          | -0.2799  | 0.2455    | -1.14   | 0.2586 |
| Measured Signal    | 191.72   | 7.976     | 24.04   | <.0001 |

Table 2: Summary of Fit for Camera Signal VS Weight Plot

VOLUME AND DENSITY CALCULATIONS

The stereo camera measurements correspond to the physical volume in the camera view, but this does not indicate how much volume is actually moved through the elevator. This measurement must be combined with speed and sampling frequency in a discrete time integration to get the actual accumulated volume that has passed by the camera on the elevator, and dumped into the wagon. This quantity hereafter referred to as volume, even though the actual units equate to (stereo volume) * (meters), with stereo volume being the unit-less output of the stereo camera
that has not been scaled to coordinate with any particular units of volume. Therefore, even though
the terms “volume” and “density” referred to here have the typical physical meaning, all plots using
volume or density will be shown without units.

\[
\text{"Volume" = } \sum[V_m \ast v_e \ast \Delta t] \xrightarrow{\text{Calibrate}} \frac{\text{Weight of "Volume"}}{\text{"Volume"}} = \text{"Density"}
\]

\[V_m = \text{Stereo Signal Corresponding to Volume Measured on Elevator}\]

\[v_e = \text{Elevator Slat Velocity}\]

\[\Delta t = \text{Sampling Rate (change in time between volume measurements)}\]

*Equation 1: Volume and Density*

**FULL SYSTEM LAB TESTING**

As described in the “materials” section, the setup shown in Fig. 9, Fig. 10, and Fig. 11 were used to
test the full system by simulating harvest conditions, but replacing sugarcane with bamboo as a
material. Results show a strong trend between volume flow and mass flow (R² of 96% for straight
line fit) and a coefficient of variation of 4.6% for the densities of the runs. Since bamboo (and
harvested sugarcane) are not homogeneous materials, and therefore do not have a consistent bulk
density at low volumes, some of the variation in density values can likely be attributed to the random
piling/stacking of the bamboo in the elevator slats. The volume measurement error of the camera is
not easily tested and quantified because the accuracy is dependent on the randomness of the material
to find matches and create a disparity map. However, it is expected that the camera error is a
Gaussian distribution such that, over the course of filling a typical 10 ton wagon (> 200 seconds
harvesting at 7.5Hz sampling), the camera volume measurement error will be minimal.
Summary of Regression Line Fit

| Term                  | Estimate | Std Error | t Ratio | Prob>|t| |
|-----------------------|----------|-----------|---------|------|
| Intercept             | 0.9793   | 0.852     | 1.15    | 0.2663 |
| Volume Flow (unitless/sec) | 37.42   | 1.694     | 22.09   | <.0001* |
**Measured Density Variations**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>39.51</td>
</tr>
<tr>
<td>Std Dev</td>
<td>1.818</td>
</tr>
<tr>
<td>Std Err Mean</td>
<td>0.4171</td>
</tr>
<tr>
<td>Upper 95% Mean</td>
<td>40.39</td>
</tr>
<tr>
<td>Lower 95% Mean</td>
<td>38.63</td>
</tr>
<tr>
<td>Coefficient of Variation</td>
<td>4.6%</td>
</tr>
<tr>
<td>N</td>
<td>19</td>
</tr>
</tbody>
</table>

*Table 3: Statistical Summary for Full System Bamboo Testing*

**CONCLUSIONS**

Given the strong correlation between average stereo volume and mass flow, as well as the low coefficient of variation in densities observed, it is concluded that lab testing effectively proved the conceived stereo camera-based system and paved the way for field testing as a yield monitor to evaluate its capacity to achieve the system goals.
CHAPTER 3: FIELD EVALUATION AND REFINEMENT OF YIELD PREDICTION

INTRODUCTION

Although the results of the bamboo testing showed very strong trends, indicating great potential for prediction capabilities, there are many factors that can complicate prediction and reduce accuracy in actual field conditions. The literature review highlights many studies that have noted strong trends in field trials of other attempted solutions, but nothing has materialized in the form of a commercial product of acceptable accuracy. A major difference between this system and the other research noted in the literature review is the extent of testing performed on the system. This study sought to evaluate the system rigorously in a variety of field and operating conditions to fully assess the potential as a commercial yield monitoring solution. Table 4 data summary and Fig 16 histograms of averaged ground speed and fan speed per run highlights the full extent of testing. This summary of testing helps to build confidence in the results presented and conclusions drawn further in the paper, and also distinguishes the work done from previous attempts to invent a sugarcane yield monitor, as noted in the literature review.

RESEARCH OBJECTIVES

The objectives of the field testing phase are as follows:

1. Conduct an unbiased evaluation of the conceived system to achieve the system goals stated in chapter 1, in typical harvesting conditions.
   a. This includes a thorough analysis of density changes within and between fields.
      Assuming camera measurement error is negligible due to Gaussian distribution of error and large number of samples per wagon load as mentioned in chapter 2, this is the limiting factor in prediction accuracy and determines calibration frequency needs.
2. Refine system to improve prediction accuracy as needed and where opportunities exist

MATERIALS

The materials used for field testing were consolidated in the materials section of chapter 2. It can be seen that the field setup is only slightly modified from the lab system. The yield plots generated in this chapter were made using Ag Leader’s Spatial Management System Advanced software.

