2008

# Development and modeling of a slope insensitive combine cleaning shoe

James Monroe Hershbarger
*Iowa State University*

## Recommended Citation

Hershbarger, James Monroe, "Development and modeling of a slope insensitive combine cleaning shoe" (2008). *Retrospective Theses and Dissertations*. 15423.
http://lib.dr.iastate.edu/rtd/15423

# Development and modeling of a slope insensitive combine cleaning shoe

by

James Monroe Hershbarger

A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Agricultural Engineering (Agricultural Power and Machinery)

Program of Study Committee:
Stuart Birrell, Major Professor
Max Morris
Brian Steward

Iowa State University

Ames, Iowa

2008

# TABLE OF CONTENTS

# LIST OF TABLES

# LIST OF FIGURES

# ACKNOWLEDGMENTS

Many people were critical to my success during my time at Iowa State University. I would like to thank Dr. Stuart Birrell for his guidance and help during my research. His patience and thorough explanation of concepts was key to my understanding of the intricacies as well as the successful execution of my project. I would also like to thank Dr. Max Morris, who crafted the design of experiments for my research. Without him I would still be working on the thousands of runs I would have had to complete without his assistance. I would especially like to thank Kevin Ehrecke for all the useful ideas and advice that he had for me as well as keeping such great enthusiasm about the project. I also want to thank Mark Dilts, Ben Schlesser, and Adam VanDeWalle for getting me acquainted with the department and helping me with various portions of my project. Thanks also go to Brad Dilts, who designed an excellent test stand and provided a great foundation for future research. I also want to express my gratitude to Landon Aldinger, Ty Luellen, Karl Moritz, Travis Ohms, Joe Freund, Jacob Baker, and Kyle Shipley for their assistance during my experiments. Last but not least, I want to thank my wife Megan Hershbarger, whose love and support kept me on focus throughout graduate school.

# ABSTRACT

An experimental cleaning shoe was developed to compensate for sloped land by adjustment of shake speed, fan speed, and shake geometry. Grain loss on the cleaning shoe decreased compared to a conventional cleaning shoe exposed to similar conditions. Average grain losses of 0.710% and 6.560% on 5- and 10-degree side slopes in corn were reduced to 0.118% and 0.256% on the same side slopes using only modified shake geometry. Similar reductions in grain loss were seen in wheat, from 7.521% and 15.272% on both side slopes to 3.941% and 4.722% using only modified shake geometry. Grain loss prediction models were developed for each crop with $R^2$ values of 0.8111 and 0.8440. Through modification of fan and shake speeds and shake geometry to field conditions, grain loss reduced from averages of 1.276% to 0.675

# CHAPTER 1. INTRODUCTION

The modern combine is a complex machine that is able to process a wide variety of crops in a diverse range of conditions. While today's combines are the most efficient models available, they are still vulnerable to some of the problems that have historically plagued combines. Combines have excellent efficiency and low grain loss when operated on level ground, but when any amount of tilt is added to the machine either to the side or fore-aft, grain capacity decreases and grain losses increase significantly. Through the use of rotary thresher-separators, one of the primary sources of grain loss on uneven land is eliminated: the conventional threshing cylinder and straw walkers. What remains is the cleaning shoe, for which designs remain essentially unchanged since the introduction of the first combine. The cleaning shoe consists of a transverse fan blowing up through a series of oscillating sieves that are level in the horizontal plane. A mixture of grain, chaff, and small straw is handled by the cleaning shoe: it is introduced to the chaffer sieve where it is partially suspended by the air blast from beneath. From the air blast and the oscillating motion of the sieve, denser grain particles are allowed to fall through the sieve and are collected while chaff and straw are conveyed out of the machine and deposited on the ground. While this system works well on level land, when the combine is tilted its performance is reduced significantly.

When the machine is not on level terrain, handling of the mixture by the cleaning shoe is completely different from level-ground operation, leading to increased grain loss from the cleaning shoe. When the combine is going uphill, the louvers of the chaffer are more parallel to the horizontal plane than when the machine is on flat ground. This effectively decreases the area that grain is able to fall through and causes grain to remain on the chaffer and to travel along with the material-other-than-grain (MOG), ultimately escaping the machine along with the MOG. When the combine travels downhill, crop material has a tendency to stay inside the machine, resulting in satisfactory grain loss but somewhat higher amounts of trash in the grain tank. When operating on a side-hill, the grain and MOG mixture tends to move toward the downhill side of the cleaning shoe, leaving a large part of the chaffer void of any material. The resulting opening allows air from the fan to escape rather than support the grain and MOG mixture, limiting the aerodynamic separation of grain from MOG. The material is only sifted, which results in the chaff and straw carrying a substantial amount of the crop out of the machine as it exits.

A previously developed experimental cleaning shoe overcame side-hill losses by modifying shake geometry while allowing study of the effect of fan speed and shake speed on longitudinal slope losses. This shoe was mostly successful in clean-grain-only trials, but further study of the response of the cleaning shoe to clean grain and MOG is essential to completely prove that the shoe is able to compensate for sloped-land grain losses in real-world conditions. This study attempts to show that the cleaning shoe is effective when fed grain and chaff and that through development of controls for fan and shake speeds as well as shake geometry based on field conditions, grain losses on the developed cleaning shoe are significantly lower than current production cleaning shoes when operating on sloped terrain.

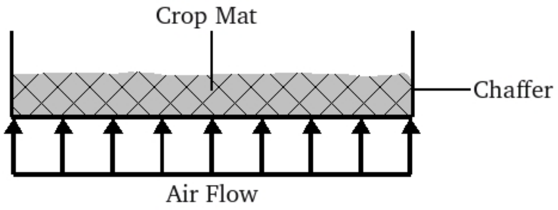
# CHAPTER 2. REVIEW OF LITERATURE

## 2.1 Effect of contoured terrain on cleaning shoe grain loss

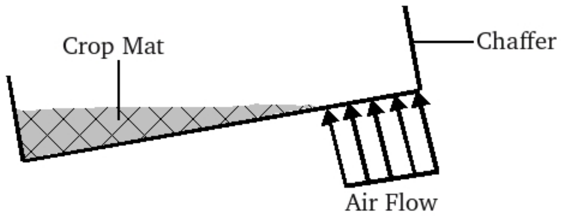
Even before development of the mobile combine, increased grain loss from the cleaning shoe on uneven land was experienced during harvest. An important part of setting up a stationary grain cleaner was ensuring a level footing before operation (Bichel and Cornish, 1974). Without a level machine, both capacity and cleaning efficiency suffer, resulting in increased grain loss. Cleaning shoes are typically mounted stationary inside a combine, so machine orientation is still an important factor during harvest. Sloped terrain affects cleaning shoe grain loss in both the lateral and longitudinal axes. Stahl, Freye, and Kutzbach (1981) reported that cleaning shoe grain loss increases as longitudinal slope increases, as observed when a combine travels up a hill while Huynh and Powell (1978) noted that cleaning shoe grain loss decreases with a decreasing longitudinal slope as seen when a combine moves down a hill. Similarly, as the cleaning shoe is operated on a side-hill slope, grain loss increases significantly as lateral slope increases in either direction (Quick, 1973).

## 2.2 Mode of increased grain loss in a tilted orientation

The mechanism through which grain loss from the cleaning shoe increases on contoured land is well understood. A mixture of grain and MOG consisting of short straw, chaff, and partially threshed grain is handled by the cleaning shoe (Bilanski and Dongre, 1974). The cleaning process is a combination of aerodynamic separation imparted by the fan and mechanical separation imparted by the oscillating sieve, with aerodynamic separation being the prominent mode of separation throughout the process. Craessaerts, Saeys, Missotten, and De Baerdemaeker (2007) stated that cleaning shoe losses are primarily caused by a nonuniform air pressure profile underneath the mixture of grain and MOG known as the crop mat. A nonuniform air pressure profile implies that there are areas of the crop mat through which it is easier for air to escape than others, causing a breakdown of aerodynamic separation.



(a) On level ground

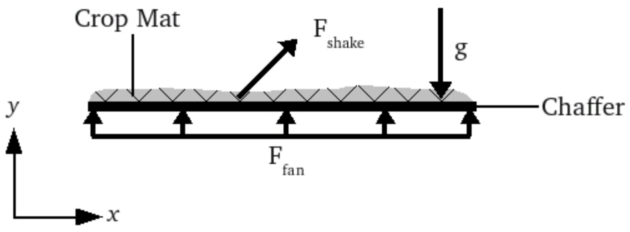


(b) On a side-hill

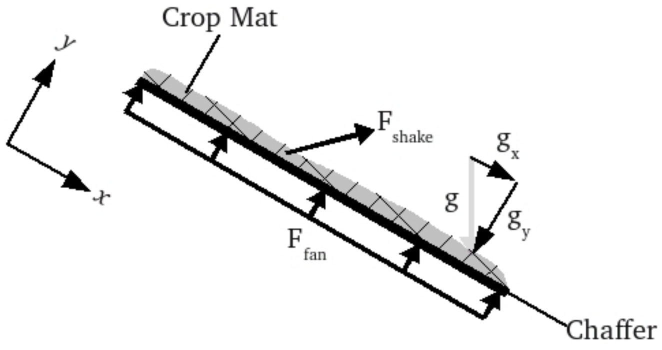
Figure 2.1 Comparison of crop material distribution on the chaffer when level and on a side-hill

The phenomenon that occurs when the combine operates on side-hill inclines that results in higher grain loss from the cleaning shoe was best described by Bichel and Kent (1974). When the combine is tilted to the side, all material in the cleaning shoe that is normally evenly distributed accumulates on the downhill side of the chaffer, as shown in Figure 2.1. On level ground, the crop mat is uniform and air pressure is evenly distributed under the chaffer, as shown in Figure 2.1(a). When the cleaning shoe tilts to the side and material distribution is no longer uniform, the air stream takes the "path of least resistance" through the uphill portion of the chaffer that lacks crop material, as shown in Figure 2.1(b). This escape of air results in a loss of air pressure below the crop mat. The fluidized bed of crop material that is required for efficient aerodynamic separation can no longer be maintained due to the loss of air pressure beneath the crop mat and as a result, the separation of grain from MOG is a purely mechanical sifting action imparted by the oscillating sieve which is significantly less efficient than the combination of aerodynamic and mechanical separation that typically occurs. Higher grain loss from the cleaning shoe is the result of this breakdown, with acceptable grain loss returning to the cleaning shoe only when the machine is brought back to a level orientation.

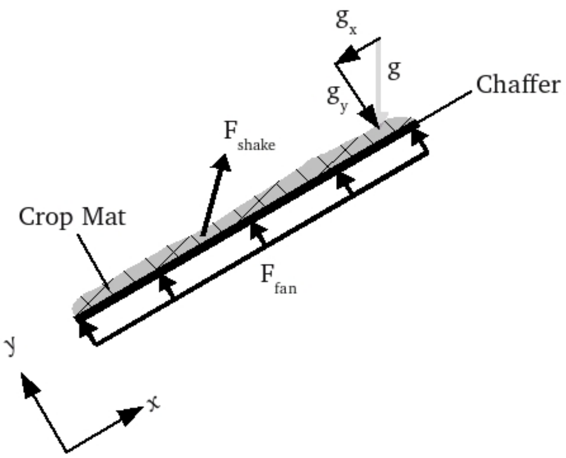
Huynh and Powell (1978) explained the losses on longitudinal slopes as a function of grain dwell time and velocity which are dictated primarily by the magnitude of force directed in the plane of the chaffer. When operating on flat ground, the crop mat in a cleaning shoe experiences forces imparted from the chaffer in the positive $x$ and $y$ directions, as shown in the frame of reference of the combine in Figure 2.2(a). Another force in the positive $y$ direction comes from the air pressure created by the fan. The force of gravity only acts in the negative $y$ direction. As shoe inclination angle increases gravity becomes componentized into a force acting in the positive $x$ direction as well as a portion of the original force of gravity in the negative $y$ direction, as shown in Figure 2.2(b). The decrease of the force of gravity in the $y$ direction is significant because it reduces the amount of force necessary to keep a fluidized bed of material, yet fan speed on the combine stays constant, which results in an air pressure below the chaffer that is higher than necessary for aerodynamic separation. Thus grain is blown from the chaffer rather than falling through and becoming captured by the combine. Due to the additional force by gravity in the positive $x$ direction and the decreased force of gravity in the positive $y$ direction as well as an increased force from the fan pressure in



(a) On level ground



(b) Traveling uphill



(c) Traveling downhill

Figure 2.2 Forces acting on the crop mat when the combine is level, oriented uphill, and oriented downhill the positive $x$ direction, grain dwell time decreases and grain velocity increases. This results in grain exiting the shoe along with the MOG at a higher proportion than on level ground. The opposite occurs in a downhill orientation, seen in Figure 2.2(c). A component of gravity acts in the negative $x$ direction and results in an increase of grain dwell time and a decrease in grain velocity. Thus grain is more able to stay inside the machine and grain loss is minimal in this orientation.

## 2.3 Methods of decreasing cleaning shoe grain loss on contoured land

Figure 2.3 A hillside combine (Hillco Technologies, 2008)

Several different mechanisms have been developed to deal with the problem of cleaning shoe performance on sloped ground. The most common method used for side-hill correction is the side-hill combine, shown in Figure 2.3. Through a system of linkages, controllers and hydraulics, a side-hill machine tilts the drive components of an otherwise standard combine to maintain level footing on the side of a hill (Witzel and Vogelaar, 1955). This system is utilized in hillside combines available from John Deere. While this method is robust for side-hill applications and works reasonably well, it only corrects for lateral and not longitudinal machine orientations. There are also limits to the amount of tilt that the machine can compensate for before roll-over becomes a concern.

A similar method of side-hill and longitudinal slope compensation involves mounting the cleaning shoe on a sub-frame within the combine that allows tilting in either axis (Hyman, Sheehan, and Rowland-Hill, 1985). The tilt of the cleaning shoe can be set by either actuators or simply gravity (Vold, 1905; Heald, 1893). While these methods show improvement in grain loss over a baseline machine on sloped ground, they pose the safety issue of a moving center of gravity during operation of the machine due to the constant reorientation of the cleaning shoe relative to the rest of the combine. These methods also have the downfall of requiring a larger chassis to accommodate the cleaning shoe's orientation within the machine. A side-hill-only version of this cleaning shoe is currently available from Case IH.

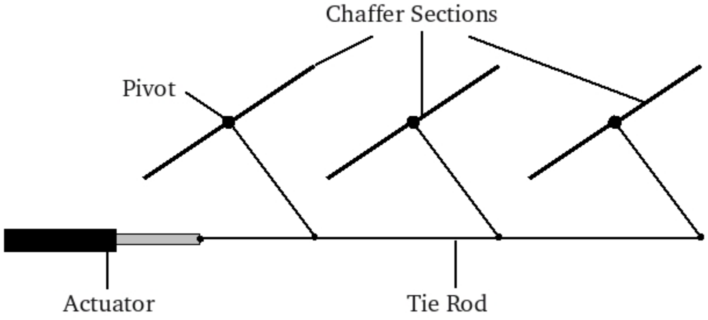


Figure 2.4 A multiple-section chaffer with actuator for side-hill compensation

One method of side-hill compensation involves keeping the cleaning shoe stationary within the combine and splitting the chaffer into multiple sections, each section with its own longitudinal pivot (Bozarth, 1948). The sections move together through the use of a tie rod that holds the angle of each chaffer section relative to the other sections, as shown in Figure 2.4. When encountering a hillside, an actuator linked to the tie rod extends or retracts, causing the chaffer sections to rotate on their pivots to remain level relative to the ground. When back on level land, the actuator returns to its original position which causes each section to pivot back to a standard configuration. While this mechanism is particularly novel, it brings with it the problem of sealing between each chaffer element when in a side-hill configuration (Murphy, 1993; Sacquitne, 2005; Mackin and Herlyn, 2007).

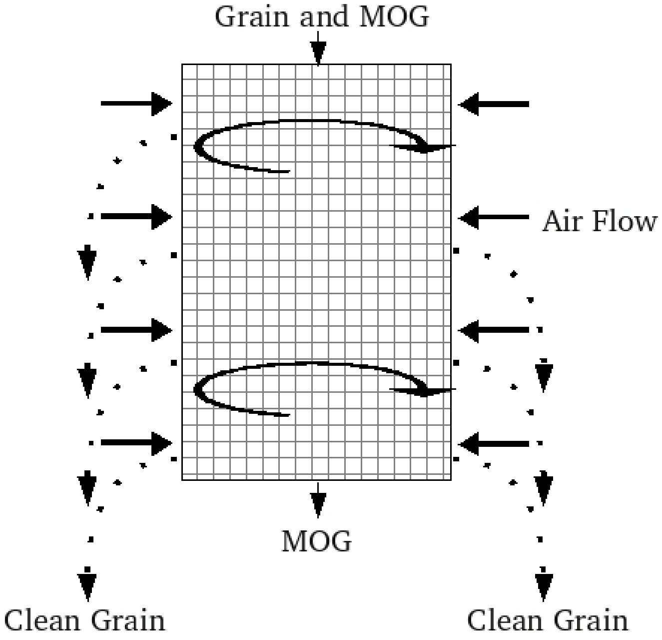


Figure 2.5 A rotary cleaning shoe

Some methods of minimizing grain loss on contoured land attempt to eliminate any effects of gravity on the cleaning shoes. Park and Harmond (1966) discussed a vertical rotary cleaner that separates grain from chaff by introducing the mixture to the inside of a rotating screen sized to allow grain to pass through it, shown in Figure 2.5. The grain is then cleaned by applying a blast of air that passes through the screen and escapes out the rotating axis of the screen. Thus the crop passes through the screen and chaff is blown out of the cleaner. This cleaner has good efficiency and is proven to be effective in wide varieties of crops (Park, 1974). The downfall of this system is sealing the device to limit air leakage from the inlet, though it has been mostly overcome by continued seal development (SaijPaul, Huber, Drew, and Jones, 1976).

An air elutriation cleaning system was introduced in Hamilton and Butson (1979). This system works by elevating the crop and MOG mixture and then dropping it down a chamber with a fan blowing up it, as seen in Figure 2.6. In this system, chaff is blown out of the machine while the grain is collected at the bottom of the chamber and conveyed to the clean grain tank. The downfalls of this design are the higher levels of contamination of grain by short straw that are observed relative to a traditional combine. In addition, this design has never been tested and compared to a conventional cleaning shoe on sloped terrain.