METHODS

FIELD TESTING DATA

The results presented in this chapter consist of the experimental trials listed in Table 4 (obtained using the setup described in Fig 11): The larger percentage of data collected in green cane in Table 4 is consistent with the larger percentage of growers using mechanical harvesters to cut green cane, and the general worldwide trend towards harvesting green instead of burnt. The primary focus of the trials was ensuring the field and machine conditions were representative of typical harvesting conditions. There was also some focus on pressing the machine to more extreme operating conditions to induce large changes in certain characteristics of the material in the elevator, such as mass flow and bulk density. This allowed for collection of a larger range of data, identification of corner cases, and ultimately stronger conclusions regarding the capabilities of the system. Figure 16 summarizes, in histograms, the factors and their levels. Although mass flow is not a directly controllable factor, it is shown to emphasize the wide range of flow rates encountered, since at least one method noted in the literature review suffered loss of accuracy at varying (higher) flow rates. The factors that were intentionally varied include fan speed in green cane, and ground speed in both green and burnt. The ground speed factor was varied in an approximate normal distribution in which the mean is centered on typical harvesting speed. Green cane received more attention in variation of the levels (wider range of speeds) due to aforementioned reasons. Fan speed levels in green cane
were mostly varied around 900 rpm +/- 100 rpm, with some tests conducted at extreme speeds around 1200 rpm to 1300 rpm. There was concern by operators about loss of product at the higher fan speeds, so the extreme fan speeds were not tested extensively. Fan speed levels were not tested extensively in burnt cane due to inconsistency of trash content in field being a confounding factor.
<table>
<thead>
<tr>
<th>Date</th>
<th>Region</th>
<th>Farm (letters) + Field (numbers)</th>
<th># loads between 2.5 tons and 10 tons</th>
<th>Green/Burnt</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>7/9/2013</td>
<td>Brazil</td>
<td>B1</td>
<td>5</td>
<td>Green</td>
<td></td>
</tr>
<tr>
<td>7/10/2013</td>
<td>Brazil</td>
<td>B1</td>
<td>14</td>
<td>Green</td>
<td></td>
</tr>
<tr>
<td>7/11/2013</td>
<td>Brazil</td>
<td>B2</td>
<td>13</td>
<td>Green</td>
<td></td>
</tr>
<tr>
<td>7/12/2013</td>
<td>Brazil</td>
<td>B2</td>
<td>13</td>
<td>Green</td>
<td>load cell on hitch broke</td>
</tr>
<tr>
<td>11/20/2013</td>
<td>Louisiana</td>
<td>M1</td>
<td>12</td>
<td>Green</td>
<td></td>
</tr>
<tr>
<td>11/21/2013</td>
<td>Louisiana</td>
<td>M1</td>
<td>19</td>
<td>Green</td>
<td></td>
</tr>
<tr>
<td>11/22/2013</td>
<td>Louisiana</td>
<td>M1</td>
<td>13</td>
<td>Green</td>
<td></td>
</tr>
<tr>
<td>12/6/2013</td>
<td>Louisiana</td>
<td>M2</td>
<td>14</td>
<td>Green</td>
<td></td>
</tr>
<tr>
<td>12/8/2013</td>
<td>Louisiana</td>
<td>M3</td>
<td>19</td>
<td>Green</td>
<td></td>
</tr>
<tr>
<td>12/9/2013</td>
<td>Louisiana</td>
<td>M3</td>
<td>14</td>
<td>Green</td>
<td></td>
</tr>
<tr>
<td>12/10/2013</td>
<td>Louisiana</td>
<td>M4</td>
<td>22</td>
<td>Green</td>
<td></td>
</tr>
<tr>
<td>12/11/2013</td>
<td>Louisiana</td>
<td>M4</td>
<td>10</td>
<td>Green</td>
<td></td>
</tr>
<tr>
<td>12/12/2013</td>
<td>Louisiana</td>
<td>R1</td>
<td>17</td>
<td>Burnt</td>
<td>variable burn quality</td>
</tr>
<tr>
<td>12/12/2013</td>
<td>Louisiana</td>
<td>R2</td>
<td>10</td>
<td>Burnt</td>
<td>clean burn/no trash</td>
</tr>
<tr>
<td>12/13/2013</td>
<td>Louisiana</td>
<td>R2</td>
<td>29</td>
<td>Burnt</td>
<td>burn quality unknown</td>
</tr>
<tr>
<td>12/14/2013</td>
<td>Louisiana</td>
<td>R2</td>
<td>15</td>
<td>Burnt</td>
<td>burn quality unknown</td>
</tr>
<tr>
<td>12/16/2013</td>
<td>Louisiana</td>
<td>R3</td>
<td>16</td>
<td>Burnt</td>
<td>variable burn quality</td>
</tr>
<tr>
<td>12/17/2013</td>
<td>Louisiana</td>
<td>R3</td>
<td>21</td>
<td>Burnt</td>
<td>variable burn quality</td>
</tr>
<tr>
<td>12/18/2013</td>
<td>Louisiana</td>
<td>R3</td>
<td>12</td>
<td>Burnt</td>
<td>variable burn quality</td>
</tr>
<tr>
<td>12/18/2013</td>
<td>Louisiana</td>
<td>R4</td>
<td>7</td>
<td>Burnt</td>
<td>clean burn/some mud</td>
</tr>
<tr>
<td>12/19/2013</td>
<td>Louisiana</td>
<td>R4</td>
<td>22</td>
<td>Burnt</td>
<td>clean burn/some mud</td>
</tr>
<tr>
<td>1/22/2014</td>
<td>Texas</td>
<td>TX1</td>
<td>13</td>
<td>Green</td>
<td></td>
</tr>
<tr>
<td>1/23/2014</td>
<td>Texas</td>
<td>TX1</td>
<td>27</td>
<td>Green</td>
<td></td>
</tr>
<tr>
<td>2/4/2014</td>
<td>Texas</td>
<td>TX2</td>
<td>6</td>
<td>Green</td>
<td></td>
</tr>
<tr>
<td>2/6/2014</td>
<td>Texas</td>
<td>TX2</td>
<td>2</td>
<td>Green</td>
<td></td>
</tr>
<tr>
<td>2/26/2014</td>
<td>Texas</td>
<td>TX3</td>
<td>3</td>
<td>Green</td>
<td></td>
</tr>
<tr>
<td>2/27/2014</td>
<td>Texas</td>
<td>TX3</td>
<td>30</td>
<td>Green</td>
<td></td>
</tr>
<tr>
<td>3/20/2014</td>
<td>Texas</td>
<td>TX4</td>
<td>16</td>
<td>Green</td>
<td></td>
</tr>
<tr>
<td>3/21/2014</td>
<td>Texas</td>
<td>TX4</td>
<td>10</td>
<td>Green</td>
<td></td>
</tr>
<tr>
<td>3/22/2014</td>
<td>Texas</td>
<td>TX4</td>
<td>15</td>
<td>Green</td>
<td>Some mixed burnt</td>
</tr>
</tbody>
</table>

| 35 | 3 | 14 | 439 |

*Table 4: Field Data Summary*
FACTORs affecting density

Density changes are the major factor that limit accuracy of a volumetric-based yield monitor.

Components that determine density are listed below, followed by a listing of the specific factors. Not
all factors can be finely controlled and/or measured. The factors that can, be controlled such as fan speed and vehicle speed, are varied extensively in the data set, over the full range (and beyond) of what would normally be seen in operation (see Figure 16). By gathering data from different regions, farms, fields, and different days, it has been possible to build confidence that most or all other factors listed under “field conditions” and “machine conditions” were included in the data set.

<table>
<thead>
<tr>
<th>Components of Density</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extraneous Material Content</td>
<td>Trash has very little weight compared to the billets, but takes up a significant volume</td>
</tr>
<tr>
<td>Billet Size</td>
<td>Mud/dirt can possibly cause the cane to stack differently than it would when clean</td>
</tr>
<tr>
<td>Characteristics of Trash (e.g. Tough/Soft, Large/Small)</td>
<td>The size of the billets (both length and thickness) affects how they pile/stack in the elevator</td>
</tr>
<tr>
<td>Billet Fiber Density</td>
<td>Tougher, leafier trash could cause higher stackin gin elevator than thinner, less leafy trash</td>
</tr>
<tr>
<td>Leaf/Trash Fiber Density</td>
<td></td>
</tr>
<tr>
<td>Moisture Content</td>
<td></td>
</tr>
</tbody>
</table>

Table 5: Components of Density

<table>
<thead>
<tr>
<th>Specific Factors Affecting Density</th>
<th>Rank (1=low effect, 3=high effect)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category</td>
<td>Sub-Category</td>
</tr>
<tr>
<td>Operator (fully controllable, rapid changes)</td>
<td>Primary Extractor Speed</td>
</tr>
<tr>
<td></td>
<td>Secondary Extractor Speed (*located after measurement point so very little effect for this application)</td>
</tr>
<tr>
<td></td>
<td>Harvest Speed</td>
</tr>
<tr>
<td></td>
<td>Topper Engaged, Topper Height</td>
</tr>
<tr>
<td></td>
<td>Loading of elevator with fan off at row ends</td>
</tr>
</tbody>
</table>
### Field Conditions
(not controllable, generally changes slowly over space/time)

<table>
<thead>
<tr>
<th>Field Conditions</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Humidity/Temperature</td>
<td>1</td>
</tr>
<tr>
<td>Cane posture (e.g. standing, lying, tangled)</td>
<td>1</td>
</tr>
<tr>
<td>Cane moisture content</td>
<td>2</td>
</tr>
<tr>
<td>Trash/debris/mud content</td>
<td>3</td>
</tr>
<tr>
<td>Stock thickness and fiber content</td>
<td>2</td>
</tr>
<tr>
<td>Row Length (less turning = less trash)</td>
<td>1</td>
</tr>
</tbody>
</table>

### Machine Conditions
(not controllable by operator - but changes very slowly over time or not at all)

<table>
<thead>
<tr>
<th>Machine Conditions</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of drum chopper blades (determines billet size)</td>
<td>2</td>
</tr>
<tr>
<td>Cutter blades condition (dull/sharp)</td>
<td>1</td>
</tr>
<tr>
<td>Primary fan blade condition</td>
<td>1</td>
</tr>
</tbody>
</table>

---

Table 6: Specific Factors Affecting Density

---

**Figure 17:** Trash is a significant part of the Volume but Contributes Little Weight
RESULTS (EVALUATION OF DENSITY VARIATION)

As noted in chapter 2, the density value is the stereo volume divided into the weight of the volume measured, and so it serves the dual purpose of both a conversion factor between stereo volume measured and weight predicted, as well as a means to quantify variability of prediction as a yield monitor. The goals of the system are specified at a per field level, and so the focus of further analysis is on density variations within a given field. However, the system value increases if it can move between fields without the necessity of recalibration, so inter-field variation is analyzed as well. It is recognized that density will vary between green cane and burnt cane due to the trash content, so these crop conditions are evaluated separately during some parts of the analysis as appropriate.

GREEN CANE

The group plot of densities by field in Fig. 18 is shown as a visual assessment of both inter-field and intra-field variability in green cane.

Figure 18: Group Plot of Densities by Field
ANALYSIS OF DENSITY VARIATION WITHIN FIELDS

The intra-field variation is summarized by the coefficient of variation for each field, and the average CV for all fields shown in the totals, in Fig 3.5. This variation ranges from less than 5% to nearly 30%, with an average of 15%.

<table>
<thead>
<tr>
<th>Level</th>
<th>Number</th>
<th>Mean</th>
<th>Std Dev</th>
<th>CV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>19</td>
<td>0.581</td>
<td>0.134</td>
<td>23.0</td>
</tr>
<tr>
<td>B2</td>
<td>13</td>
<td>0.929</td>
<td>0.180</td>
<td>19.4</td>
</tr>
<tr>
<td>M1</td>
<td>44</td>
<td>0.392</td>
<td>0.040</td>
<td>10.2</td>
</tr>
<tr>
<td>M2</td>
<td>14</td>
<td>0.397</td>
<td>0.018</td>
<td>4.4</td>
</tr>
<tr>
<td>M3</td>
<td>33</td>
<td>0.387</td>
<td>0.026</td>
<td>6.7</td>
</tr>
<tr>
<td>M4</td>
<td>32</td>
<td>0.427</td>
<td>0.036</td>
<td>8.5</td>
</tr>
<tr>
<td>TX1</td>
<td>40</td>
<td>0.722</td>
<td>0.201</td>
<td>27.9</td>
</tr>
<tr>
<td>TX2</td>
<td>8</td>
<td>1.077</td>
<td>0.216</td>
<td>20.1</td>
</tr>
<tr>
<td>TX3</td>
<td>33</td>
<td>0.750</td>
<td>0.128</td>
<td>17.0</td>
</tr>
<tr>
<td>TX4</td>
<td>41</td>
<td>0.813</td>
<td>0.118</td>
<td>14.5</td>
</tr>
<tr>
<td>Total</td>
<td>277</td>
<td></td>
<td></td>
<td>15.2</td>
</tr>
</tbody>
</table>