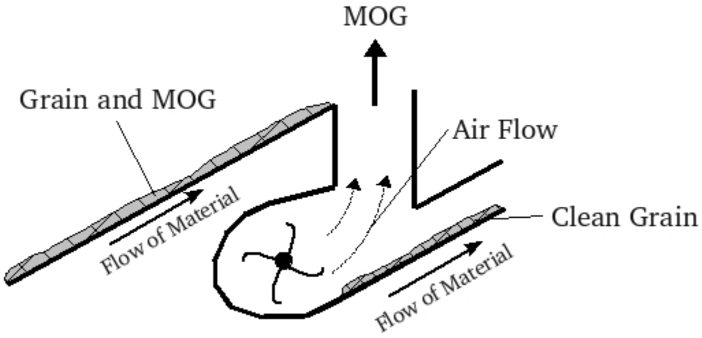


Figure 2.6 An air-elutriation cleaning system

Other solutions involve using a conventional cleaning shoe and controlling fan speed or air distribution to minimize grain loss from the cleaning shoe on contoured land. Stahl, Freye, and Kutzbach (1981) discussed the use of a split axial fan and control system that slows down the uphill side of the fan and speeds up the downhill side in order to direct air where it is most needed when operating on a side-hill. Cleaning shoe grain loss is significantly reduced using this system. Other solutions based on this idea use adjustable baffles to direct air to the side of the shoe where material accumulates

(Potter, 1955).

Other developments involve altering the distribution of material on top of the chaffer. Clipston (1938) described a movable divider system that adjusts to shift material to the uphill side of the chaffer when in a side-hill orientation. Harris and Harris (1986) discusses adding baffles to the sides of the chaffer to induce turbulence in the air stream to reduce material accumulation on the chaffer surface when in a side-hill orientation. Both developments showed improvements in side-hill performance of the cleaning shoe.

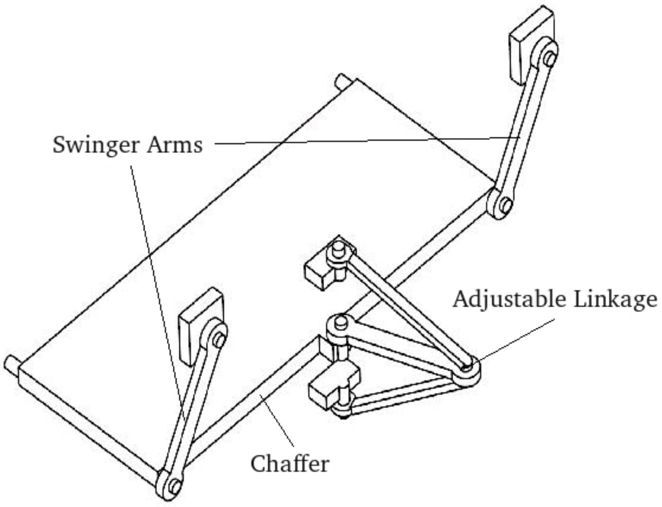


Figure 2.7 A chaffer with adjustable shake geometry

The final method that attempts to compensate for side-hill slopes is modification of shake geometry of the cleaning shoe. Glaubitz, Eis, and Fromme (1986) described a mechanism that imparts a side displacement on the chaffer frame when at the extents of its movement, shown in Figure 2.7. The chaffer continues to shake fore and aft as in a conventional shoe and also shakes in the downhill direction of a side slope on the fore stroke and in the uphill direction on the aft stroke. This design has a problem of inducing a twisting action into the chaffer when viewed from the top, resulting in a less efficient swinging path for moving material uphill. Duquesne and Somers (2008) solved this problem and ensures a purely linear path of side displacement by continuously adjusting the mechanism throughout the chaffer's movement. This development allows significantly lower cleaning losses on hill-sides while not requiring major design changes to a conventional cleaning shoe. This method is offered as an option on some combines from New Holland and Claas to allow side-hill slope correction.

A simpler modification to a conventional cleaning shoe to allow a side displacement was described by Heidjann and Fromme (1982). In this design, shown in Figure 2.8, the swinger arm is modified to have an adjustable swing axis so that it can operate in either a conventional configuration or add side shake into the chaffer motion to correct for either side-hill direction. This mechanism is the simplest of all available designs and requires little modification to the rest of the combine. The downfall of modifying the shake geometry is that the combine body must be widened to accommodate side displacement of the sieves and considerations must be made in the design of the combine for the lateral forces that are not typically experienced due to the side displacement of the sieves.

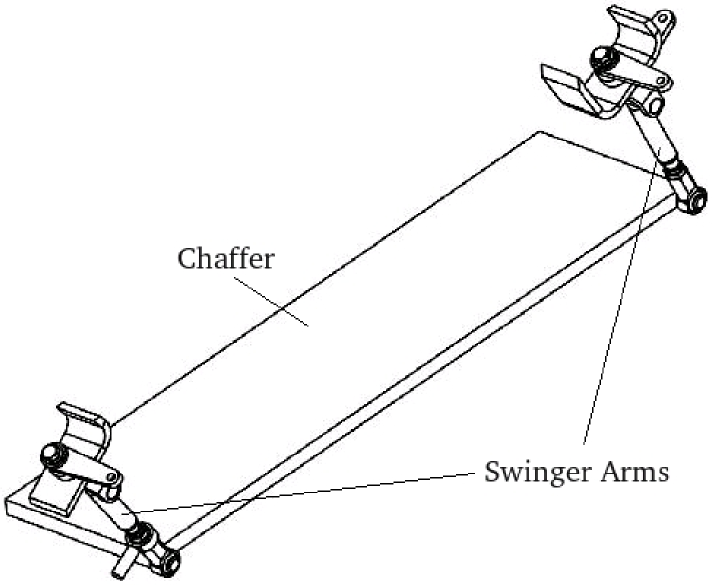


Figure 2.8 A chaffer using rotating swinger arms to modify shake geometry

## 2.4 Performance of various slope compensation methods

There is little published literature about the performance of the different methods of slope compensation with respect to reducing grain loss besides the general observations available from patent applications for the different mechanisms. A laboratory study of the performance of the adjustable-axis swinger arm concept was described by Dilts (2005). In this study, the adjustable-axis swinger arm as well as variable speed shoe shake and fan speeds were tested to determine their effects on both lateral and longitudinal slopes. The results were favorable for the adjustable swing axis swinger arm concept which was shown to significantly decrease side-hill shoe losses. Adjustment of shake speed also showed some effects on reducing longitudinal slope losses. The study was incomplete, however, as only clean corn was run through the cleaning shoe, which resulted in a recommended fan speed of zero to be necessary for optimal operation due to the lack of MOG in the tests.

As that study showed great promise in minimizing side-hill losses and, to a lesser extent, longitudinal slope losses, work is now required to show the effects of controlling shoe shake and fan speed as well as shake geometry on grain loss using both clean grain and MOG. With the current study, a full model will be available to determine cleaning shoe grain loss in any physical orientation as a function of crop factors as well as cleaning shoe operating parameters.

# CHAPTER 3. OBJECTIVES

The objective of this project was to determine if a cleaning shoe with variable shake geometry, fan speed, and shake speed could be comparable in performance on both level land and on any combination of lateral and longitudinal slopes with minimal grain loss observed in any case. In order to achieve this goal, there were three separate goals to complete: modification of previous clean-grain test stand to accommodate grain-and-MOG test runs; completion of all necessary runs to sufficiently develop a statistical model for grain loss; and determination of a model that predicts grain loss as a function of the crop and field conditions as well as cleaning shoe operational parameters.

## 3.1 Modification of previous test stand

Because the clean-grain-only test stand was based on a 60-series John Deere half-width cleaning shoe, all modifications were required to stay true to the production machine as much as possible to ensure similar material handling between the test stand and production machine. In order to complete this objective, care would have to be taken to make sure that all crop material entrances and exits as well as side and top paneling and any interior obstructions were similar to the production machine. Additional paneling was required to be sealed and not allow crop material or air to exit in a way that was not true to the production machine design.

## 3.2 Completion of test runs

Each test run was required to comply with previous clean-grain testing procedure, with any necessary steps resulting from the addition of MOG to the grain that was run through the machine. After each test, grain from the test stand was required to be weighed directly from the test stand, cleaned, and weighed again to determine the amount of trash in each sample. Material discharged from the rear of the machine was required to also be cleaned and any grain removed was required to be weighed to obtain an exact grain loss from the cleaning shoe.

## 3.3 Statistical modeling

The recorded data was required to be fit to an appropriate statistical model that best described the response of grain loss to field and control factors of the test stand. Any appropriate reductions in the model was required to be performed to determine the simplest model possible. From the simplified model, equations were required to be developed to find operational factors for cleaning shoe operation in any field and crop conditions and machine orientation which resulted in minimal grain loss.

# CHAPTER 4. TEST STAND DEVELOPMENT

## 4.1 Test stand design

The test stand used for this study was modeled around a John Deere 60-series combine cleaning shoe. It was essentially a production cleaning shoe with some key modifications made to facilitate testing of cleaning shoe parameters on level ground or complex slopes. The cleaning shoe was reduced to half the width of a conventional cleaning shoe to reduce material requirements for each test run. Custom swing arms were installed to the chaffer frame to allow a side input of up to 50 mm either to the left or right of the machine. The swing arms were of the rotating swing axis type, whereby adjusting the angle of the swing pivot relative to the body of the combine altered the chaffer motion to change from conventional shoe motion to a conventional motion with side displacement at a minimum on the fore-stroke of the oscillation and at a maximum at the aft-stroke of the oscillation. The swing arms were kept at the same relative angles through the use of tie rods, allowing simple adjustment of side displacement. To accommodate the extra displacement from the use of side input, the body panels were widened and custom seals were used to reduce grain leakage below the chaffer during conventional swinging and swinging with side displacement. Two electric motors with variable frequency drives were used on the test stand: one for the sieve motion and one for the fan. Shake speed was continuously adjustable up to 350 RPM and fan speed was continuously adjustable up to 1100 RPM. The cleaning shoe was fixed in a frame that allowed up to 17 degrees of tilt in longitudinal slopes, lateral slopes, or any combination thereof.

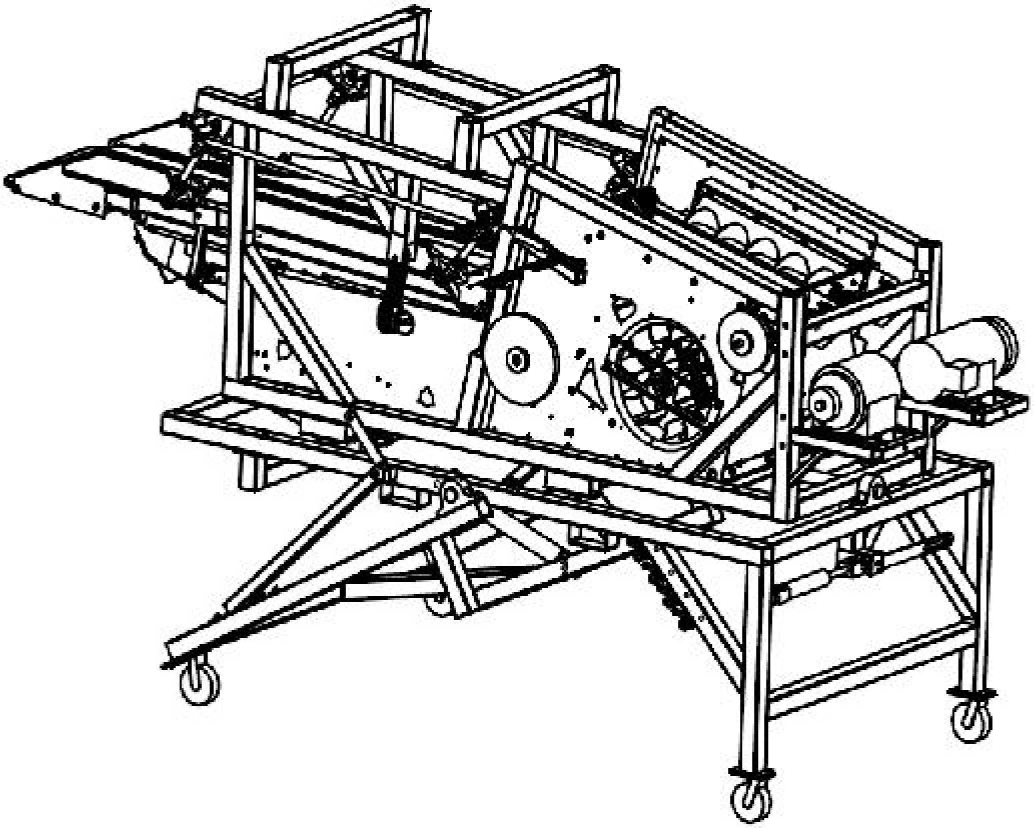


Figure 4.1 Test stand used for previous clean-grain only study

The previous test stand, shown in Figure 4.1, was not equipped to handle the addition of MOG because it lacked proper enclosure from the outside environment. To solve this, the body panels were extended upward to meet upper panels whose positions and sizes were made to match the inside of a production John Deere 60-series combine. The uppermost panel held the place of the engine deck while the panels toward the front represented the position of the rotor. The rear panels were identical in geometry to the production machine. A panel inside the test stand represented the return pan's location. The return pan typically oscillates to bring crop material from the rear of the rotor to the front of the cleaning shoe. The panel in the test stand was fixed, but no crop and minor MOG accumulation occurred on the panel. The addition of rubber curtains on the sides of the chaffer was necessary to prevent material from overflowing on extreme side slopes. Rubber curtains were also added to the front of the enclosure immediately after the feed augers to prevent the back-flow of air and to prevent any pre-cleaning of the crop and MOG mixture before it entered the test stand. The revised test stand is shown in Figure 4.2.

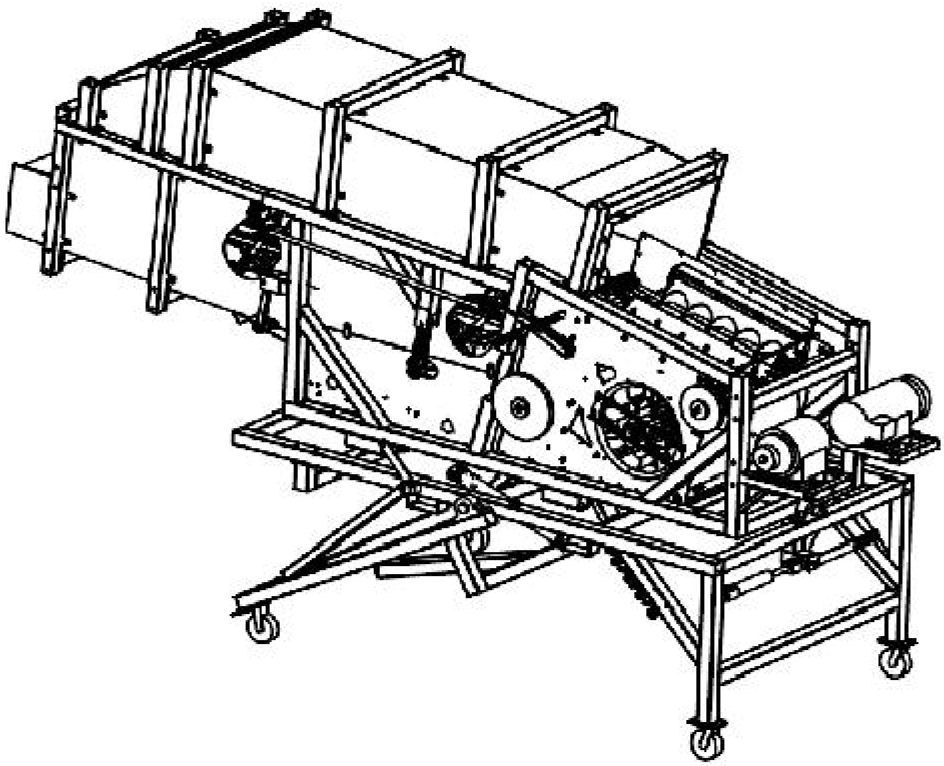


Figure 4.2 Revised test stand used in this study.

A conveyor belt from a production draper head was used to feed the test stand with grain and MOG. Side walls were present on the conveyor belt to accommodate larger amounts of materials. Clean grain and tailings were collected from the shoe and held in bins during testing. An enclosure surrounded the back end of the test stand to collect discarded MOG and grain, with bins placed inside the enclosure to facilitate material handling.

Instrumentation was used to monitor various operating parameters during test runs. Conveyor belt speed, fan speed, and shake speed were measured by hall effect sensors mounted to each respective driveshaft. Inclination angles as well as side input were monitored by potentiometers mounted to pivot points on the frame of the test stand. Each sensor output was conditioned and recorded using custom circuitry and software.

## 4.2 Testing procedure

The desired grain feed rate and MOG-to-grain ratio was first determined for the run. The MOG was then weighed out and the proper amount for the test was added to the conveyor belt and spread out evenly. The proper amount of grain for the test was then weighed out and spread evenly on top of the MOG. The orientation of the test stand was then set, after which the desired fan and shake speeds were set. The desired side input was set by adjusting a turnbuckle. A “dry run” was then performed with the fan and shake motor engaged to ensure correct setup of the test stand. The data acquisition system was then activated to begin recording data. The test was run by activating the conveyor belt with the test stand in operation. During the run, clean grain fell from the lower sieve and into a collection bin while material from the tailings was collected in a bin where the tailings return auger is typically mounted on a production machine. The test stand was then run at varying fan and shake speeds to ensure complete cleanout of all material from the test stand. A mass balance of material fed into and collected from the test stand is shown in Figure 4.3.

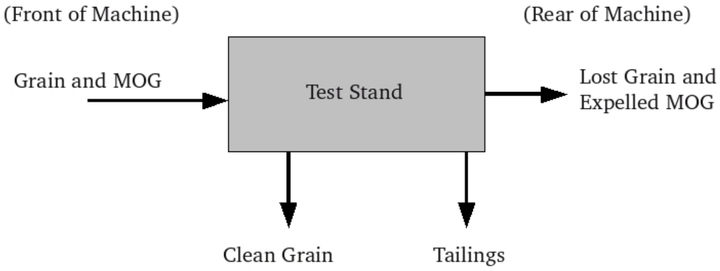


Figure 4.3 Mass balance of material flows through the test stand.

After the run was complete, the weights of the material in the clean grain and tailings bins were recorded. The collected grain was run separately through a Clipper model M-2B fanning mill, where any trash was removed from the grain. The cleaned grain was then weighed and weights were recorded. The chaff from the rear of the machine was then gathered and run through the fanning mill, with care taken to ensure all grain was thoroughly removed from the MOG. The grain that was removed was then weighed and its weight was recorded. Grain loss was calculated by dividing the weight of grain found in the expelled MOG by the weight of the grain initially fed into the test stand. At that point the test was completed and all weights were recorded in the data acquisition program. A typical test took approximately 35-55 minutes, depending on crop type as well as grain and MOG feed rates.

# CHAPTER 5. EXPERIMENTAL METHOD

## 5.1 Testing materials

Because the initial clean-grain experiments were performed with only clean corn and were found to be satisfactory to continue research, the testing material used for this study consisted of clean corn and corn MOG for the first set of experiments and clean wheat and wheat MOG was used for the second set of experiments. The corn MOG used for experimentation was from the 2006 harvest from a combine operating in the field. The wheat MOG used was from the processing of wheat bales through a combine rotor test stand in a laboratory in January 2008. While the corn MOG contained little residual grain and could be used directly on the test stand, the wheat MOG had to be cleaned prior to testing to remove residual grain. The wheat MOG was cleaned by running it through the cleaning shoe at baseline factory-specified settings and then through the fanning mill. All grain and MOG from each crop was of the same moisture content which was considered to be field dry in each case. The grain used for all experiments consisted of #2 yellow dent *zea mays* and hard red winter *triticum aestivum* for the corn and wheat runs, respectively. Each testing run lasted a duration of 15 seconds of actual test stand operation, plus time after the run to ensure that all material has completely evacuated the test stand.

## 5.2 Baseline establishment and proof of concept

Before a full design of experiments (DOE), an initial set of runs was performed to determine baseline losses on level land. During the runs, the chaffer and sieve openings were also fine-tuned to provide realistic grain losses on level land of less than one percent. The fan and shake speeds were held at conventional factory-specified settings and no side input was used for these tests. For corn, grain flow rates of 10, 20, 30, 40, and 50 tons per hour were run through the machine with a fixed MOG to grain mass ratio of 1 pound of MOG per 15 pounds of grain. The final machine was set up with a 16 mm chaffer opening and 17 mm sieve opening on a long-toothed chaffer and sieve, which provided realistic grain losses at each flow rate. In the case of wheat, grain flow rates of 4, 9, 14, 19, and 24 tons per hour were used with a constant MOG-to-grain ratio of 1 pound of MOG per 6 pounds of grain. Chaffer and sieve openings were also set to obtain realistic losses for wheat on level land using a general-purpose chaffer and sieve. The chaffer and sieve openings used for wheat were 11.5 mm and 13 mm, respectively.

After the baseline runs were completed, a set of proof-of-concept runs were performed. The purpose of these runs was to make sure that adding in side input would reduce losses when the test stand was in a side-hill orientation. The test stand was again operated at standard fan and shake speeds. The machine was tilted 5 and 10 degrees to the side with no side input and tests were performed at each flow rate with a constant MOG-to-grain ratio of 1:15 for corn and 1:6 for wheat. A 12.5 mm and 25 mm side input was then added to a 5 and 10 degree side tilt, respectively, and the tests were re-run. These proof-of-concept runs were performed for both corn and wheat. Longitudinal slopes were not considered for these runs because it was not initially clear whether fan or shake speed have the most impact on grain loss in those orientations. Because these runs verified that side input would compensate for a side slope, a full DOE was developed to fully test the response of grain loss by controlling fan and shake speed, side input, longitudinal and lateral slopes, and grain and MOG feed rates.

## 5.3 Design of experiments

This study used seven experimental factors, of which four were termed field factors and the remaining three were termed control factors. Field parameters were defined as those that were beyond the control of a combine operator, while control parameters were those that were adjustable to respond to field factors. Field variables included longitudinal and lateral slopes and grain and MOG feed rates. Control variables used were fan and shake speeds and side displacement of chaffer sieve. Because a full factorial design of experiments would have consisted of a very large number of runs due to the number of variables of interest to the study, a reduced design of experiments was developed.

The DOE for this study follows the DOEs used for the previous clean-grain only study with the addition of another field variable, MOG-to-grain ratio. The DOE was a modified central composite design (MCCD) consisting of 51 runs with no blocking. The MCCD was chosen after noting success in initial clean-corn testing with a central composite design and improving on the design by including the effect of symmetry in lateral slopes and side input effects to reduce the number of runs necessary for sufficient model development, as explained in Morris, Dilts, Birrell, and Dixon (2008). The DOE provided a second-order response surface without the need for a full factorial DOE by using specific test setups to define the corners of the test design while using axial points to define the extremes of each variable individually. There were several repetitions of tests near the middle of the operating range to balance out the effect of the extremes. A second-order response model was used due to its ability to adequately model the physical system and easily provide a control surface to define optimal settings for each control variable based on field parameters. The same DOE was used for both corn and wheat testing. The developed DOE is shown in Table 5.1. The values are coded, with

0 representing the center point, ±1 representing the corner points, and ±2 representing the axial points. The center point was considered the baseline testing point and the typical operating conditions of the machine in the field.

The coded values match up to the actual testing parameters shown in Table 5.2 for corn and Table 5.3 for wheat. Side slopes were tilted to the left and side inputs were used at settings to correct for the left-tilted side slope. Negative longitudinal slopes indicate an uphill orientation and positive longitudinal slopes indicate a downhill orientation. Fan speeds were scaled to match an equivalent air flow with a production shoe for both crops. Blank values indicate a configuration that was not tested. These blank values which correspond to side slopes to the right and side inputs to correct for a right-tilted machine were not tested due to the assumed symmetrical behavior of the system when tilted in either direction.

## 5.4 Statistical modeling

Morris, Dilts, Birrell, and Dixon (2008) explained the effect of using physically symmetrical factors in a second-order surface response model, which results in fewer initial terms being present than in a model without such factors. The general formula for a surface response model is given as

$$Grain\ Loss,\ \% = \beta_0 + \sum_{i=1}^{7} \beta_i x_i + \sum_{i=1}^{7} \beta_{ii} x_i^2 + \sum_{i=1}^{6} \sum_{j=i+1}^{7} \beta_{ij} x_i x_j + \epsilon \tag{5.1}$$

where every $\beta$ is a coefficient that is determined experimentally, every $x$ is the value of a factor for a single experimental run, and $\epsilon$ is the error. The experimental factors are shown in Table 5.4.

This model assumes interaction between all of the factors. From earlier runs, as well as the analysis shown in Morris, Dilts, Birrell, and Dixon (2008), it is known that side slope and side input have no interaction with the other factors and interact only with

Table 5.1 Design of experiments used in this study for both crops

| **Grain Feed Rate** | **MOG/Grain Ratio** | **Longitudinal Slope** | **Lateral Slope** | **Fan Speed** | **Shake Speed** | **Side Input** |
|---|---|---|---|---|---|---|
| +1 | +1 | +1 | +1 | +1 | +1 | +1 |
| +1 | +1 | -1 | 0 | +1 | +1 | +1 |
| -1 | +1 | +1 | 0 | +1 | -1 | 0 |
| -1 | +1 | -1 | +1 | +1 | -1 | 0 |
| -1 | +1 | -1 | 0 | -1 | +1 | 0 |
| -1 | +1 | +1 | +1 | -1 | +1 | 0 |
| +1 | +1 | -1 | +1 | -1 | -1 | +1 |
| +1 | +1 | +1 | 0 | -1 | -1 | +1 |
| +1 | -1 | -1 | +1 | +1 | +1 | 0 |
| +1 | -1 | +1 | 0 | +1 | +1 | 0 |
| -1 | -1 | -1 | 0 | +1 | -1 | +1 |
| -1 | -1 | +1 | +1 | +1 | -1 | +1 |
| -1 | -1 | +1 | 0 | -1 | +1 | +1 |
| -1 | -1 | -1 | +1 | -1 | +1 | +1 |
| +1 | -1 | +1 | +1 | -1 | -1 | 0 |
| +1 | -1 | -1 | 0 | -1 | -1 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| -1 | +1 | +1 | 0 | +1 | +1 | +1 |
| -1 | +1 | -1 | +1 | +1 | +1 | +1 |
| +1 | +1 | +1 | +1 | +1 | -1 | 0 |
| +1 | +1 | -1 | 0 | +1 | -1 | 0 |
| +1 | +1 | -1 | +1 | -1 | +1 | 0 |
| +1 | +1 | +1 | 0 | -1 | +1 | 0 |
| -1 | +1 | -1 | 0 | -1 | -1 | +1 |
| -1 | +1 | +1 | +1 | -1 | -1 | +1 |
| -1 | -1 | -1 | 0 | +1 | +1 | 0 |
| -1 | -1 | +1 | +1 | +1 | +1 | 0 |
| +1 | -1 | -1 | +1 | +1 | -1 | +1 |
| +1 | -1 | +1 | 0 | +1 | -1 | +1 |
| +1 | -1 | +1 | +1 | -1 | +1 | +1 |
| +1 | -1 | -1 | 0 | -1 | +1 | +1 |
| -1 | -1 | +1 | 0 | -1 | -1 | 0 |
| -1 | -1 | -1 | +1 | -1 | -1 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | +2 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | +2 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | +2 | 0 |
| 0 | 0 | 0 | 0 | 0 | -2 | 0 |
| +2 | 0 | 0 | 0 | 0 | 0 | 0 |
| -2 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | +2 | 0 | 0 | 0 | 0 |
| 0 | 0 | -2 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | +2 |
| 0 | 0 | 0 | 0 | 0 | 0 | +2 |
| 0 | 0 | 0 | 0 | 0 | 0 | +2 |
| 0 | 0 | 0 | +2 | 0 | 0 | 0 |
| 0 | 0 | 0 | +2 | 0 | 0 | 0 |
| 0 | 0 | 0 | +2 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | -2 | 0 | 0 |
| 0 | -2 | 0 | 0 | 0 | 0 | 0 |

Table 5.2 Testing parameters for corn runs

| **Coded Value** | **-2** | **-1** | **0** | **+1** | **+2** |
|---|---|---|---|---|---|
| **Grain feed rate (tons/hr)** | 10 | 20 | 30 | 40 | 50 |
| **Side slope (degrees)** | | | 0 | 5 | 10 |
| **Longitudinal slope (degrees)** | -10 | -5 | 0 | 5 | 10 |
| **MOG/Grain mass ratio** | 1:25 | 1:20 | 1:15 | 1:10 | 1:5 |
| **Fan speed (RPM)** | 600 | 675 | 750 | 825 | 900 |
| **Shake speed (RPM)** | 250 | 275 | 300 | 325 | 350 |
| **Side input (mm)** | | | 0 | 15 | 30 |

Table 5.3 Testing parameters for wheat runs

| **Coded Value** | **-2** | **-1** | **0** | **+1** | **+2** |
|---|---|---|---|---|---|
| **Grain feed rate (tons/hr)** | 4 | 9 | 14 | 19 | 24 |
| **Side slope (degrees)** | | | 0 | 5 | 10 |
| **Longitudinal slope (degrees)** | -10 | -5 | 0 | 5 | 10 |
| **MOG/Grain mass ratio** | 1:10 | 1:8 | 1:6 | 1:4 | 1:2 |
| **Fan speed (RPM)** | 500 | 550 | 625 | 700 | 750 |
| **Shake speed (RPM)** | 250 | 275 | 300 | 325 | 350 |
| **Side input (mm)** | | | 0 | 15 | 30 |

each other. Therefore, any terms which imply interaction between side slope or side input and any other factor can be removed to simplify the model. Further, it is observed from pilot runs that the cleaning shoe loses grain in the same way as tilted to the left or right side. From this observation, then, the linear terms for side slope and side input can be removed, as their effects cancel each other out due to their symmetry about the

Table 5.4 Experimental factors

| **Variable** | **Factor name** |
|---|---|
| $x_1$ | Grain feed rate |
| $x_2$ | MOG/Grain ratio |
| $x_3$ | Longitudinal slope |
| $x_4$ | Side slope |
| $x_5$ | Fan speed |
| $x_6$ | Shake speed |
| $x_7$ | Side input |

center point. The equation that can be used for a full model, then, is given as

$$\begin{aligned}
\textit{Grain Loss}, \quad &= \beta_0 + \sum_{i=1,2,3,5,6} \beta_i x_i + \sum_{i=1}^{7} \beta_{ii} x_i^2 + \\
&\beta_{12}x_1x_2 + \beta_{13}x_1x_3 + \beta_{15}x_1x_5 + \beta_{16}x_1x_6 + \\
&\beta_{23}x_2x_3 + \beta_{25}x_2x_5 + \beta_{26}x_2x_6 + \\
&\beta_{35}x_3x_5 + \beta_{36}x_3x_6 + \\
&\beta_{47}x_4x_7 + \beta_{56}x_5x_6 + \epsilon
\end{aligned} \tag{5.2}$$

This model was used as a starting point for modeling experimental data. If it was observed that any factor or interaction of factors was not significant to the model during analysis, those were also removed to further simplify the model.

# CHAPTER 6. RESULTS AND DISCUSSION

## 6.1 Baseline establishment

Baseline loss curves are shown for corn in Figure 6.1 and for wheat in Figure 6.2. Due to difficulties in fine-tuning the chaffer and sieve openings to provide consistent results, wheat grain losses are greater than 1% at higher grain flow rates, but are still suitable for baseline results.

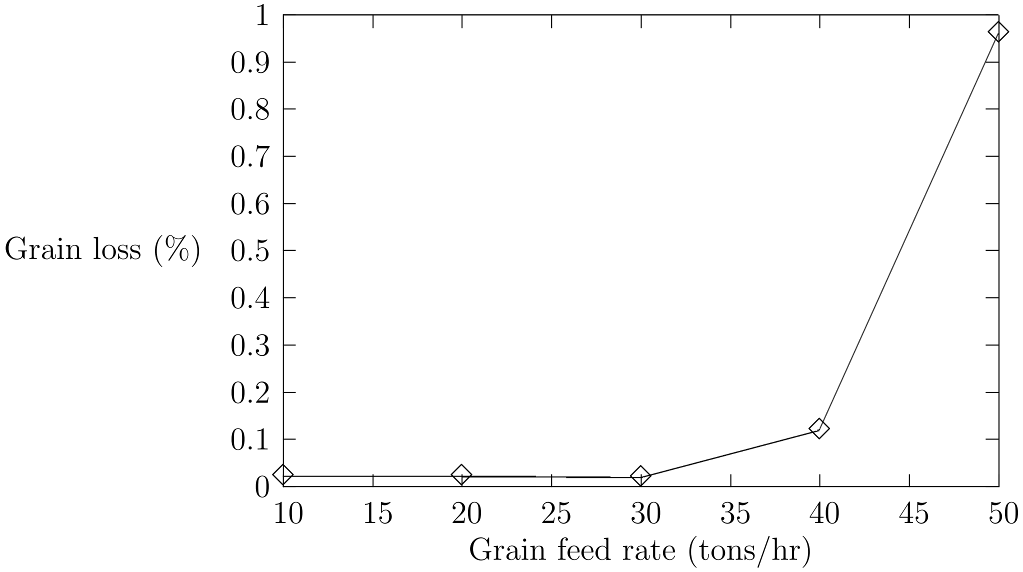


Figure 6.1 Baseline loss curve for corn

Overall, both loss curves respond with an expected behavior of grain loss being minimal at the median grain flow rate and increasing as grain feed rate both increases and decreases. Grain loss increases at lower feed rates because there is less material on

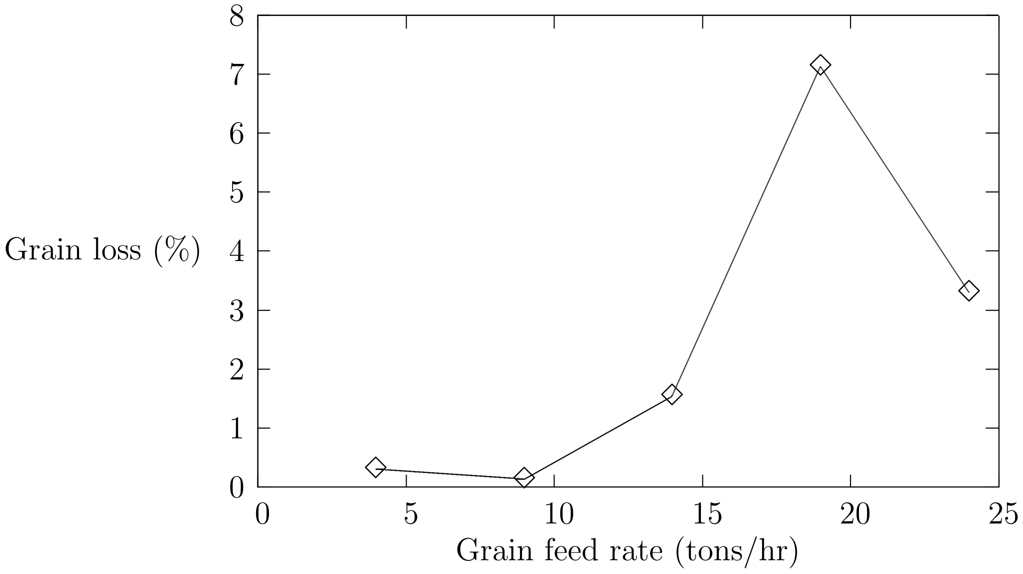


Figure 6.2 Baseline loss curve for wheat

the chaffer surface. Since there is less material, the crop mat thickness is reduced as compared to middle flow rates. Because the crop mat is thin, there is a higher possibility for unevenness of material to develop on the chaffer, thus reducing the effectiveness of aerodynamic separation and allowing grain to be carried out of the machine along with the MOG. At higher grain flow rates, higher grain loss occurs because the fan cannot supply enough air to the crop mat to ensure complete separation of the grain from the MOG. As a result, grain that is not separated aerodynamically undergoes the same fate as encountered at a low grain flow rate and is lost from the machine.

One deviation from the trend of increasing grain loss at lower grain flow rates is seen at the lowest extreme grain flow rate for corn, where the grain loss is the same as at the next higher grain flow rate. This is due to the ease of separation of corn from corn MOG compared to the separation of wheat from wheat MOG, which will be explored in depth later in the chapter.

A deviation from the trend of increasing grain loss with flow rate is seen in the wheat baseline curve, where grain loss decreased at the highest extreme grain flow rate from the next highest grain flow rate. This occurs due to the high feed rate of crop material greatly reducing transient effects during testing. The amount of material in the cleaning shoe can be thought of as a damper on the system; as crop material mass increases, transient effects are less pronounced and the system reaches steady state more quickly than at lower grain flow rates. From observations on production combines in the field, grain loss is typically higher at transient states such as the introduction of a steady flow of crop material to the machine or running the machine until it is empty as is typical at the completion of a pass during harvest. In the case of the test stand at lower material feed rates, the machine never fully enters steady-state operation at lower grain feed rates and remains in the transient state of operation throughout the duration of crop material being present in the machine due to the relatively low amount of crop material present in the cleaning shoe. At the highest flow rate the machine quickly enters steady-state operation due to the high amount of crop material present in the cleaning shoe which results in lower grain loss than at the next lower grain feed rate. This is not seen as a major issue due to this flow rate being the extreme condition and the generally increasing trend that is observed with wheat which follows previous observations.