*Table 7: Means, Std Dev, and CV for Each Field*

ANALYSIS OF VARIATION BETWEEN FIELDS

A plot of the group mean for each field in Fig. 19, and the connecting letters report in Fig. 20, suggests the mean density shifts across fields for a specific region to be more stable and have less variation than the density variation within any given field. However, if all regions are evaluated together, the variation is well over 100%.
Figure 19: Means Plot for Average Field Densities (Green Cane)

\[ \alpha = 0.050 \]

<table>
<thead>
<tr>
<th>Level</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>TX2 A</td>
<td>1.076</td>
</tr>
<tr>
<td>TX2 A B</td>
<td>0.929</td>
</tr>
<tr>
<td>TX4 B C</td>
<td>0.813</td>
</tr>
<tr>
<td>TX3 C D</td>
<td>0.750</td>
</tr>
<tr>
<td>TX1 D</td>
<td>0.722</td>
</tr>
<tr>
<td>B1 E</td>
<td>0.581</td>
</tr>
<tr>
<td>M4 F</td>
<td>0.427</td>
</tr>
<tr>
<td>M2 F</td>
<td>0.397</td>
</tr>
<tr>
<td>M1 F</td>
<td>0.392</td>
</tr>
<tr>
<td>M3 F</td>
<td>0.387</td>
</tr>
</tbody>
</table>

Levels not connected by same letter are significantly different.

Table 8: Connecting Letters Report (ANNOVA) for Mean Field Densities (Green Cane)

**NONLINEAR TRANSFORMATION OF VOLUME**

The variation shown in Table 7 is far too great to meet the system goals. However, upon further investigation, it was noted that the density consistently follows a useful trend, shown in Fig. 20.
The graph indicates a decrease in bulk density as the volume of material flow increases, when measured on the elevator. This is likely caused by two factors:

1. The machine cleaning functions (such as primary extractor fan) are more effective at removing trash in low volumes than high volumes.
2. The cane packs more loosely in the elevator at higher volumes.

From this information, several nonlinear functions were explored in an attempt to de-weight the increases in volume flow at the same rate that the density decreased. This effectively makes the transformed density values relatively constant over the range of volume flows measured. Upon exploring several functions, a square root transform showed good fit consistently across fields. Some examples of the square root curve fit to the density by volume flow are shown in Figs. 21, 22, 23, along with the % variability explained ($R^2$ fit). The form of the equation for these figures
is as follows (facilitates an assessment of relative changes of response variable with changes in explanatory variable):

\[
\text{fit line} = C \times \frac{\sqrt{\text{Volume}}}{\text{Volume}}, \quad C = \text{Multiplier/Scaling constant}
\]

*Equation 2: Density Change with Volume Fit Line*

The Sqrt transform modifies the volume and density values shown in Equation 1 as follows:

\[
"\text{Sqrt Volume}" = \sum \left[ \sqrt{V_m} \times v_e \times \Delta t \right] \quad \text{Calibrate} \quad \frac{\text{Weight of } "\text{Sqrt Volume}"}{"\text{Sqrt Volume}"} = "\text{Sqrt Density}"
\]

*Equation 3: Sqrt Volume and Sqrt Density*

*Figure 21: Square Root Fit to Fields B1, B2, M1, M2, M3, M4*
Figure 22: Square Root Fit to Field TX1

Figure 23: Square Root Fit to Field TX3
ANALYSIS OF TRANSFORMED DENSITY VARIATION WITHIN FIELDS

Figures 24, 25 and Table 9 display the results post transformation of the volume using a square root function. If Fig. 25 is compared with Fig. 20, it can be seen that the trend was effectively eliminated (used to explain variability), and Table 9 shows the variation per field is significantly reduced after applying the sqrt transform. The results show that the system goal of less than 5% variation within fields is met for many of the fields, and an average of all fields CV’s of 5.6% (also shown in Table 9) indicates the goal is nearly met overall – see “Opportunities for Improvement in Green Cane Yield Predictions” for further discussion.

Figure 24: Group Plot of Densities by Field after SQRT Transform of Stereo Volume
Table 9: Means, StdDev, CV per Field after SQRT Transform

<table>
<thead>
<tr>
<th>Field</th>
<th># Loads</th>
<th>Mean</th>
<th>Std Dev</th>
<th>CV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>19</td>
<td>0.121</td>
<td>0.008</td>
<td>6.3</td>
</tr>
<tr>
<td>B2</td>
<td>13</td>
<td>0.124</td>
<td>0.012</td>
<td>9.5</td>
</tr>
<tr>
<td>M1</td>
<td>44</td>
<td>0.107</td>
<td>0.007</td>
<td>6.8</td>
</tr>
<tr>
<td>M2</td>
<td>14</td>
<td>0.122</td>
<td>0.005</td>
<td>4.1</td>
</tr>
<tr>
<td>M3</td>
<td>33</td>
<td>0.106</td>
<td>0.003</td>
<td>3.0</td>
</tr>
<tr>
<td>M4</td>
<td>32</td>
<td>0.110</td>
<td>0.005</td>
<td>4.3</td>
</tr>
<tr>
<td>TX1</td>
<td>40</td>
<td>0.137</td>
<td>0.009</td>
<td>6.3</td>
</tr>
<tr>
<td>TX2</td>
<td>8</td>
<td>0.122</td>
<td>0.006</td>
<td>5.0</td>
</tr>
<tr>
<td>TX3</td>
<td>33</td>
<td>0.141</td>
<td>0.004</td>
<td>3.1</td>
</tr>
<tr>
<td>TX4</td>
<td>41</td>
<td>0.119</td>
<td>0.009</td>
<td>7.6</td>
</tr>
<tr>
<td>Total</td>
<td>277</td>
<td></td>
<td></td>
<td>Average 5.6</td>
</tr>
</tbody>
</table>