## 6.2 Proof of concept

Results of the proof of concept runs for corn are shown in Figures 6.3 and 6.4 for a 5 and 10 degree side slope, respectively. Proof of concept results for wheat are shown in Figures 6.5 and 6.6 for a 5 and 10 degree side slope, respectively. The plots show the grain losses on level land (baseline), when the machine is run at either a 5 or 10 degree side slope with no side input as typical in a conventional machine, and when the machine is run at a 5 or 10 degree side slope with a 12.5 mm side input for a 5 degree side slope and a 25 mm side input for a 10 degree slope. The amounts of side input tested are determined by analytical models of the chaffer shake geometry using clean corn as the operating material found in the previous clean-grain-only research.

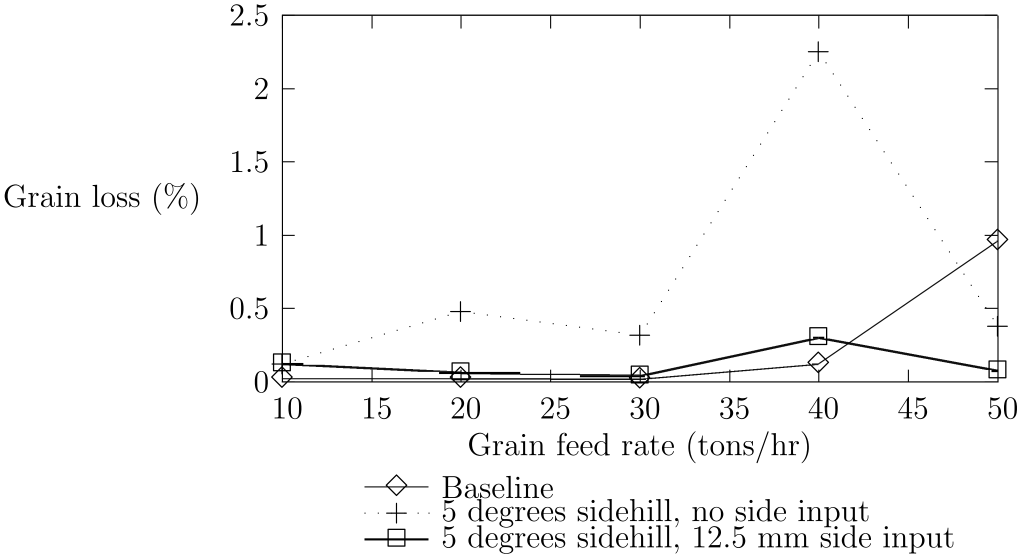


Figure 6.3 Proof of concept loss curves for corn with 5 degree side slope

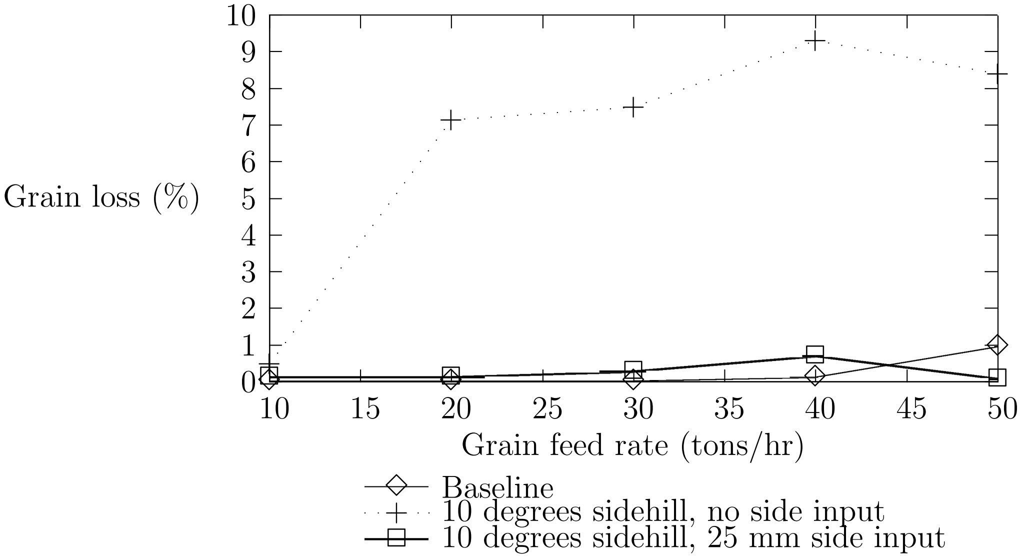


Figure 6.4 Proof of concept loss curves for corn with 10 degree side slope

For both corn and the wheat, the loss curves for the 5 and 10 degree tilted with and without side input continue to follow the trend of increasing grain losses at increasing grain flow rates. The loss curves for corn at both tilts and side inputs show a lower grain loss at the extreme highest grain flow rate than at the next highest grain flow rate. This is attributed to the high grain flow rate forcing the cleaning shoe to the steady-state mode of operation as experienced with the wheat baseline loss curves. The loss curves for wheat at both side tilts and side inputs shows a steady increase of grain loss as grain feed rate increases, but levels off at the highest grain flow rate for all but the 10 degree tilt with 25 mm side input plot. This is again due to the dynamic response of the cleaning shoe at the highest grain flow rate and is therefore not a cause for concern. For the corn runs, grain losses increase from an average of 0.228% at baseline to an average of 0.710% and 6.560% when the cleaning shoe is tilted to the side 5 and 10 degrees, respectively. For the wheat runs, grain losses increased from an average of 2.483% to an average of 7.521% and 15.272% when when machine is tilted 5 and 10 degrees to the side, respectively.

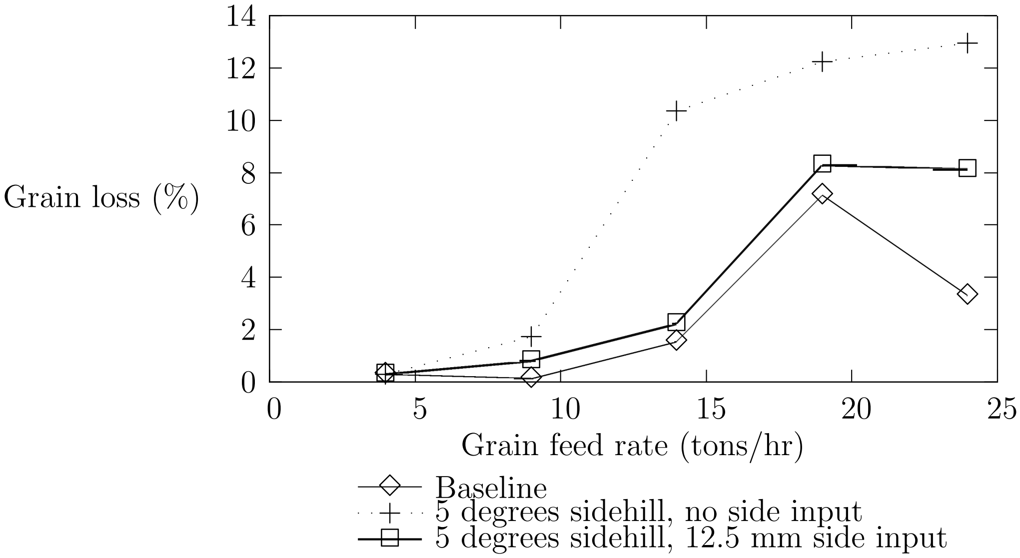


Figure 6.5 Proof of concept loss curves for wheat with 5 degree side slope

The addition of 12.5 mm of side input for a 5 degree side slope and 25 mm of side input for a 10 degree side slope reduces grain loss considerably for both corn and wheat in the proof of concept runs. For corn, side input reduces grain loss to an average of 0.118% and 0.256% for a 5 and 10 degree side slope, respectively, while for wheat a reduction

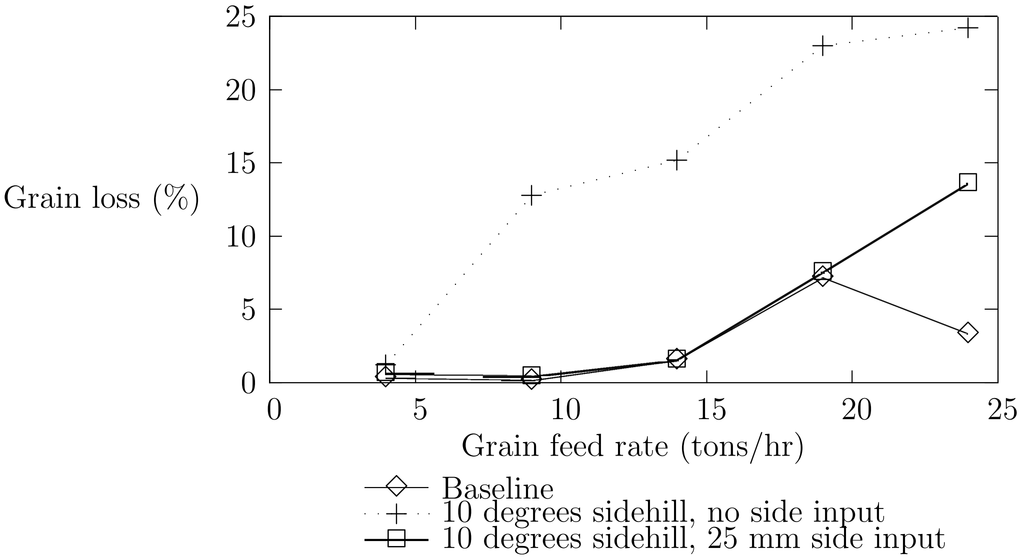


Figure 6.6 Proof of concept loss curves for wheat with 10 degree side slope

to an average of 3.941% and 4.722% for a 5 and 10 degree side slope, respectively is observed with the addition of side input. These reductions are comparable with grain losses observed on level land.

## 6.3 Corn design of experiments

Due to the non-normal nature of the grain loss data, a log-transform of grain loss is performed prior to model development. This process also helps to distinguish better between the smaller grain losses that are experienced as well as to minimize the effect of extremely large grain losses that are encountered in some runs. The log-transform does not affect the derivation of control algorithms from the surface-response model because the log function has a one-to-one relationship with its independent variable. In other words, minimizing $log[f(x)]$ has the same effect as minimizing $f(x)$ by itself.

When applied to the data collected in the corn DOE, the full model has an $R^2$ value of 0.8535 and uses 24 parameters. The full model is reduced using the stepwise reduction method with an alpha level of 0.05 to yield the reduced model. The reduced grain loss model for corn has an $R^2$ value of 0.8111 and uses only 9 parameters. The model is defined as

$$\begin{aligned} log(Grain\ Loss,\ \%) &= \beta_0 + \beta_1 x_1 + \beta_5 x_5 + \beta_{44} x_4^2 + \beta_{77} x_7^2 + \\ &\quad \beta_{13} x_1 x_3 + \beta_{16} x_1 x_6 + \beta_{47} x_4 x_7 + \beta_{56} x_5 x_6 + \epsilon \end{aligned} \tag{6.1}$$

From this model it is seen that grain feed rate and fan speed linearly affect grain loss, side slope and side input both affect grain loss quadratically, and interaction terms exist between grain feed rate and both longitudinal angle and shake speed. An interaction is also found between side slope and side input as well as between fan and shake speeds. The reduced model coefficients are shown in Table 6.1. The coefficients include unit conversions, so operational parameters can be used directly in the model to predict grain loss.

Table 6.1 Model coefficients for corn

| **Term** | **Value** | **Std. Error** | **t Ratio** | **P> \|t\|** |
|---|---|---|---|---|
| $\beta_0$ | 0.9526936 | 0.661057 | 1.44 | 0.1558 |
| $\beta_1$ | 0.2142502 | 0.079789 | 2.69 | 0.0098 |
| $\beta_5$ | -0.013909 | 0.003444 | -4.04 | 0.0002 |
| $\beta_{44}$ | 0.014348 | 0.002503 | 5.73 | <.0001 |
| $\beta_{77}$ | 0.000641 | 0.000279 | 2.30 | 0.0257 |
| $\beta_{13}$ | 0.0046886 | 0.000402 | 11.66 | <.0001 |
| $\beta_{16}$ | -0.000686 | 0.000262 | -2.62 | 0.0115 |
| $\beta_{47}$ | -0.008724 | 0.002038 | -4.28 | <.0001 |
| $\beta_{56}$ | 3.8278e-5 | 0.000011 | 3.45 | 0.0011 |

The grain loss predicted by the model versus measured grain loss for each run in the DOE is shown in Figure 6.7. The model does a fairly good job of predicting grain loss for lower and middle grain losses, however as measured grain loss increases, the predicted grain loss tends to be lower than the actual grain loss. The under-prediction typically occurs on runs with a higher grain feed rate, a combination of uphill and side slope, an extreme side slope condition, or when side input is utilized while the machine is not tilted to the side.

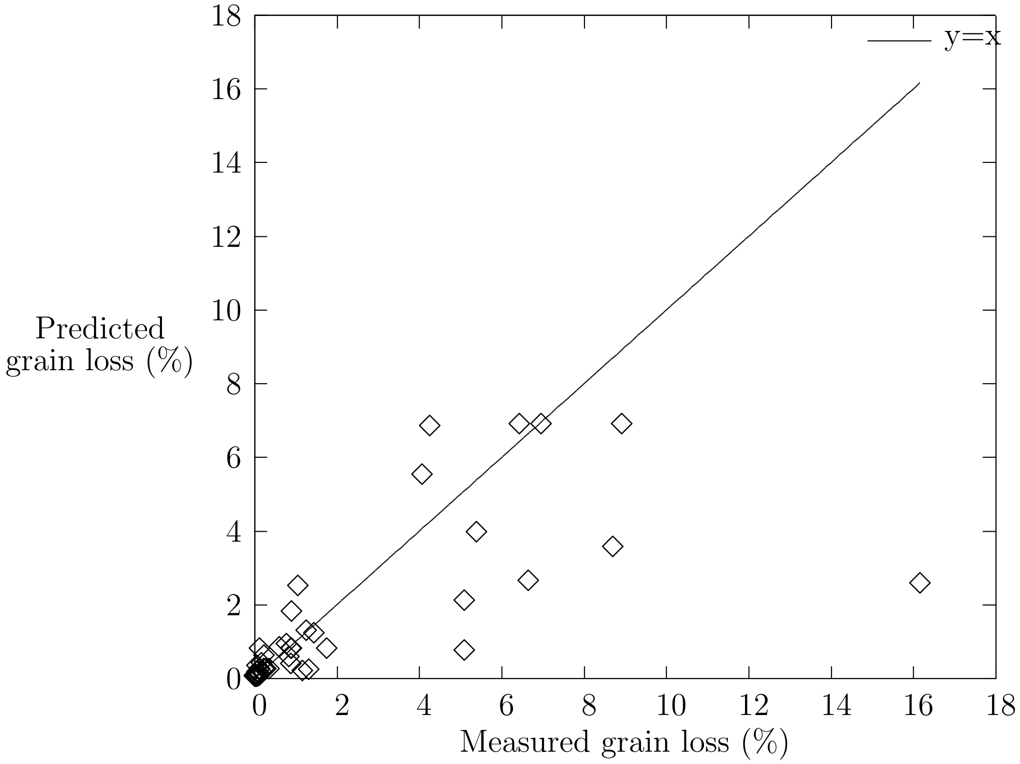


Figure 6.7 Predicted grain loss versus measured grain loss for corn

It should be noted that a full surface response model without the symmetry assumption mentioned in the previous chapter was fitted to the data. As expected, all factors and combinations of factors eliminated using the assumption of symmetry of factor response were found to be not significant when finding a sufficient reduced model. This verifies the symmetry assumptions made in the DOE as well as in determining a simplified model for grain loss.

## 6.4 Wheat design of experiments

As with corn, a log-transformation is first applied to the recorded grain loss to normalize the wheat data. The full 24-parameter model for grain loss has a $R^2$ value of 0.8636. Through the use of a stepwise reduction with an alpha level of 0.05 a 14-factor model with a $R^2$ value of 0.8440 was found. The reduced grain loss model for wheat is given as

$$\begin{aligned} log(Grain\ Loss,\ \%) &= \beta_0 + \beta_1 x_1 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{33} x_3^2 + \beta_{44} x_4^2 + \beta_{66} x_6^2 + \\ &\quad \beta_{77} x_7^2 + \beta_{12} x_1 x_2 + \beta_{15} x_1 x_5 + \beta_{26} x_2 x_6 + \beta_{35} x_3 x_5 + \\ &\quad \beta_{47} x_4 x_7 + \beta_{56} x_5 x_6 + \epsilon \end{aligned} \tag{6.2}$$

This model shows that only grain feed rate linearly affects grain loss. Quadratic effects are seen by every factor except fan speed. This model shows interaction between grain feed rate and both MOG-to-grain ratio and fan speed. Interaction also exists between MOG-to-grain ratio and shake speed, longitudinal slope and fan speed, side slope and side input, and fan and shake speeds. The coefficients for the reduced wheat grain loss model are shown in Table 6.2.

Table 6.2 Model coefficients for wheat

| **Term** | **Value** | **Std. Error** | **t Ratio** | **P> \|t\|** |
|---|---|---|---|---|
| $\beta_0$ | -8.640535 | 1.810352 | -4.77 | <.0001 |
| $\beta_1$ | 1.2118631 | 0.241212 | 5.02 | <.0001 |
| $\beta_{11}$ | -0.012066 | 0.005042 | -2.39 | 0.0208 |
| $\beta_{22}$ | -33.82714 | 8.988837 | -3.76 | 0.0005 |
| $\beta_{33}$ | -0.013172 | 0.005042 | -2.61 | 0.0121 |
| $\beta_{44}$ | 0.0154062 | 0.004273 | 3.61 | 0.0008 |
| $\beta_{66}$ | -5.522e-5 | 1.827e-5 | -3.02 | 0.0041 |
| $\beta_{77}$ | 0.0010397 | 0.000476 | 2.19 | 0.0340 |
| $\beta_{12}$ | -1.674157 | 0.335438 | -4.99 | <.0001 |
| $\beta_{15}$ | -0.000661 | 0.000285 | -2.31 | 0.0252 |
| $\beta_{26}$ | 0.1235102 | 0.021702 | 5.69 | <.0001 |
| $\beta_{35}$ | 0.0002695 | 3.251e-5 | 8.29 | <.0001 |
| $\beta_{47}$ | -0.011285 | 0.003405 | -3.31 | 0.0018 |
| $\beta_{56}$ | 2.4433e-5 | 0.000014 | 1.74 | 0.0892 |

The predicted grain loss versus measured grain loss for each wheat run is shown in Figure 6.8. The model developed for wheat does a much better job of predicting grain loss than the corn model. The model is able to predict grain loss with fewer errors in predicting significantly higher or lower grain losses than observed during experimentation. There is no pattern to runs in which there are large errors in prediction, so it is assumed that random error is the source of errors in grain loss prediction for the wheat model.

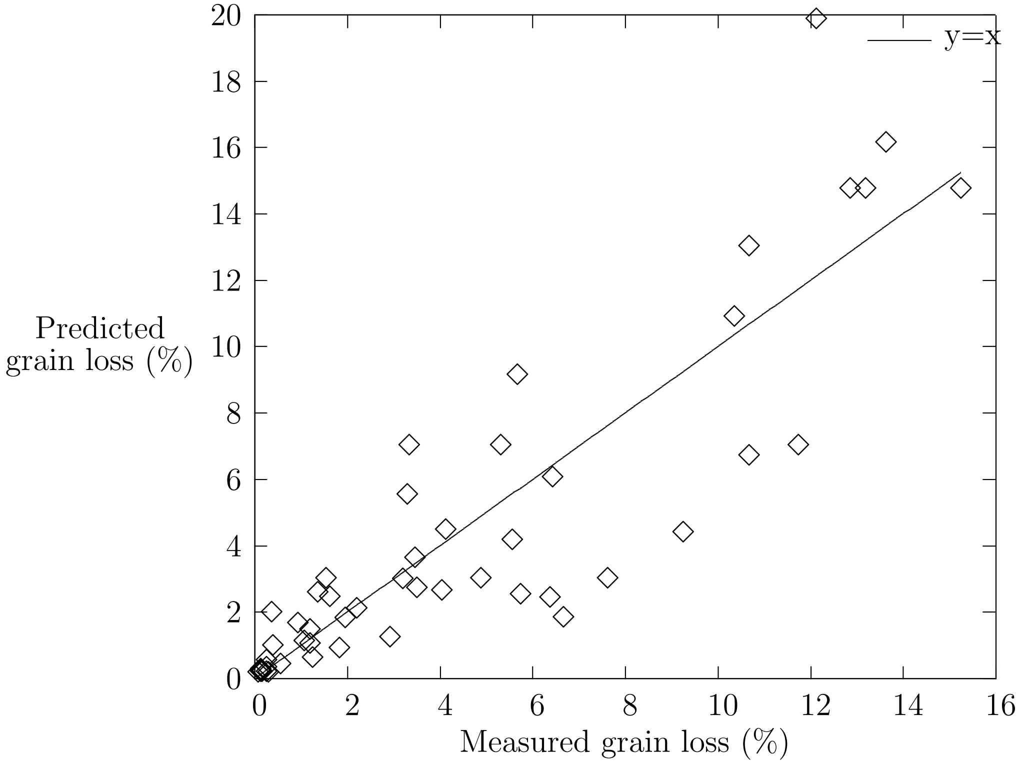


Figure 6.8 Measured and predicted grain losses for wheat

As with the corn model, a full response surface was fit to the data to ensure that the symmetry assumption is correct for wheat as well. Again the factors assumed to be zero quickly become non-significant during model reduction and are excluded from the model. From both models, the symmetry assumption is appropriate for experimental design as well as for model fitting for a diverse range of crop types.

## 6.5 Design of experiments validation runs

A set of validation runs are performed to ensure validity of the data collected from the DOE. The runs are performed around higher extreme points that are different from higher extremes that were tested in the DOE. To determine which runs to perform for validation, three runs with different configurations of non-symmetric variables are chosen. From each run selected, every combination of side slope and side input that is not originally used in the DOE is tested. The validation runs performed are shown in Table 6.3. Validation runs are performed on both crops in a random order.

Table 6.3 Validation runs performed on each crop

| Grain Feed Rate | MOG/Grain Ratio | Longitudinal Slope | Lateral Slope | Fan Speed | Shake Speed | Side Input |
|---|---|---|---|---|---|---|
| +1 | -1 | +1 | +1 | -1 | 0 | 0 |
| +1 | -1 | +1 | +1 | -1 | +1 | 0 |
| +1 | -1 | +1 | +1 | -1 | +1 | +1 |
| -1 | -1 | +1 | +1 | -1 | 0 | +1 |
| -1 | -1 | +1 | +1 | -1 | 0 | 0 |
| -1 | -1 | +1 | +1 | -1 | +1 | +1 |
| +1 | -1 | +1 | -1 | -1 | 0 | +1 |
| +1 | -1 | +1 | -1 | -1 | +1 | 0 |
| +1 | -1 | +1 | -1 | -1 | +1 | +1 |

The data from the validation runs is then used with the model developed from each DOE. The principle behind this is that the developed model from the original DOE should predict grain loss with similar accuracy for the data that it was developed on as well as an additional set of runs that was not used for model determination. A plot of predicted grain loss versus measured grain loss for the DOE and validation data with comparison best-fit lines for corn is shown in Figure 6.9.

Table 6.4 Coefficients for calibration, validation, and full-set best-fit lines for corn

| Line Type | Slope | Y-intercept | $R^2$ |
|---|---|---|---|
| Calibration | 0.8118 | 0.1663 | 0.8016 |
| Validation | 0.6717 | 1.7597 | 0.8232 |
| Full set | 0.8271 | 0.2863 | 0.8215 |

The values of the coefficients of the best-fit lines are shown in Table 6.4, as are $R^2$ values. Figure 6.9 shows that the validation set does not differ much from the calibration set of data because the slopes of the best-fit lines are similar and because the addition of the validation runs to the DOE runs does not greatly change the slope of the calibration

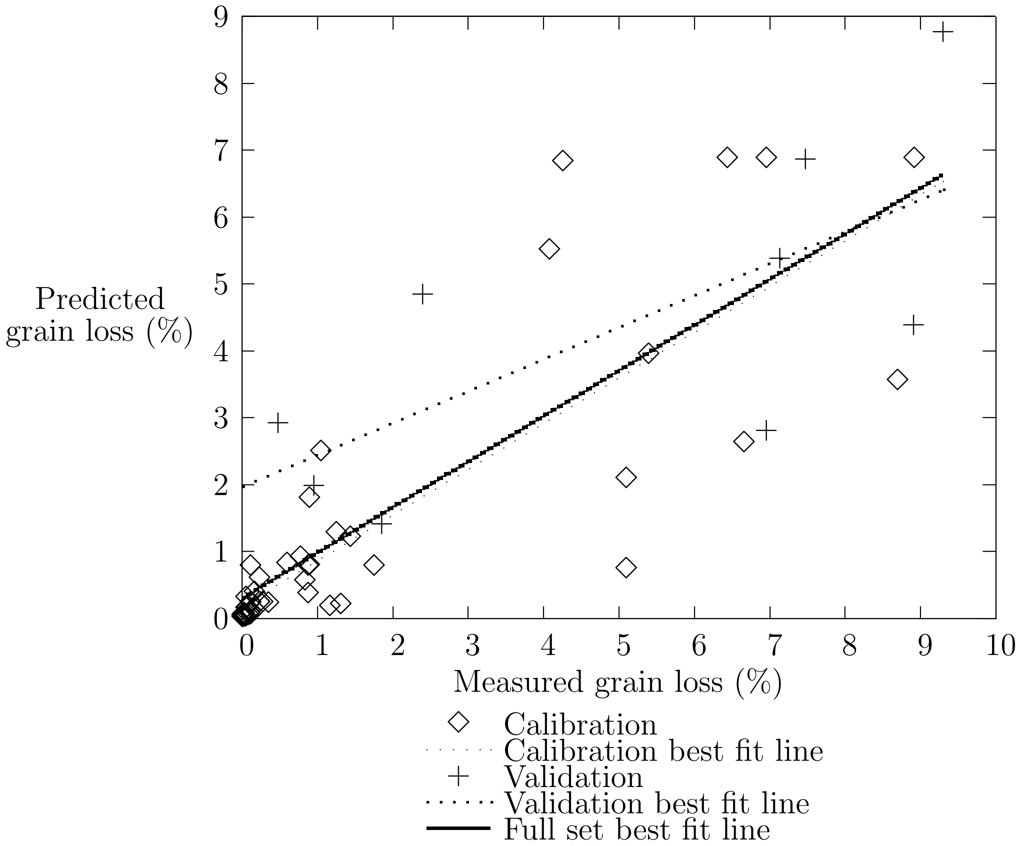


Figure 6.9 Calibration and validation data for corn

best-fit line. This shows that for corn, the design of experiments and response of the cleaning shoe is random and not influenced by the choices of tests used in the DOE.

The same calibration and validation methodology is used with wheat. A plot of predicted loss versus measured loss for wheat for the DOE, validation set of runs, and all runs combined is shown in Figure 6.10 with the values of the coefficients and $R^2$ values for the best-fit lines shown in Table 6.5. Because the slopes of the best-fit lines for both the calibration and validation sets are similar to each other and because the addition of the validation runs changes the slope of the full set of runs very little compared to the slope of the DOE best-fit line, the runs selected for the wheat DOE were random and were not influenced by any experimental factors.

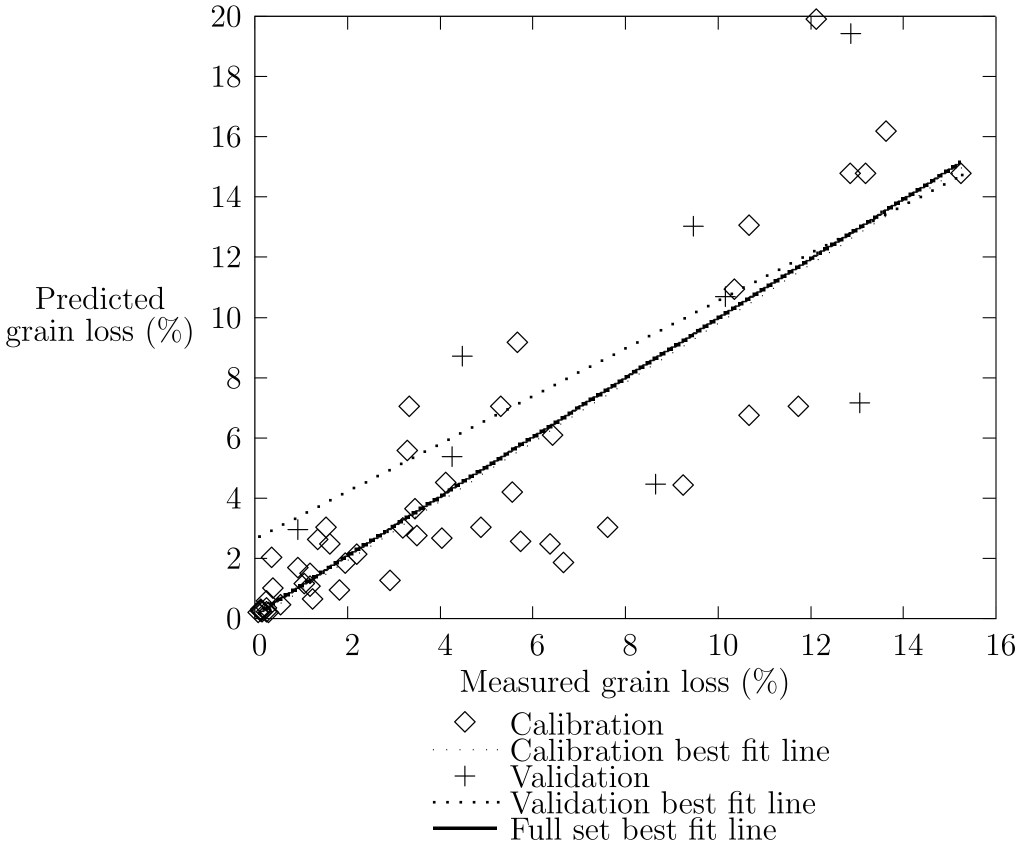


Figure 6.10 Calibration and validation data for wheat

Table 6.5 Coefficients for calibration, validation, and full-set best-fit lines for wheat.

| **Line Type** | **Slope** | **Y-intercept** | $R^2$ |
|---|---|---|---|
| Calibration | 0.9840 | -0.0491 | 0.7791 |
| Validation | 0.7915 | 2.6474 | 0.4136 |
| Full set | 0.9870 | 0.0932 | 0.7447 |

## 6.6 Finding control factors which minimize grain loss from the corn grain loss model

Control factors which minimize grain loss based on field factors are found from each crop model, with varying results from each. Taking the partial derivatives of the corn grain loss model with respect to each control variable yields

$$\begin{aligned}
\frac{d[log(Grain\ Loss,\ \%)]}{dx_5} &= \beta_5 + \beta_{56}x_6 && (6.3)\\
\frac{d[log(Grain\ Loss,\ \%)]}{dx_6} &= \beta_{16}x_1 + \beta_{56}x_5 && (6.4)\\
\frac{d[log(Grain\ Loss,\ \%)]}{dx_7} &= 2\beta_{77}x_7 + \beta_{47}x_4 && (6.5)
\end{aligned}$$

Each coefficient in the partial derivatives is the same as used in the model. These partial derivatives represent the stationary point, or point from which adjustments can be made in order to reduce grain loss, for each factor. Each equation is set equal to zero to find the stationary values for each factor. The rearranged equations are given as

$$\begin{aligned}
x_5 &= -\frac{\beta_{16}x_1}{\beta_{56}} && (6.6)\\
x_6 &= -\frac{\beta_5}{\beta_{56}} && (6.7)\\
x_7 &= -\frac{\beta_{47}x_4}{2\beta_{77}} && (6.8)
\end{aligned}$$

where $x_5$ is fan speed, $x_6$ is shake speed, and $x_7$ is side input. From these equations it is seen that stationary fan speed is dependent on grain feed rate and is on average lower than the factory-equipped fan speed. Stationary shake speed is determined to be a constant with a value of 333.2170 RPM, which is higher than the factory shake speed of 300 RPM. Side input is found to be dependent on side slope at 38.3875 mm for a 5 degree side slope and 76.7746 mm for a 10 degree side slope; both values are significantly higher than those found from the analytical model in the previous clean-grain-only study. Because all these values are realistically within the bounds of the experiment, an analysis can be done without modification to these values to determine the best values for these factors to minimize grain loss.

The next step is to determine whether these stationary points represent a minimum, maximum, or a saddlepoint for each factor. A saddlepoint is defined as a point where adjusting the value of the factor one way results in a decrease in response while adjusting the value in the other direction results in an increase in response. A minimum and maximum point represents values that can be adjusted in either direction and results in an increase or decrease in response. To determine the types of points, the matrix of coefficients in the partial derivatives is considered, which in the case of the corn model is given as

$$\begin{bmatrix} 0 & \beta_{56} & 0 \\ \beta_{56} & 0 & 0 \\ 0 & 0 & 2\beta_{77} \end{bmatrix}$$

The eigenvalues are then found for this matrix to determine the nature of the stationary points. The eigenvalues of the matrix are $-\beta_{56}$, $\beta_{56}$, and $2\beta_{77}$. The mixed signs indicate that a saddlepoint is present and will dictate the modifications to the factors. The eigenvectors must next be found. Vectors proportional to the eigenvectors associated with these eigenvalues are given, in the same order as the eigenvalues are listed, as

$$\begin{bmatrix} -1 \\ 1 \\ 0 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \\ 0 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

Each vector is proportional to the eigenvector for the purposes of readability.

Because the objective is to minimize response, the eigenvector that is of interest is the one that is associated with a negative eigenvalue, which numerically is the first eigenvector. Thus, fan speed and shake speed should be inversely modified with the same relative values within practical limits from the stationary points in order to minimize grain loss. Because the last value of the eigenvector, that relating to side input, is zero, no adjustment to the stationary point of side input needs to be made.

The fan and shake speeds are modified such that the shake speed is decreased by ten percent of its stationary value and fan speed is increased by ten percent of its stationary value. Thus the average value used for fan speed is 608.5438 RPM and the shake speed is a constant at 299.8950 RPM. To determine the efficacy of using the modified control factor equations, the modified value for fan speed and shake speed and the stationary value for side input is input into the corn grain loss model for each test performed in the DOE. The resulting predicted grain loss is then compared to the predicted grain loss for each run. The results of using modified control factors compared to the predicted grain loss is shown in Figure 6.11.

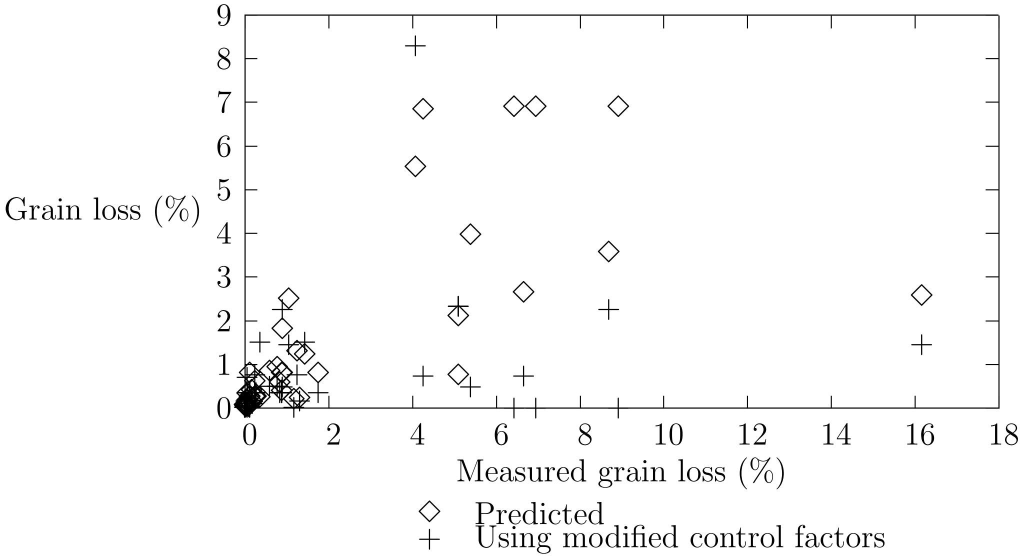


Figure 6.11 Results of modified control factors on corn

In most cases, the use of the modified control factors yields less predicted grain loss than was predicted from the original testing factors, with an average grain loss of 1.276% using the prediction equation being reduced to an average grain loss of 0.675% using the modified control factors. There are a few cases where using these values resulted in a higher grain loss. These runs all occurred with the machine at an uphill slope and typically either a higher or lower than normal grain flow rate. The reason for the increased losses is a result of the combination of an uphill slope and an increased shake speed.