Figure 25: Density by Volume Flow after SQRT Transformation
BIAS ERROR AND CALIBRATION FREQUENCY REQUIREMENTS

The goal of achieving less than 5% bias error per field is dependent on the standard deviation of the density and the number of calibrations performed, per the formula for standard error of the mean.

Figure 26 examines the bias error for increasing number of samples, assuming an average standard deviation of 5.6%, as is shown in Table 9. Each sample represents a wagon load that is greater than 2.5 tons and less than 10 tons. The resulting curve from statistical theory indicates that two calibrations will, on average, produce an absolute bias error less than 4%. It is possible that taking just one or two unlucky calibrations, and using that for predicting the yield throughout the field, could cause the error to be greater than acceptable. For this reason a 95% CI is shown in Fig 27, and indicates that taking five calibrations will lead to an absolute bias error less than 5% in 95% of cases. This also determines the error in total predicted field weight, as stated in the system goals section of chapter 1.

![Figure 26: Plot of Standard Error of the Mean Density with Increasing # of Calibrations Using STDEV of 5.6%](image-url)
Before leaving the topic of mean error and calibrations, it must also be recognized and emphasized that there is a spatial dependency within fields that has not been examined due to the limited data set. It would be a false presumption to consider every wagon load from a given field as an independent sample, as is assumed by sampling theory in Fig. 26 and 27. For example, it is expected that the density at the field edges will, on average, be different than the density in the middle of the field, and so on. Therefore, there is opportunity in this area to examine a robust calibration scheme upon further data collection.

ANALYSIS OF TRANSFORMED DENSITY VARIATION BETWEEN FIELDS

On comparing Fig. 19 & Table 8 to Fig. 28 & Table 10, it can be seen that the SQRT transformation of the volumes reduced the variation of densities between fields. Now the number of statistically
different mean densities is half the number it was before (Table 10), and the difference between the lowest and highest densities is only 30%.

![Means Plot of Densities by Field after SQRT Transform](image)

*Figure 28: Means Plot of Densities by Field after SQRT Transform*

<table>
<thead>
<tr>
<th>Field</th>
<th>Least Sq Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>TX3</td>
<td>A 0.141</td>
</tr>
<tr>
<td>TX1</td>
<td>A 0.137</td>
</tr>
<tr>
<td>B2</td>
<td>B 0.124</td>
</tr>
<tr>
<td>TX2</td>
<td>B 0.122</td>
</tr>
<tr>
<td>M2</td>
<td>B 0.122</td>
</tr>
<tr>
<td>B1</td>
<td>B 0.121</td>
</tr>
<tr>
<td>TX4</td>
<td>B 0.119</td>
</tr>
<tr>
<td>M4</td>
<td>C 0.110</td>
</tr>
<tr>
<td>M1</td>
<td>C 0.107</td>
</tr>
<tr>
<td>M3</td>
<td>C 0.106</td>
</tr>
</tbody>
</table>

Levels not connected by same letter are significantly different.

*Table 10: Means Plot of Densities by Field after SQRT Transform*

**Opportunities for Improvement in Green Cane Yield Predictions**

From the results presented thus far, including an overall variation of 5.6% for green cane, the system has strong commercial potential as a yield monitor. Even though the target goal is 5% variation, it is unlikely that a 0.6% difference would ultimately prevent a decision to commercialize the product, or a farmer from buying it. However, there is also convincing evidence that the goals of the system are
met under certain operating constraints. In addition, there is some evidence that the characteristic shape of the curve for density plotted against volume flow can be fit more closely by a customized curve (other than a square-root curve), which would translate to reduced variability as well. However, this would require more data to explore the trend and ensure no over fitting.

Figure 29 was generated by calculating the differences in fan speed settings of wagon loads measured within steady-state conditions during harvesting in a field, and plotting against the corresponding SQRT density change. Steady-state conditions refers to isolation of the measurements from changing environmental conditions, such as moisture/dew on the leaves in the morning drying off as the day progresses. From this plot, there is strong evidence of a trend (two sided p-value < 0.0001). This is on a load by load basis and suggests it can be expected on average that a 100 rpm change in fan speed (approximately 11% to 12% of normal operating speed) will produce a change in density that is greater than 7%.

Fig 30 facilitates a comparison on a field by field basis. From this plot, there is strong evidence that the fields where fan speed was varied more, the density varied more as well (two-sided p-value = .0027). From the corresponding linear equation, this data suggests that operating with [roughly] 4% variability in fan speeds or less will produce a corresponding in-field density variation that is at or below the goal of 5%.