## 6.7 Control factors which minimize grain loss from the wheat grain loss model

As with the factor modifications with the corn model, the first step is to take the first derivative of the model with respect to the control variables. This results in the equations

$$\frac{d[log(Grain\ Loss,\ \%)]}{dx_5} = \beta_{15}x_1 + \beta_{35}x_3 + \beta_{56}x_6 \tag{6.9}$$

$$\frac{d[log(Grain\ Loss,\ \%)]}{dx_6} = 2\beta_{66}x_6 + \beta_{26}x_2 + \beta_{56}x_5 \tag{6.10}$$

$$\frac{d[log(Grain\ Loss,\ \%)]}{dx_7} = 2\beta_{77}x_7 + \beta_{47}x_4 \tag{6.11}$$

Again each coefficient is the same as used in the model. Setting each first derivative equation to zero and rearranging to yield a stationary value equation results in the equations

$$x_5 = -\frac{\beta_{26}x_2 + 2\beta_{66}x_6}{\beta_{56}} \tag{6.12}$$

$$x_6 = -\frac{\beta_{15}x_1 + \beta_{35}x_3}{\beta_{56}} \tag{6.13}$$

$$x_7 = -\frac{\beta_{47}x_4}{2\beta_{77}} \tag{6.14}$$

where $x_5$ is fan speed, $x_6$ is shake speed, and $x_7$ is side input. It is seen from these equations that fan speed is dependent on MOG-to-grain ratio and shake speed with the average stationary value of fan speed higher than the middle fan speed used in the DOE. Shake speed is dependent on grain feed rate and longitudinal slope with the average value of shake speed considerably higher than the average fan speed used in the DOE. As with the corn model, side input is dependent only on lateral tilt, with a side input of 28.5200 mm for a 5 degree side slope and a side input of 57.0399 mm for a 10 degree side slope.

The average value for shake speed is outside the range of values used during experimentation, which means that in order to keep the other factor values within a reasonable range, shake speed must be set as a constant at a reasonable value, which in this case will be the factory shake speed. This simplifies the eigenvalue analysis greatly because it results in the matrix of first derivatives being defined as

$$\begin{bmatrix} \beta_{56} & 0 \\ 0 & 2\beta_{77} \end{bmatrix}$$

The eigenvalues for this matrix are $\beta_{56}$ and $2\beta_{56}$, with the associated eigenvectors given as

$$\begin{bmatrix} 1 \\ 0 \end{bmatrix} \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

In the case of the wheat model, both eigenvalues are positive, which indicates that the stationary values given will result in minimal response and thus the lowest possible grain loss without modification. The results of using the stationary values for the fan speed and side input as well as the factory shake speed versus measured grain loss is shown in 6.12. In general, the use of the control factors found results in good reduction in grain loss in all cases, with an average grain loss of 4.224% observed from the prediction formula being reduced to an average grain loss of 1.486% using the calculated control factors.

## 6.8 Similarities and differences in crop models

Having two independent crop models with significantly different crop types allows for comparison of responses of grain loss between the two crops as well as explanation of differences between grain loss models for each crop. The linear term for grain feed rate, the quadratic terms for side slope as well as side input, as well as the interactions between side input and side slope and shake speed and fan speed exist in both models. The grain loss model for corn includes interaction factors between grain feed rate and longitudinal slope and also between grain feed rate and shake speed. These terms are

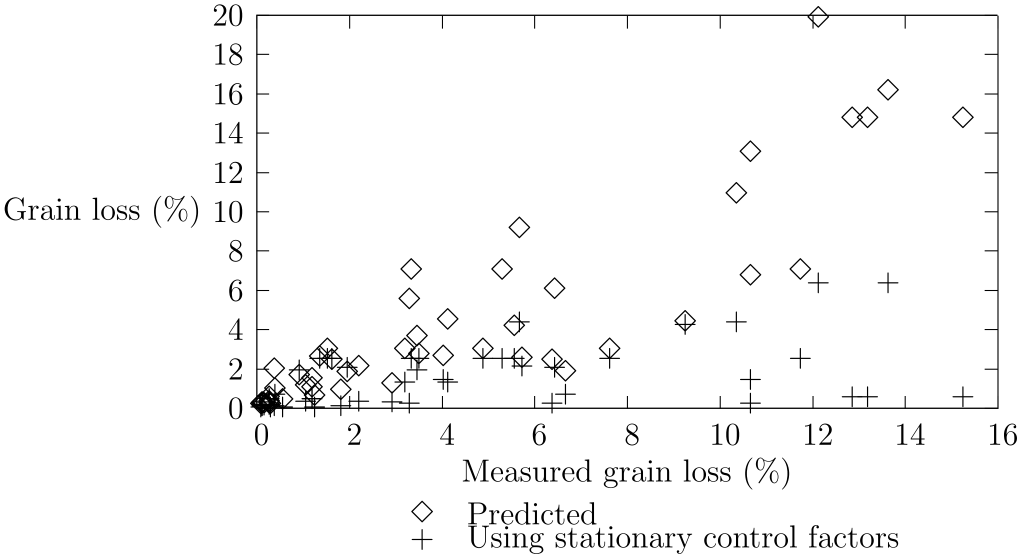


Figure 6.12 Results of modified control factors on wheat

not explicitly found in the wheat model, however interaction terms between grain feed rate and MOG/grain ratio and interaction between MOG-to-grain ratio and shake speed can be looked at as a pair to see that grain feed rate and shake speed exists in the wheat model and are linked through MOG-to-grain ratio. The same can be said about the pair of interaction terms consisting of the interaction between grain feed rate and fan speed and the interaction between fan speed and longitudinal slope found in the wheat grain loss model. These terms when paired infer a link between grain feed rate and longitudinal slope through fan speed in the wheat grain loss model.

The paired interaction terms also help to differentiate the wheat grain loss model from the corn model. The variable common in the first pair is MOG-to-grain ratio. In the second pair of interaction variables, fan speed is common to both. While MOG-to-grain ratio is not seen as a factor in the corn model, fan speed is. Thus including the linked factors above, all factors present in the corn model are also present in the wheat model. There are several factors present in the wheat model that are not present in the corn model. These include quadratic terms for grain feed rate, MOG-to-grain ratio, longitudinal slope, and shake speed. The presence of these variables indicates that the cleaning shoe's response to wheat is more sensitive to these extra factors than with corn.

The inclusion of extra factors in the wheat model is easily explained by differentiating the corn and wheat crop materials. With the corn and corn MOG mixture, the ratio between grain bulk density and MOG bulk density is 15.039. The types of particles in the corn MOG are also very different from a kernel of corn. The particle types found in corn MOG, shown in the right of Figure 6.13, consist of large flake-style particles from the husk and leaves as well as sections of stalk. Figure 6.14, a distribution of particle sizes found in corn and wheat MOG, shows the most common particle size of corn MOG as being one inch.

Figure 6.13 A sample of wheat and corn MOG

Wheat and especially wheat MOG is more dense than corn MOG and has a ratio between grain and MOG bulk densities of 12.891. The particles found in wheat MOG, shown in the left of Figure 6.13, are short sections of stalk and chaff. The distribution of wheat MOG particle sizes seen in Figure 6.14 shows the most common particle size of wheat MOG being one half of an inch. Because wheat MOG is fine and more similar to the grain, it is more difficult to separate than corn. In addition to these overall differences between the two crops, the MOG-to-grain ratios greatly differ between each crop, with wheat having more than twice the MOG per pound of grain than corn in a typical run.

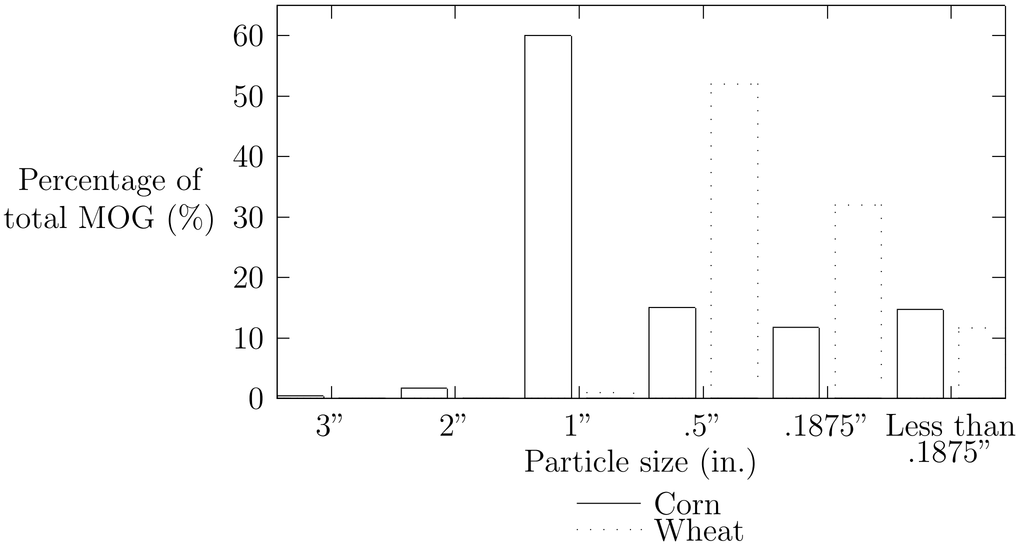


Figure 6.14 Particle sizes found in MOG for each crop

With wheat being the crop that is in general more difficult to separate from MOG than corn, the extra factors listed previously come into more importance with wheat than with corn. Grain feed rate and MOG-to-grain ratio hold more importance with wheat because of the crop and MOG being more similar to each other and more difficult to separate than with corn. Longitudinal slope and shake speed also has more effect with wheat than with corn because the presence of more MOG in the mixture means that there is a higher likelihood of the grain being carried out with the MOG in situations where these factors become significant rather than being separated and captured.

## 6.9 Comparing and contrasting control factors between crops

Comparing the two sets of control factor equations can also help to differentiate between the two crops and the response of the cleaning shoe with each. The average stationary fan speed value for corn is found to be 565.3139 RPM, which is lower than the factory fan speed for corn. Meanwhile, the stationary value of fan speed for wheat is 784.8252 RPM, which is higher than the factory fan speed for wheat. These differences show the effect of having more MOG in the cleaning shoe; with less MOG as experienced with corn, the fan speeds are lower because aerodynamic separation is not as critical, while with wheat the fan speed is higher which indicates that aerodynamic separation is more necessary for minimal grain loss. Comparison cannot be performed for shake speeds, since the stationary value for shake speed in the wheat model was not practical.

The stationary value for side input for corn of 38.3873 mm for a 5 degree slope is much higher than the stationary value of side input for wheat of 28.5200 mm for the same side slope. This can be explained by the overall grain feed rate differences between the two crops. Because corn has an overall higher grain feed rate than wheat, more force is required to throw it uphill than with wheat. Therefore more side displacement is required to correct for the same lateral angle.

## 6.10 Sensitivity analysis of side input in side-sloped conditions

Because the stationary value of side input for corn is significantly higher than the test stand was originally designed for, it is necessary to investigate how sensitive grain loss is to side input when the machine is operated on a side slope, with an end goal of reducing side input while keeping side slope grain losses at acceptable levels. The analysis is performed only using corn data, but it is assumed that a similar procedure could be done using wheat data. To find the effects of reducing side input, the stationary values of side inputs for 5 and 10 degrees are scaled down 75%, 50%, 30%, 20%, and 10% of the stationary values of side inputs for both side slopes. Along with the factory fan and shake speeds, each reduced side input is used with the corn grain loss model to determine predicted grain losses at each grain flow rate at a 5 and 10-degree side slope. Actual data is also used from the proof-of-concept runs for comparison to modeled results and represents a 32% reduction in side input from the stationary value of side input. Loss curves for a 5 degree side slope with reductions in side input are shown in Figure 6.15 with loss curves for a 10 degree side slope with reductions in side input shown in Figure 6.16.

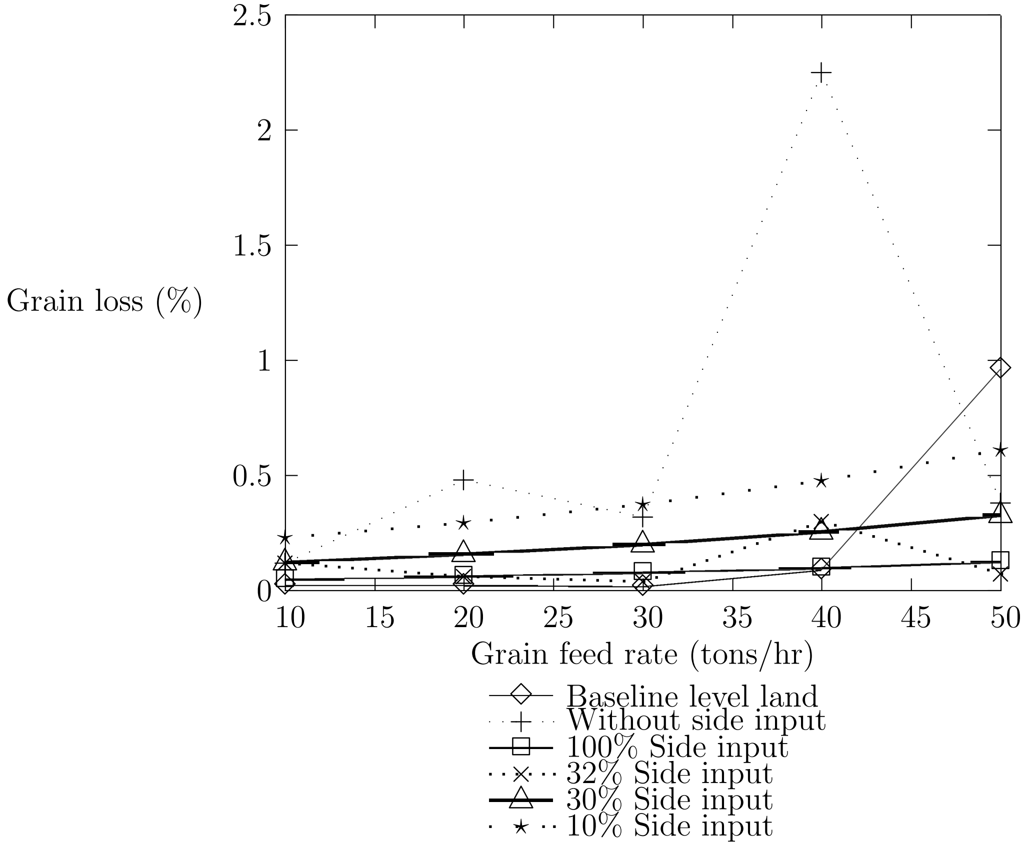


Figure 6.15 Results of reducing side input on a 5 degree slope

Because the 75% and 50% reductions in side input result in grain losses that are very close to the grain loss using full side input, the loss curves for each reduction are omitted from both plots. The 20% reduced side input loss curve is also omitted in both plots for readability. As seen in both figures, the maximum side input yields the lowest grain losses. If the side input is reduced to only 10% of the full side input for a 5 degree slope, grain loss can be kept well below the ideal grain loss of less than one percent. On a 10

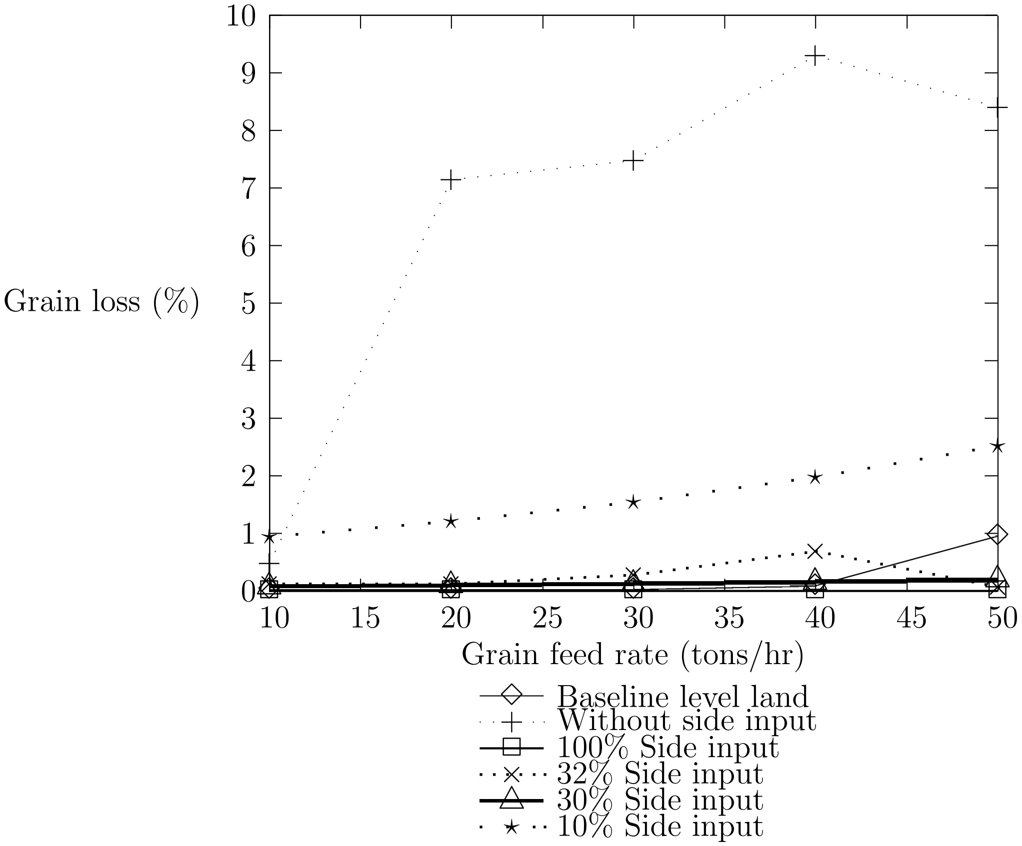


Figure 6.16 Results of reducing side input on a 10 degree slope

degree side slope, the side input can be decreased to around 30% of the full side input and still achieve grain loss below 1%. In order to encompass all side slope situations, a 30% reduction of side input is ideal for minimizing side slope losses while keeping the cleaning shoe's design compact.

## 6.11 Use of side input on level land

One issue with the original clean corn experiments is an apparent increase of capacity that the cleaning shoe has when running with side input. During the corn-and-MOG DOE runs it is observed that running the cleaning shoe on level land with a side input produces grain loss that is biased towards the side of the machine that is typically uphill when tilted to the side. It is also noted that grain loss increases when the machine is in this configuration, but it is initially unclear how side input affected grain loss throughout the entire range of grain feed rates and side inputs. To investigate this, a full-factorial experiment is performed with the grain feed rate and side input factors. The results of these runs are shown in Figure 6.17.

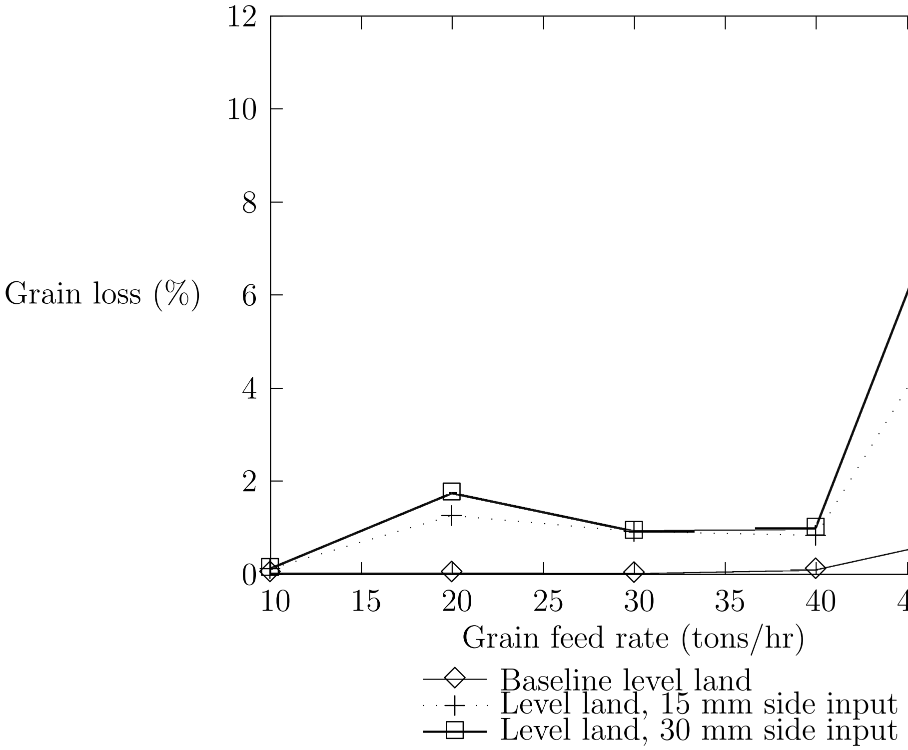


Figure 6.17 Results of using side input without lateral slope

For every feed rate, the addition of side input on a level machine will increase grain loss. While grain loss stays at a reasonable level through the 10 ton/hr to 40 ton/hr range of grain feed rates, at the highest extreme grain feed rate grain loss increases significantly. Grain loss is expected to increase dramatically if the shoe were tilted uphill or if fan or shake speeds are modified. Though there may be a slight capacity increase from adding side shake into the cleaning shoe, the potential gains are overshadowed by the actual losses. While these results are for corn only, the same behavior is observed for wheat so it is assumed that similar results would occur in the same conditions with wheat as the operating material.

# CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS

## 7.1 Conclusions

A slope insensitive cleaning shoe is developed based off the design for a production cleaning shoe using variable-speed fan and shake drives to compensate for longitudinal slopes. To compensate for side slopes, a swinger arm is used that allows lateral displacement of the chaffer frame, effectively throwing crop material uphill to ensure an even crop mat and efficient aerodynamic separation. Results from clean grain tests necessitate continued testing with MOG and multiple crops to fully validate the response of the shoe in all possible environmental conditions.

The proof-of-concept runs show that using only side input as a factor to compensate for side slope conditions provides grain loss that is favorable and close to level-land grain loss. Further, the use of side input to correct for lateral slopes works for both corn and wheat crops. Grain loss models for both crops gave valuable insight on how to adjust cleaning shoe operating parameters during various environmental situations to minimize grain loss. When working in corn, fan speed should be adjusted proportionally to grain feed rate while shake speed should be held at a constant value higher than the factory-supplied shake speed, though with modification to the stationary values, shake speed can be brought back to nearly the factory shake speed to maintain minimal grain loss. Overall, fan speed should be set lower than the factory recommended speed due to the ease of separation of corn from corn MOG. When working in wheat, MOG-to-grain ratio affects grain loss much more than in corn, which results in a more complex grain loss model. In wheat, fan speed should be adjusted based on the grain feed rate as well as the longitudinal slope of the cleaning shoe to minimize grain loss. Shake speed should be held constant at the factory speed when working in wheat. In general, fan speed for wheat should be higher than the factory recommended speed to ensure efficient separation of the more difficult to separate wheat and wheat MOG mixture. The modified values for fan and shake speed factors as well as the stationary values found for side inputs can reduce sloped grain losses significantly to well within the normal operating parameters of a cleaning shoe.

While the full side input determined to be necessary to compensate for side slopes of a given angle will provide excellent minimization of grain loss on lateral slopes, side input can be reduced to approximately 30% of the full side input and still provide acceptable losses on side slopes. This reduction can save valuable space in the combine chassis and minimize any necessary reinforcements to deal with the lateral forces not typically experienced in the cleaning shoe. Side input is not an ideal candidate for full-time use on level land, though initial testing showed possible increased capacities. When utilizing side input on completely level land, grain loss increases as the chaffer throws crop material uphill when there is no force from gravity to pull it back downhill.

## 7.2 Recommendations for further study

Though much information is available from this research, there are other considerations that must be taken into account before the modified cleaning shoe is ready for mass production. The first issue that needs to be addressed is the variation in moisture of both grain and MOG. Moisture can have a tremendous effect on cleaning efficiency and knowing the response of the cleaning shoe with that factor included among the other factors is critical. If possible, testing at different temperatures should be considered as that can also have an effect on grain loss that is not presently tested.

Another area that should be explored is chaffer and sieve openings. When considering uphill and downhill slopes, adjusting these openings can have a great effect on grain loss. A mechanism is already available for production combines to allow remote adjustment of chaffer and sieve elements, so the addition of this factor could provide reductions in grain loss without major design work. When adding in louver openings as an experimental factor, it should be kept in mind to also factor in clean grain dockage and distribution of material between clean grain and tailings return to ensure a good compromise is made between low grain losses and high grain quality while keeping loads on areas of the combine at similar levels as presently found.

A final factor that should be considered is chaffer louver design and its effects on the crop mat when utilizing side input. The current test stand uses production chaffer elements which are relatively flat. By using a different chaffer design with a focus on side-to-side as well as fore-aft displacement, required side input for side slopes could be greatly decreased and the shoe could require minimal design revision before going into production. Addition of modifiable shake geometry to the lower sieve may also aid in minimizing side slope losses and removing some of the burden of side slope correction from the chaffer.

While testing of the additional factors could be completed in the laboratory environment, the addition of the other factors increases the number of runs required for a DOE as well as complicates material handling greatly. It is therefore recommended that the experimental cleaning shoe be tested in a mobile combine. The ease of testing as well as the availability of diverse conditions during harvest would be very beneficial for further research as well as determination of future designs as cleaning shoe development progresses.

# APPENDIX: DATA TABLES

Table A.1 Data from corn baseline establishment runs

| **Grain Loss (%)** | **Grain Feed Rate (ton/hr)** | **MOG/Grain Ratio (lb/lb)** | **Longitudinal Slope (deg.)** | **Lateral Slope (deg.)** | **Fan Speed (RPM)** | **Shake Speed (RPM)** | **Side Input (mm)** |
|---|---|---|---|---|---|---|---|
| 0.022 | 10 | 1:15 | 0 | 0 | 750 | 300 | 0 |
| 0.022 | 20 | 1:15 | 0 | 0 | 750 | 300 | 0 |
| 0.018 | 30 | 1:15 | 0 | 0 | 750 | 300 | 0 |
| 0.090 | 40 | 1:15 | 0 | 0 | 750 | 300 | 0 |
| 0.960 | 50 | 1:15 | 0 | 0 | 750 | 300 | 0 |

Table A.2 Data from wheat baseline establishment runs

| **Grain Loss (%)** | **Grain Feed Rate (ton/hr)** | **MOG/Grain Ratio (lb/lb)** | **Longitudinal Slope (deg.)** | **Lateral Slope (deg.)** | **Fan Speed (RPM)** | **Shake Speed (RPM)** | **Side Input (mm)** |
|---|---|---|---|---|---|---|---|
| 0.300 | 4 | 1:6 | 0 | 0 | 625 | 300 | 0 |
| 0.133 | 9 | 1:6 | 0 | 0 | 625 | 300 | 0 |
| 1.543 | 14 | 1:6 | 0 | 0 | 625 | 300 | 0 |
| 7.137 | 19 | 1:6 | 0 | 0 | 625 | 300 | 0 |
| 3.300 | 24 | 1:6 | 0 | 0 | 625 | 300 | 0 |

Table A.3 Data from corn proof-of-concept runs

| **Grain Loss (%)** | **Grain Feed Rate (ton/hr)** | **MOG/Grain Ratio (lb/lb)** | **Longitudinal Slope (deg.)** | **Lateral Slope (deg.)** | **Fan Speed (RPM)** | **Shake Speed (RPM)** | **Side Input (mm)** |
|---|---|---|---|---|---|---|---|
| 0.120 | 10 | 1:15 | 0 | 5 | 750 | 300 | 0 |
| 0.480 | 20 | 1:15 | 0 | 5 | 750 | 300 | 0 |
| 0.320 | 30 | 1:15 | 0 | 5 | 750 | 300 | 0 |
| 2.250 | 40 | 1:15 | 0 | 5 | 750 | 300 | 0 |
| 0.380 | 50 | 1:15 | 0 | 5 | 750 | 300 | 0 |
| 0.120 | 10 | 1:15 | 0 | 5 | 750 | 300 | 12.5 |
| 0.060 | 20 | 1:15 | 0 | 5 | 750 | 300 | 12.5 |
| 0.040 | 30 | 1:15 | 0 | 5 | 750 | 300 | 12.5 |
| 0.300 | 40 | 1:15 | 0 | 5 | 750 | 300 | 12.5 |
| 0.072 | 50 | 1:15 | 0 | 5 | 750 | 300 | 12.5 |
| 0.480 | 10 | 1:15 | 0 | 10 | 750 | 300 | 0 |
| 7.140 | 20 | 1:15 | 0 | 10 | 750 | 300 | 0 |
| 7.480 | 30 | 1:15 | 0 | 10 | 750 | 300 | 0 |
| 9.300 | 40 | 1:15 | 0 | 10 | 750 | 300 | 0 |
| 8.400 | 50 | 1:15 | 0 | 10 | 750 | 300 | 0 |
| 0.120 | 10 | 1:15 | 0 | 10 | 750 | 300 | 25 |
| 0.120 | 20 | 1:15 | 0 | 10 | 750 | 300 | 25 |
| 0.280 | 30 | 1:15 | 0 | 10 | 750 | 300 | 25 |
| 0.690 | 40 | 1:15 | 0 | 10 | 750 | 300 | 25 |
| 0.072 | 50 | 1:15 | 0 | 10 | 750 | 300 | 25 |

Table A.4 Data from wheat proof-of-concept runs

| **Grain Loss (%)** | **Grain Feed Rate (ton/hr)** | **MOG/Grain Ratio (lb/lb)** | **Longitudinal Slope (deg.)** | **Lateral Slope (deg.)** | **Fan Speed (RPM)** | **Shake Speed (RPM)** | **Side Input (mm)** |
|---|---|---|---|---|---|---|---|
| 0.300 | 4 | 1:6 | 0 | 5 | 625 | 300 | 0 |
| 1.733 | 9 | 1:6 | 0 | 5 | 625 | 300 | 0 |
| 10.371 | 14 | 1:6 | 0 | 5 | 625 | 300 | 0 |
| 12.253 | 19 | 1:6 | 0 | 5 | 625 | 300 | 0 |
| 12.950 | 24 | 1:6 | 0 | 5 | 625 | 300 | 0 |
| 0.300 | 4 | 1:6 | 0 | 5 | 625 | 300 | 12.5 |
| 0.800 | 9 | 1:6 | 0 | 5 | 625 | 300 | 12.5 |
| 2.229 | 14 | 1:6 | 0 | 5 | 625 | 300 | 12.5 |
| 8.274 | 19 | 1:6 | 0 | 5 | 625 | 300 | 12.5 |
| 8.100 | 24 | 1:6 | 0 | 5 | 625 | 300 | 12.5 |
| 1.200 | 4 | 1:6 | 0 | 10 | 625 | 300 | 0 |
| 12.800 | 9 | 1:6 | 0 | 10 | 625 | 300 | 0 |
| 15.171 | 14 | 1:6 | 0 | 10 | 625 | 300 | 0 |
| 22.989 | 19 | 1:6 | 0 | 10 | 625 | 300 | 0 |
| 24.200 | 24 | 1:6 | 0 | 10 | 625 | 300 | 0 |
| 0.600 | 4 | 1:6 | 0 | 10 | 625 | 300 | 25 |
| 0.400 | 9 | 1:6 | 0 | 10 | 625 | 300 | 25 |
| 1.543 | 14 | 1:6 | 0 | 10 | 625 | 300 | 25 |
| 7.516 | 19 | 1:6 | 0 | 10 | 625 | 300 | 25 |
| 13.550 | 24 | 1:6 | 0 | 10 | 625 | 300 | 25 |

Table A.5 Data from corn design of experiments. Includes predicted grain loss from the final corn grain loss model as well as predicted grain loss using modified control factors

| **Run Number** | **Grain Loss (%)** | **Grain Feed Rate (ton/hr)** | **MOG/Grain Ratio (lb/lb)** | **Longitudinal Slope (deg.)** | **Lateral Slope (deg.)** | **Fan Speed (RPM)** | **Shake Speed (RPM)** | **Side Input (mm)** | **Predicted Grain Loss (%)** | **Modified Controls Grain Loss (%)** |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.12 | 30 | 0.066666667 | 0 | 0 | 750 | 250 | 0 | 0.09863243 | 0.41506644 |
| 2 | 0.08 | 30 | 0.066666667 | 0 | 0 | 900 | 300 | 0 | 0.15104595 | 0.41506644 |
| 3 | 6.66 | 40 | 0.1 | 5 | 5 | 675 | 275 | 15 | 2.61815306 | 0.91841899 |
| 4 | 0.168 | 50 | 0.06666 | 0 | 0 | 750 | 300 | 0 | 0.38134716 | 0.23095607 |
| 5 | 0.28 | 30 | 0.04 | 0 | 0 | 750 | 300 | 0 | 0.23388561 | 0.41506644 |
| 6 | 0.12 | 40 | 0.1 | -5 | 5 | 825 | 275 | 0 | 0.05098384 | 0.01121925 |
| 7 | 0.36 | 20 | 0.05 | 5 | 0 | 825 | 275 | 15 | 0.21953212 | 1.67371316 |
| 8 | 0.18 | 20 | 0.1 | -5 | 0 | 825 | 325 | 15 | 0.1156283 | 0.1191059 |
| 9 | 0.12 | 30 | 0.066666667 | 0 | 0 | 750 | 300 | 30 | 0.77438184 | 0.41506644 |
| 10 | 0.03 | 40 | 0.1 | -5 | 0 | 675 | 275 | 15 | 0.063567 | 0.03422039 |
| 11 | 5.1 | 20 | 0.1 | 5 | 0 | 675 | 325 | 0 | 2.08452205 | 2.59950236 |
| 12 | 6.96 | 30 | 0.066666667 | 0 | 10 | 750 | 300 | 0 | 6.87100568 | 0.00479549 |
| 13 | 0.01 | 20 | 0.05 | -5 | 5 | 825 | 275 | 15 | 0.01220803 | 0.06064867 |
| 14 | 5.1 | 20 | 0.1 | 5 | 0 | 675 | 275 | 15 | 0.73370713 | 2.59950236 |
| 15 | 16.17 | 40 | 0.05 | 5 | 0 | 675 | 325 | 15 | 2.54538419 | 1.80365253 |
| 16 | 0.84 | 30 | 0.066666667 | 0 | 0 | 750 | 350 | 0 | 0.55460943 | 0.41506644 |
| 17 | 1.17 | 40 | 0.05 | -5 | 5 | 675 | 275 | 0 | 0.17039514 | 0.01742501 |
| 18 | 0.031 | 20 | 0.1 | -5 | 0 | 825 | 275 | 0 | 0.01158144 | 0.1191059 |
| 19 | 8.7 | 40 | 0.1 | 5 | 0 | 825 | 325 | 15 | 3.54804562 | 2.80131573 |
| 20 | 0.24 | 30 | 0.066666667 | 0 | 0 | 750 | 300 | 0 | 0.23388561 | 0.41506644 |
| 21 | 4.26 | 40 | 0.1 | 5 | 5 | 675 | 325 | 0 | 6.82305411 | 0.91841899 |
| 22 | 1.44 | 20 | 0.05 | 5 | 0 | 825 | 325 | 0 | 1.20454762 | 1.67371316 |
| 23 | 0.058 | 10 | 0.0667 | 0 | 0 | 750 | 300 | 0 | 0.14344535 | 0.7459434 |
| 24 | 0.12 | 30 | 0.2 | 0 | 0 | 750 | 300 | 0 | 0.23388561 | 0.41506644 |
| 25 | 8.92 | 30 | 0.066666667 | 0 | 10 | 750 | 300 | 0 | 6.87100568 | 0.00479549 |
| 26 | 0.12 | 20 | 0.1 | -5 | 5 | 675 | 325 | 0 | 0.22235851 | 0.03904919 |

Table A.6 Data from corn design of experiments (continued)

| **Run Number** | **Grain Loss (%)** | **Grain Feed Rate (ton/hr)** | **MOG/Grain Ratio (lb/lb)** | **Longitudinal Slope (deg.)** | **Lateral Slope (deg.)** | **Fan Speed (RPM)** | **Shake Speed (RPM)** | **Side Input (mm)** | **Predicted Grain Loss (%)** | **Modified Controls Grain Loss (%)** |
|---|---|---|---|---|---|---|---|---|---|---|
| 27 | 0.01 | 30 | 0.066666667 | -10 | 0 | 750 | 300 | 0 | 0.0099525 | 0.01766226 |
| 28 | 0.9 | 40 | 0.1 | 5 | 0 | 825 | 275 | 0 | 1.79269106 | 2.80131573 |
| 29 | 0.24 | 20 | 0.1 | 5 | 5 | 825 | 275 | 0 | 0.58846895 | 0.85225392 |
| 30 | 4.08 | 30 | 0.066666667 | 10 | 0 | 750 | 300 | 0 | 5.4963572 | 9.754142 |
| 31 | 0.06 | 40 | 0.1 | -5 | 5 | 825 | 325 | 15 | 0.02180712 | 0.01121925 |
| 32 | 0.88 | 30 | 0.066666667 | 0 | 0 | 750 | 300 | 30 | 0.77438184 | 0.41506644 |
| 33 | 0.9 | 40 | 0.05 | 5 | 5 | 825 | 275 | 15 | 0.78337619 | 0.59133239 |
| 34 | 0.24 | 30 | 0.066666667 | 0 | 0 | 750 | 300 | 0 | 0.23388561 | 0.41506644 |
| 35 | 0.013 | 40 | 0.05 | -5 | 0 | 825 | 275 | 15 | 0.04588021 | 0.05314888 |
| 36 | 0.6 | 20 | 0.05 | 5 | 5 | 675 | 275 | 0 | 0.81532328 | 0.54873141 |
| 37 | 1.32 | 20 | 0.05 | -5 | 0 | 675 | 325 | 15 | 0.2000998 | 0.18498754 |
| 38 | 1.26 | 20 | 0.1 | 5 | 5 | 825 | 325 | 15 | 1.26971796 | 0.85225392 |
| 39 | 0.03 | 40 | 0.05 | -5 | 0 | 825 | 325 | 0 | 0.04990377 | 0.05314888 |
| 40 | 1.76 | 30 | 0.066666667 | 0 | 0 | 750 | 300 | 30 | 0.77438184 | 0.41506644 |
| 41 | 0.032 | 20 | 0.05 | -5 | 0 | 675 | 275 | 0 | 0.03870678 | 0.18498754 |
| 42 | 0.06 | 20 | 0.05 | -5 | 5 | 825 | 325 | 0 | 0.30994855 | 0.06064867 |
| 43 | 6.44 | 30 | 0.066666667 | 0 | 10 | 750 | 300 | 0 | 6.87100568 | 0.00479549 |
| 44 | 0.018 | 20 | 0.1 | -5 | 5 | 675 | 275 | 15 | 0.01691422 | 0.03904919 |
| 45 | 0.12 | 30 | 0.066666667 | 0 | 0 | 750 | 300 | 0 | 0.23388561 | 0.41506644 |
| 46 | 0.78 | 20 | 0.05 | 5 | 5 | 675 | 325 | 15 | 0.91090148 | 0.54873141 |
| 47 | 1.05 | 40 | 0.05 | 5 | 0 | 675 | 275 | 0 | 2.4837721 | 1.80365253 |
| 48 | 0.007 | 40 | 0.05 | -5 | 5 | 675 | 325 | 15 | 0.03773816 | 0.01742501 |
| 49 | 0.09 | 40 | 0.1 | -5 | 0 | 675 | 325 | 0 | 0.03580119 | 0.03422039 |
| 50 | 0.88 | 30 | 0.066666667 | 0 | 0 | 600 | 300 | 0 | 0.36215785 | 0.41506644 |
| 51 | 5.4 | 40 | 0.05 | 5 | 5 | 825 | 325 | 0 | 3.94272328 | 0.59133239 |