As a final note on green cane, Fig 31 is a plot of the SQRT density VS Volume Flow for the fields in the data set that produced the highest flowing volumes. The strong evidence of a trend (two-sided p-value < 0.0001) indicates opportunity exists to find a better nonlinear transformation of the volume, at least at higher flows. While this is not further investigated here due to a need for more data to...
confirm the trend in other regions, it provides direction for further data collection and analysis to refine the system and reduce variability.

| Term                        | Estimate | Std Error | t Ratio | Prob>|t| |
|-----------------------------|----------|-----------|---------|-------|
| Intercept                   | -4.072e-5| 0.000856  | -0.05   | 0.9621|
| Fan Speed Change (RPM)      | 8.8514e-5| 8.9e-6    | 9.94    | <.0001*|

*Figure 29: Fan Speed Changes and Projected Corresponding Density Change*
| Term            | Estimate | Std Error | t Ratio | Prob>|t| |
|----------------|----------|-----------|---------|-------|
| Intercept      | 1.706    | 1.176     | 1.45    | 0.1972|
| Fan Speed CV   | 0.743    | 0.152     | 4.89    | 0.0027*|

Figure 30: Fan Speed Changes and Projected Corresponding Density Change

| Term          | Estimate  | Std Error   | t Ratio | Prob>|t| |
|---------------|-----------|-------------|---------|-------|
| Intercept     | 0.0919    | 0.002991    | 30.74   | <.0001*|
| Vol Flow      | 0.000125  | 2.087e-5    | 5.99    | <.0001*|

Figure 31: Imperfect Fit of SQRT Transformation at High Volume Flows
BURNT CANE

The analysis of burnt cane will commence similar to green cane, starting with observing the density variations and then looking for useful trends/patterns that can be leveraged for improved prediction. An important note is that the data for burnt cane is all from one region, so extending conclusions to other regions is much riskier in this case. Figure 32 shows the group plot by field for the burnt cane in the data set.

![Group Plot of Linear Densities by Field for Burnt Cane](image)

**Figure 32: Group Plot of Linear Densities by Field for Burnt Cane**

**Density Changes within Fields**

The variation of density within fields for burnt cane, as shown in Table 9, is much less than green cane without nonlinear transformation of the volume, but it is still not good enough to meet the system goals, prompting further action/investigation. The burn quality of field “R1” was notably variable, which contributed to the lower density and much higher variability.
<table>
<thead>
<tr>
<th>Field</th>
<th># Loads</th>
<th>Mean</th>
<th>Std Dev</th>
<th>CV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>17</td>
<td>0.747</td>
<td>0.106</td>
<td>14.14</td>
</tr>
<tr>
<td>R2</td>
<td>54</td>
<td>0.971</td>
<td>0.061</td>
<td>6.29</td>
</tr>
<tr>
<td>R3</td>
<td>49</td>
<td>0.817</td>
<td>0.079</td>
<td>9.72</td>
</tr>
<tr>
<td>R4</td>
<td>29</td>
<td>0.872</td>
<td>0.061</td>
<td>6.99</td>
</tr>
<tr>
<td>Total</td>
<td>149</td>
<td>9.29</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Table 11: Variation per Field for Burnt Cane*

**Density Changes between Fields**

As mentioned, we only have one region from which to draw conclusions about burnt cane, but the difference between lowest and highest mean field densities is large at 30%. The connecting letter report for a 95% CI affirms the large difference in mean densities between fields in that there is a unique density for every field.

![Means Plot by Field for Burnt Cane Data](image)

*Figure 33: Means Plot by Field for Burnt Cane Data*

\[ \alpha = 0.050 \]

<table>
<thead>
<tr>
<th>Field</th>
<th>Least Sq Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>R2</td>
<td>0.9709</td>
</tr>
<tr>
<td>R4</td>
<td>0.8718</td>
</tr>
<tr>
<td>R3</td>
<td>0.8171</td>
</tr>
<tr>
<td>R1</td>
<td>0.7475</td>
</tr>
</tbody>
</table>

Levels not connected by same letter are significantly different.

*Table 12: Connecting Letters Report for Mean Density By Field for Burnt Cane*
**NONLINEAR TRANSFORMATION OF VOLUME**

Similar to green cane there exists a decrease in bulk density with higher volume flows as seen in Fig. 34. This again is likely due to trash, albeit less than green cane, as well as more loosely packed cane in larger volumes on the elevator. Some further comments regarding Fig 34:

1. It is important to focus on the trend within a particular field (same color/shape), because it can be seen it follows a different trend than the overall group of burnt cane together.

2. This data has a very limited flow range for each field, when compared with the green cane data shown in Fig. 20. Typical green cane flow ranges are greater than five times the flow range per field of the burnt cane, as can be seen in comparing Figs 35 through 37 to Figs 21 through 23. This makes identifying the best trend visually much more difficult, and numerical methods can lead to over fitting with a small dataset like this.

3. A SQRT transformation on volume is chosen for analysis in this paper because it leads to better results than using the measured volume values, but it is recognized more data is needed to confirm the best fit transformation.

4. The solid round purple data points, which tend to follow under the rest of the data points, are from field “R1” which was noted to be very trashy and had the lowest density of the group.
Figure 34: Burnt Cane Density Plotted against Volume Flow

Figure 35: SQRT Curve Fit to Field R2
Figure 36: SQRT Curve Fit to Field R3

Figure 37: SQRT Curve Fit to Field R4
VARIATION WITHIN FIELDS AFTER SQRT TRANSFORM

As with green cane, the square root transformation of the volume helped to reduce variability, although not to the same magnitude (see Table 13). Figure 39 displays fields R2, R3, and R4 densities after transform, and no significance of a trend with volume flow is found. However, field “R1” is again unique in that the square root transformation was not sufficient to fully correct the trend, although it shows some improvement. Other curves attempted produced better results, but they were obtained using numerical methods, and as stated early the dataset is not sufficiently large to bolster confidence in using extra parameters to fit the data. If R1 is considered a separate type, somewhere between burnt and green cane, then the variation results from fields R2, R3, and R4 are encouraging and indicate a strong possibility of fully achieving the goal of 5% STDEV upon confirmation with a wider range of data for burnt cane. For practical purposes, the results are close enough (5.2% for average CV of fields R2, R3, & R4) that the goal may be considered achieved for burnt cane from this data set. Additionally, we classify field R1 separately as mixed burnt/green in need of more data from similar scenarios for further analysis.
Figure 38: Group Plot SQRT Densities by Field for Burnt Cane

Figure 39: SQRT Density by Volume Flow for Burnt Cane
Table 13: Coefficient of Variation in Burnt Cane after SQRT Transform on Volume

<table>
<thead>
<tr>
<th>Field</th>
<th># Loads</th>
<th>Mean</th>
<th>Std Dev</th>
<th>CV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>17</td>
<td>0.146</td>
<td>0.013</td>
<td>8.81</td>
</tr>
<tr>
<td>R2</td>
<td>54</td>
<td>0.177</td>
<td>0.008</td>
<td>4.51</td>
</tr>
<tr>
<td>R3</td>
<td>49</td>
<td>0.178</td>
<td>0.011</td>
<td>5.95</td>
</tr>
<tr>
<td>R4</td>
<td>29</td>
<td>0.192</td>
<td>0.010</td>
<td>5.25</td>
</tr>
<tr>
<td>Total</td>
<td>149</td>
<td>0.192</td>
<td>0.010</td>
<td>6.13</td>
</tr>
</tbody>
</table>

Variation between Fields after SQRT Transform

Although the range of values after transformation did not improve after transformation (the highest density is 31% more than lowest density), fields R2 and R3 are no longer statistically different (Table 14), so there appears that there may be an advantage gained across fields for burnt cane with the SQRT transform. More data is necessary before concluding this though.

Figure 40: Means Plot for Burnt Cane after SQRT Transform
\[ \alpha = 0.0500 \]

**Level**

<table>
<thead>
<tr>
<th>Level</th>
<th>Least Sq Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>R4</td>
<td>0.1921</td>
</tr>
<tr>
<td>R3</td>
<td>0.1777</td>
</tr>
<tr>
<td>R2</td>
<td>0.1765</td>
</tr>
<tr>
<td>R1</td>
<td>0.1462</td>
</tr>
</tbody>
</table>

Levels not connected by same letter are significantly different.

*Table 14: Connecting Letter Report for Burnt Cane after SQRT Transform (95% CI)*

**GEO-CORRECTION OF YIELD DATA FOR MEASUREMENT DELAY**

There is a time delay between when the harvested cane is cut by the base cutter, and travels through the machine to the measurement point on the elevator. This time must be accounted for so that the data can be shifted in space to the correct point in the field. Figure 41 accurately depicts the time delay. The plots show the time it takes for the camera to detect no material in the elevator, after the machine has stopped moving but the elevator remains on. Well over 200 similar plots were studied, with special attention given to longer delay times because operators usually drive beyond the point that the crop ends, which causes a shorter delay time between when the machine stops and when material is no longer detected flowing past the camera. A delay of four seconds was repeatedly noted, and was in fact the upper limit of delay time observed. This also agreed with timed videos of product flowing through the harvester, and so it is concluded that the delay time is four seconds.
YIELD PLOTS

EQUATIONS

The Equations for harvest rate and yield are shown below. The plots of this section are focused on yield, and so harvest rate plots are not examined. In addition, the four-second delay discussed in the previous section has been applied to the latitude, longitude, and speed parameters to geo-correct the yield.

\[
\text{Harvest Rate} = \frac{\text{mass}}{\text{time}} \rightarrow \frac{\text{mton}}{\text{second}} = \frac{(\text{Volume}) \times (\text{Calibrated Density})}{\text{sample rate}}
\]

\[
\text{Yield} = \frac{\text{mass}}{\text{area}} = \frac{(\text{Harvest Rate})}{(\text{Ground Speed}) \times (\text{Row Spacing})}
\]
MEAN ERROR, STANDARD DEVIATION, AND FIELD WEIGHT ERROR

Table 15 shows the percent error of total weight predicted using the first three cartloads from a field to estimate the density (Low Resolution or LR – described in the next section). Three cartloads were used since this represents a semi-load that can be weighed at the mill, instead of requiring the farmer to have a 10-ton wagon with weigh scale readily available. As stated in the system goals and calibration frequency requirements, the mean error is dependent on the variation within the field, as well as the number of samples used to estimate the mean. Therefore, on average, the expected/mean error is higher for fields with higher standard deviations of density values (see Table 9).

<table>
<thead>
<tr>
<th>Field</th>
<th>Total Weight (HR)</th>
<th>Total Weight (LR)</th>
<th>Error (%)</th>
<th>Expected Error (absolute value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>271410</td>
<td>253120</td>
<td>-6.74</td>
<td>3.64</td>
</tr>
<tr>
<td>B2</td>
<td>449980</td>
<td>428180</td>
<td>-4.84</td>
<td>5.48</td>
</tr>
<tr>
<td>M1</td>
<td>749540</td>
<td>783330</td>
<td>4.51</td>
<td>3.93</td>
</tr>
<tr>
<td>M2</td>
<td>226370</td>
<td>230440</td>
<td>1.80</td>
<td>2.37</td>
</tr>
<tr>
<td>M3</td>
<td>331130</td>
<td>322220</td>
<td>-2.69</td>
<td>1.73</td>
</tr>
<tr>
<td>M4</td>
<td>359690</td>
<td>356490</td>
<td>-0.89</td>
<td>2.48</td>
</tr>
<tr>
<td>R1</td>
<td>218110</td>
<td>214340</td>
<td>-1.73</td>
<td>5.09</td>
</tr>
<tr>
<td>R2</td>
<td>694410</td>
<td>688440</td>
<td>-0.86</td>
<td>2.60</td>
</tr>
<tr>
<td>R3</td>
<td>892870</td>
<td>868690</td>
<td>-2.71</td>
<td>3.44</td>
</tr>
<tr>
<td>R4</td>
<td>530140</td>
<td>548590</td>
<td>3.48</td>
<td>3.03</td>
</tr>
<tr>
<td>TX1</td>
<td>538270</td>
<td>546540</td>
<td>1.54</td>
<td>3.64</td>
</tr>
<tr>
<td>TX2</td>
<td>130210</td>
<td>131720</td>
<td>1.16</td>
<td>2.89</td>
</tr>
<tr>
<td>TX3</td>
<td>662060</td>
<td>651390</td>
<td>-1.61</td>
<td>1.79</td>
</tr>
<tr>
<td>TX4</td>
<td>706420</td>
<td>646050</td>
<td>-8.55</td>
<td>4.39</td>
</tr>
</tbody>
</table>

Table 15: Field Weight Prediction Error (%) Using LR Density Value

COMPARISONS OF AGRONOMIC DECISIONS

Notes:

1. For simplicity in comparison, all plots of the same field will have equivalent legends.

2. Only some fields are shown because the resulting conclusions are similar for all fields.
The plots in this section are categorized as follows:

1. **Low Resolution (LR):** In this scenario the first three densities from the field were averaged to form the density that is used for calculating yields throughout the field. This scenario will be most similar to the target operation of the system, but will also suffer the most error because it has both mean error (bias) and error from general variations within the field.