Table A.7 Data from wheat design of experiments. Includes predicted grain loss from the final wheat grain loss model as well as predicted grain loss using modified control factors

| **Run Number** | **Grain Loss (%)** | **Grain Feed Rate (ton/hr)** | **MOG/Grain Ratio (lb/lb)** | **Longitudinal Slope (deg.)** | **Lateral Slope (deg.)** | **Fan Speed (RPM)** | **Shake Speed (RPM)** | **Side Input (mm)** | **Predicted Grain Loss (%)** | **Modified Controls Grain Loss (%)** |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.629 | 14 | 0.166642857 | 0 | 0 | 625 | 250 | 0 | 2.42239842 | 2.55231753 |
| 2 | 1.371 | 14 | 0.166642857 | 0 | 0 | 750 | 300 | 0 | 2.57405759 | 2.55231753 |
| 3 | 4.042 | 19 | 0.25 | 5 | 5 | 550 | 275 | 15 | 2.61690233 | 1.44744216 |
| 4 | 3.3 | 24 | 0.166666667 | 0 | 0 | 625 | 300 | 0 | 5.52447027 | 0.25048993 |
| 5 | 5.743 | 14 | 0.1 | 0 | 0 | 625 | 300 | 0 | 2.50703117 | 2.1448922 |
| 6 | 0.568 | 19 | 0.25 | -5 | 5 | 700 | 275 | 0 | 0.40179133 | 0.08051896 |
| 7 | 6.667 | 9 | 0.125 | 5 | 0 | 700 | 275 | 15 | 1.81587161 | 0.70669371 |
| 8 | 1.2 | 9 | 0.25 | -5 | 0 | 700 | 325 | 15 | 1.01455127 | 0.49705004 |
| 9 | 11.743 | 14 | 0.166642857 | 0 | 0 | 625 | 300 | 30 | 6.99842533 | 2.55231753 |
| 10 | 1.832 | 19 | 0.25 | -5 | 0 | 550 | 275 | 15 | 0.89362542 | 0.11672857 |
| 11 | 3.467 | 9 | 0.25 | 5 | 0 | 550 | 325 | 0 | 3.60062665 | 1.95313893 |
| 12 | 13.2 | 14 | 0.166642857 | 0 | 10 | 625 | 300 | 0 | 14.7322674 | 0.57785478 |
| 13 | 0.133 | 9 | 0.125 | -5 | 5 | 700 | 275 | 15 | 0.18162435 | 0.12405641 |
| 14 | 0.933 | 9 | 0.25 | 5 | 0 | 550 | 275 | 15 | 1.63034587 | 1.95313893 |
| 15 | 13.642 | 19 | 0.125 | 5 | 0 | 550 | 325 | 15 | 16.1271136 | 6.39810461 |
| 16 | 3.514 | 14 | 0.166642857 | 0 | 0 | 625 | 350 | 0 | 2.70040131 | 2.55231753 |
| 17 | 10.674 | 19 | 0.125 | -5 | 5 | 550 | 275 | 0 | 6.69682677 | 0.24551006 |
| 18 | 0.267 | 9 | 0.25 | -5 | 0 | 700 | 275 | 0 | 0.29993004 | 0.49705004 |
| 19 | 6.442 | 19 | 0.25 | 5 | 0 | 700 | 325 | 15 | 6.04120464 | 2.09836106 |
| 20 | 7.629 | 14 | 0.166642857 | 0 | 0 | 625 | 300 | 0 | 2.98324531 | 2.55231753 |
| 21 | 10.674 | 19 | 0.25 | 5 | 5 | 550 | 325 | 0 | 12.9995393 | 1.44744216 |
| 22 | 0.4 | 9 | 0.125 | 5 | 0 | 700 | 325 | 0 | 0.96323719 | 0.70669371 |
| 23 | 0.3 | 4 | 0.1665 | 0 | 0 | 625 | 300 | 0 | 0.14758088 | 0.05772258 |
| 24 | 0.171 | 14 | 0.5 | 0 | 0 | 625 | 300 | 0 | 0.17692421 | 0.15136763 |
| 25 | 12.857 | 14 | 0.166642857 | 0 | 10 | 625 | 300 | 0 | 14.7322674 | 0.57785478 |
| 26 | 2.933 | 9 | 0.25 | -5 | 5 | 550 | 325 | 0 | 1.21477067 | 0.34286339 |

Table A.8 Data from wheat design of experiments (continued)

| **Run Number** | **Grain Loss (%)** | **Grain Feed Rate (ton/hr)** | **MOG/Grain Ratio (lb/lb)** | **Longitudinal Slope (deg.)** | **Lateral Slope (deg.)** | **Fan Speed (RPM)** | **Shake Speed (RPM)** | **Side Input (mm)** | **Predicted Grain Loss (%)** | **Modified Controls Grain Loss (%)** |
|---|---|---|---|---|---|---|---|---|---|---|
| 27 | 0.086 | 14 | 0.166642857 | -10 | 0 | 625 | 300 | 0 | 0.14964441 | 0.06040937 |
| 28 | 1.958 | 19 | 0.25 | 5 | 0 | 700 | 275 | 0 | 1.78595092 | 2.09836106 |
| 29 | 3.2 | 9 | 0.25 | 5 | 5 | 700 | 275 | 0 | 2.96264247 | 1.34726844 |
| 30 | 9.257 | 14 | 0.166642857 | 10 | 0 | 625 | 300 | 0 | 4.38130585 | 4.26717422 |
| 31 | 1.263 | 19 | 0.25 | -5 | 5 | 700 | 325 | 15 | 0.60424419 | 0.08051896 |
| 32 | 5.314 | 14 | 0.166642857 | 0 | 0 | 625 | 300 | 30 | 6.99842533 | 2.55231753 |
| 33 | 5.684 | 19 | 0.125 | 5 | 5 | 700 | 275 | 15 | 9.11374034 | 4.41339032 |
| 34 | 4.886 | 14 | 0.166642857 | 0 | 0 | 625 | 300 | 0 | 2.98324531 | 2.55231753 |
| 35 | 2.211 | 19 | 0.125 | -5 | 0 | 700 | 275 | 15 | 2.07529329 | 0.35591664 |
| 36 | 1.2 | 9 | 0.125 | 5 | 5 | 550 | 275 | 0 | 1.44984065 | 0.48747487 |
| 37 | 0.267 | 9 | 0.125 | -5 | 0 | 550 | 325 | 15 | 0.17883394 | 0.17984493 |
| 38 | 4.133 | 9 | 0.25 | 5 | 5 | 700 | 325 | 15 | 4.45544581 | 1.34726844 |
| 39 | 1.074 | 19 | 0.125 | -5 | 0 | 700 | 325 | 0 | 1.10084858 | 0.35591664 |
| 40 | 3.343 | 14 | 0.166642857 | 0 | 0 | 625 | 300 | 30 | 6.99842533 | 2.55231753 |
| 41 | 0.133 | 9 | 0.125 | -5 | 0 | 550 | 275 | 0 | 0.22011324 | 0.17984493 |
| 42 | 0.133 | 9 | 0.125 | -5 | 5 | 700 | 325 | 0 | 0.21670268 | 0.12405641 |
| 43 | 15.257 | 14 | 0.166642857 | 0 | 10 | 625 | 300 | 0 | 14.7322674 | 0.57785478 |
| 44 | 0.133 | 9 | 0.25 | -5 | 5 | 550 | 275 | 15 | 0.24454222 | 0.34286339 |
| 45 | 1.543 | 14 | 0.166642857 | 0 | 0 | 625 | 300 | 0 | 2.98324531 | 2.55231753 |
| 46 | 0.267 | 9 | 0.125 | 5 | 5 | 550 | 325 | 15 | 0.52369925 | 0.48747487 |
| 47 | 12.126 | 19 | 0.125 | 5 | 0 | 550 | 275 | 0 | 19.8496502 | 6.39810461 |
| 48 | 6.379 | 19 | 0.125 | -5 | 5 | 550 | 325 | 15 | 2.41897148 | 0.24551006 |
| 49 | 0.379 | 19 | 0.25 | -5 | 0 | 550 | 325 | 0 | 1.973576 | 0.11672857 |
| 50 | 5.571 | 14 | 0.166642857 | 0 | 0 | 500 | 300 | 0 | 4.15377848 | 2.55231753 |
| 51 | 10.358 | 19 | 0.125 | 5 | 5 | 700 | 325 | 0 | 10.8739382 | 4.41339032 |

Table A.9 Data from corn DOE validation runs

| **Grain Loss (%)** | **Grain Feed Rate (ton/hr)** | **MOG/Grain Ratio (lb/lb)** | **Longitudinal Slope (deg.)** | **Lateral Slope (deg.)** | **Fan Speed (RPM)** | **Shake Speed (RPM)** | **Side Input (mm)** | **Predicted Grain Loss (%)** | **Modified Controls Grain Loss (%)** |
|---|---|---|---|---|---|---|---|---|---|
| 10.86 | 40 | 0.1 | 5 | 0 | 675 | 325 | 15 | 3.95332509 | 2.80131573 |
| 0.96 | 40 | 0.1 | 5 | 5 | 675 | 325 | 15 | 1.98906381 | 0.91841899 |
| 0.48 | 40 | 0.1 | 5 | 0 | 675 | 325 | 0 | 2.93072192 | 2.80131573 |
| 9.09 | 40 | 0.05 | 5 | 0 | 675 | 325 | 0 | 1.88697188 | 1.80365253 |
| 7.68 | 40 | 0.05 | 5 | 5 | 675 | 325 | 15 | 1.28067676 | 0.59133239 |
| 8.91 | 40 | 0.05 | 5 | 5 | 675 | 325 | 0 | 4.39308524 | 0.59133239 |
| 6.96 | 20 | 0.1 | 5 | 0 | 675 | 325 | 15 | 2.81186463 | 2.59950236 |
| 2.4 | 20 | 0.1 | 5 | 5 | 675 | 325 | 0 | 4.85300451 | 0.85225392 |
| 1.86 | 20 | 0.1 | 5 | 5 | 675 | 325 | 15 | 1.41475291 | 0.85225392 |

Table A.10 Data from wheat DOE validation runs

| **Grain Loss (%)** | **Grain Feed Rate (ton/hr)** | **MOG/Grain Ratio (lb/lb)** | **Longitudinal Slope (deg.)** | **Lateral Slope (deg.)** | **Fan Speed (RPM)** | **Shake Speed (RPM)** | **Side Input (mm)** | **Predicted Grain Loss (%)** | **Modified Controls Grain Loss (%)** |
|---|---|---|---|---|---|---|---|---|---|
| 19.2 | 19 | 0.25 | 5 | 0 | 550 | 325 | 15 | 10.7922165 | 2.09836106 |
| 13.074 | 19 | 0.25 | 5 | 5 | 550 | 325 | 15 | 7.15259606 | 1.44744216 |
| 4.484 | 19 | 0.25 | 5 | 0 | 550 | 325 | 0 | 8.72032771 | 2.09836106 |
| 9.474 | 19 | 0.125 | 5 | 0 | 550 | 325 | 0 | 13.0310318 | 6.39810461 |
| 10.168 | 19 | 0.125 | 5 | 5 | 550 | 325 | 15 | 10.6883262 | 4.41339032 |
| 12.884 | 19 | 0.125 | 5 | 5 | 550 | 325 | 0 | 19.4255785 | 4.41339032 |
| 8.667 | 9 | 0.25 | 5 | 0 | 550 | 325 | 15 | 4.45611031 | 1.95313893 |
| 4.267 | 9 | 0.25 | 5 | 5 | 550 | 325 | 0 | 5.36751476 | 1.34726844 |
| 0.933 | 9 | 0.25 | 5 | 5 | 550 | 325 | 15 | 2.95330965 | 1.34726844 |

Table A.11 Data from side input reduction plots

| **Grain Feed rate (ton/hr)** | **Side Slope (deg.)** | **Grain Loss (%)** | | | |
|---|---|---|---|---|---|
| | | **100% Side Input** | **32% Side Input** | **30% Side Input** | **10% Side Input** |
| 10 | 5 | 0.047029 | 0.120 | 0.164897 | 0.230112 |
| 20 | 5 | 0.060051 | 0.060 | 0.156918 | 0.293831 |
| 30 | 5 | 0.076680 | 0.040 | 0.200370 | 0.375194 |
| 40 | 5 | 0.097913 | 0.300 | 0.255853 | 0.479087 |
| 50 | 5 | 0.125026 | 0.072 | 0.326700 | 0.611748 |
| 10 | 10 | 0.001657 | 0.120 | 0.077268 | 0.949940 |
| 20 | 10 | 0.002116 | 0.120 | 0.098664 | 1.212982 |
| 30 | 10 | 0.002702 | 0.280 | 0.125984 | 1.548863 |
| 40 | 10 | 0.003450 | 0.690 | 0.160870 | 1.977751 |
| 50 | 10 | 0.004406 | 0.072 | 0.205416 | 2.525399 |

Table A.12 Data from level land operation with side input plots

| **Grain Feed Rate (ton/hr)** | **Grain Loss (%)** | |
|---|---|---|
| | **15 mm Side Input** | **30 mm Side Input** |
| 10 | 0.120 | 0.120 |
| 20 | 1.260 | 1.740 |
| 30 | 0.920 | 0.920 |
| 40 | 0.840 | 0.990 |
| 50 | 7.180 | 11.040 |

# REFERENCES

Bichel, D.C. and C.G. Cornish. 1974. The sidehill 6600 combine—a new concept for the corn belt. ASAE Paper No. 74-1599. St. Joseph, MI: ASAE.

Bilanski, W.K. and S.P. Dongre. 1968. Transporting wheat grain along the combine shoe. *Agric. Eng.* 49(7):408-410.

Bozarth, E.W. 1948. Screen leveling device. U.S. Patent No. 2,500,448.

Clipston, F.J. 1938. Automatic side hill equalizer attachment for grain combines. U.S. Patent No. 2,189,706.

Craessaerts, G., W. Saeys, B. Missotten, and J. De Baerdemaeker. 2007. A genetic input selection methodology for identification of the cleaning process on a combine harvester, part I: selection of relevant input variables for identification of the sieve losses. *Biosys. Eng.* 98(2):166-175.

Dilts, B.M. 2005. Development and modeling of a slope insensitive combine cleaning shoe. Unpublished graduate thesis. Department of Agricultural and Biosystems Engineering; Iowa State University.

Duquesne, F.R.G. and T.N.N. Somers. 2008. Grain cleaning system for a combine harvester. U.S. Patent No. 7,322,882.

Glaubitz, F., G. Eis, and W. Fromme. 1986. Arrangement for uniform distribution of agricultural products in self-propelled harvester threshers and harvester thresher provided therewith. U.S. Patent No. 4,598,718.

Hamilton, A.J. and M.J. Butson. 1979. Approaches to the problem of combine grain loss on sloping ground. *J. Agric. Eng. Res.* 24:293-299.

Harris, J.R. and L.H. Harris. 1986. Grain deflector for combines. U.S. Patent No. 4,677,991.

Heald, J.L. 1893. Combined harvesting and threshing machine. U.S. Patent No. 509,082.

Heidjann, F. and W. Fromme. 1982. Device for distributing screen material. U.S. Patent No. 4,355,647.

Hillco Technologies. 2008. Model 2955S-70S sidehill leveling system operator's manual. Publication No. D-040820CLA02A.

Huynh, V.M. and T.E. Powell. 1978. Cleaning shoe performance prediction. ASAE Paper No. 78-1565. St. Joseph, MI: ASAE.

Hyman, M., R.T. Sheehan, and E.W. Rowland-Hill. 1985. Four way leveling mechanism for combine cleaning apparatus. U.S. Patent No. 4,557,276.

Mackin, R.P. and R.S. Herlyn. 2007. Leveling by over-compensation. U.S. Patent No. 7,306,513.

Morris, M.D., B. Dilts, S.J. Birrell, and P.M. Dixon. 2008. Composite response surface designs for factors with jointly symmetric effects. *Technometrics*, to appear.

Murphy, R.G. 1993. Level bed harvester. U.S. Patent No. 5,205,786.

Park, J.K and J.E. Harmond. 1966. A vertical rotating screen separator. ASAE Paper No. 66-614. St. Joseph, MI: ASAE.

Park, J.K. 1974. Vertical rotating screens for separating seeds from trashy materials. *Trans. ASAE* 4-6(5):606-613.

Potter, H.T. 1955. Grain cleaner and separator. U.S. Patent No. 2,718,967.

Quick, G. 1973. Harvesting in the Netherlands. ASAE Paper No. 73-1557. St. Joseph, MI: ASAE.

Sacquitne, D. 2005. Floating combine sieve assembly. U.S. Patent No. 6,843,719.

SaijPaul, K.K., S.G. Huber, L.O. Drew, and C.D. Jones. 1976. Combine separation and cleaning device-design concepts. *Trans. ASAE* 19(6):1025-1028.

Stahl, T., T. Freye, and H.D. Kutzbach. 1981. Automatic control of cleaning fan speed to reduce sidehill losses. ASAE Paper No. 81-1617. St. Joseph, MI: ASAE.

Vold, O.G. 1905. Leveling attachment for separators. U.S. Patent No. 793,968.

Witzel, H.D. and B.F. Vogelaar. 1955. Engineering the hillside combine. *Agric. Eng.* 36(8):523-525,528.