2. **Medium Resolution (MR):** This scenario uses the average density calculated from all densities in the field. This is essentially a zero bias/mean error scenario, where error will be exclusively from in-field variation.

3. **High Resolution (HR):** This scenario uses the individual densities from each load to calculate the yield corresponding to the area that load was harvested from. This is the actual yield and minimizes any mean error and error from variation within fields. It serves as the baseline comparison, and ideal accuracy.

*FIELD M3*

The effect of the bias and deviation error is not easily seen in the plots of field M3 below, when comparing the LR and HR plots. This is a situation where the bias error was approximately 2.7% low (Table 15) and so the LR plot is more pessimistic than the MR & HR plots, in absolute terms. If mean error is essentially eliminated (compare MR and HR plots), then the effect of error from in-field variation is observed, although again not easily. Plots by percentage error for the MR and LR plots help visualize the difference from the HR density values in Fig 43.
Figure 42: Low Resolution, Medium Resolution, and High Resolution Yield Plots of Field M3

Figure 43: Error plots for LR and MR Yields Subtracted from HR Yield for field M3
FIELD M4

The LR plot is nearly identical to the MR plot for field M3 due to the standard deviation being low (3% - see Table 15) and the calibration getting “lucky” and falling well below the expected error. As can be seen, the LR plot is also very close to the HR plot, and there wouldn’t be any expected differences in agronomic decisions based on these plots.

*Figure 44*: Low Resolution, Medium Resolution, and high Resolution Yield Plots of Field M4
**FIELD TX3**

Figure 46 is an example where the mean error is right around the expected value (1.6% low), and when combined with the low in-field variation, there is very little difference between the LR and HR plots. This is especially clear in the error plots.
Figure 46 (top to bottom): Low Resolution, Medium Resolution, and high Resolution Yield Plots of Field TX3

Figure 47: Error plots for LR and MR Yields Subtracted from HR Yield for field TX3
FIELD TX4

Field TX4 is a good example of what happens in the case of an “unlucky” calibration. The mean error for LR was roughly 8.5% low, and although the relative differences yields are very accurate (see difference between MR and HR plots in Fig 48), the mean error makes the LR plot looks very pessimistic by accentuating the low yielding areas in the plot. The error plot also displays this by showing a large difference between the HR and LR yields throughout the map. It may be possible to minimize the chances of such situations by taking spatially diverse samples during a calibration.
CONCLUSIONS

The data collected during field testing enabled development beyond the lab testing that was sufficient to prove system functionality, to the point of arguably meeting system goals. The system has generally broke new ground in the area of non-contact volume-based yield monitors in terms of accuracy and robustness, and still shows potential improvements through refinement of the weighting algorithm and more precise operating and calibration recommendations, to be determined upon
further data collection. Additionally, this method enabled the identification of a notably interesting, as well as useful, trend of the bulk density with volume flows on the elevator.
CHAPTER 4: GENERAL CONCLUSIONS

SYSTEM GOALS

The results from testing the field are very positive, and indicate that the system has achieved the stated goals, under some general constraints of operation. Density changes over larger areas, such as field to field variation, will continue to be a challenge for a volumetric-based yield monitor, and a calibration to correct for mean density shifts will be required at a typical distance interval. Given an average calibration per field though, the agronomic decisions that can be made from the yield plots look very promising, with very little difference between the exact (HR) and predicted (LR) plots on average. Additionally, there is evidence of possible improvements that can yet be made upon collecting more data to answer key questions, which are noted in the “Continuing Development” section.

CONTINUING DEVELOPMENT

Because this system is moving towards commercialization given the positive results, there are a few key areas needed to be addressed in future testing and data collection opportunities to continue to build confidence in the system and possibly improve predictive capabilities. These areas are summarized here with the resulting questions to be answered.

VOLUME FLOW RANGES

The current data set has limited flow ranges from most fields, and even the ones with larger ranges could still be more useful if extended. Wider ranges of flow will allow for plots such as Figure 20 and Figure 34 to fully represent the physical model of how density changes with increased volume flows. Then the best fit curve can be determined with confidence and the standard deviation within fields continue to be decreased.
FIELD CONDITIONS

Even though the dataset used in the analysis presented in this paper is sizable, the full range of farming practices, harvest operations, cane varieties, soils, weather conditions, and other seasonal changes are most likely under-represented such that we cannot be fully confident that the majority of conditions have been encountered, and so further data collection in diverse conditions is needed to build this confidence.

PRECISE DENSITY SHIFT DATA

The current data set shows strong evidence of mean density shifts over fields, but these same shifts are likely quantifiable in a spatial sense, such that a more precise calibration routine can be defined based on an expected/average unit density change per unit area.

FUTURE ADVANCEMENTS

The results of the field tests discussed in this paper clearly identify trash as a major factor affecting the bulk density of the material, and ultimately having a large effect on the density variation. Therefore, future research in advancements will include an attempt to detect the trash content of the measured volume for use as an additional explanatory variable. Efforts will focus on using the stereo camera images to implement a vision-based algorithm that identifies the trash levels. For fields such as R1 with clusters of clean burnt and trashy burnt cane, some type of trash detection is necessary to reach stated goals. For more typical green cane fields, it offers a possibility of improving the already strong results presented.