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Development and evaluation of a single pass, dual stream corn stover harvester

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by

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Introduction

Corn stover is the residue that is left behind after corn grain harvest (Sheehan et al., 2003). It consists of stalks, cobs, husks, leaves, and other non-grain portions of the plant. Corn stover has advantages over other biomass sources because the grain fraction is a high value co-product, and the yield of corn stover is quite high (Shinners et al., 2005). In addition, corn is prevalent throughout the United States and is grown on more acres than any other grain crop (USDA, 2005). This combination of relatively high yield and high availability has brought corn stover to the forefront of the search for biomass to serve as an industrial feedstock for a new generation of products.

In 1999, more than 90% of corn stover was left in the field with less than 1% of the stover being collected for industrial processing and about 5% being baled for animal feed and bedding (Glassner et al., 1999). This material has historically been considered a low-value byproduct of corn grain production. Modern science has shown the benefits of maintaining some crop residue on the soil surface to prevent erosion and to recycle the nutrients remaining in the crop residue back into the soil for future use, but a portion of the stover could be removed for other uses. As a benchmark, the United States Department of Agriculture requires at least 30% of the soil surface to be covered with crop residue after planting to reduce soil erosion and qualify as conservation tillage (USDA, 2000). The remaining stover could be harvested to make ethanol or other products. In North America alone, this uncollected corn stover has the potential to be used to produce 38.4 GL of ethanol (Kim and Dale, 2004). However, before that ethanol can be produced, it is necessary to identify methods of harvesting the corn stover in an efficient and economical manner.

This project will focus on the improvement and evaluation of a single pass, dual stream harvest system based on a combine harvester. The intent of such a system is to simultaneously harvest both clean corn grain and stover as the combine travels through a field. By performing both operations at the same time using a single machine, a time savings could be realized by eliminating two to three field operations normally required if harvesting the stover by chopping, raking, and baling it. The relatively low density of corn stover creates challenges with harvesting and handling the stover. One method to increase the density of the stover is to chop it into small pieces. In general, the density of corn stover will increase with shorter cut length, but research indicates that processing the stover to lengths shorter than about 51 mm (2 in.) does not significantly benefit the densification process (Frohberg, 2005). At shorter cut lengths, more power is required to chop the material, and no significant density advantage is realized.

This research project focuses specifically on the development of a new stover chopper that mounts on the back of a combine harvester in place of the existing residue chopper. The new chopper is designed to provide uniformly chopped stover in pieces 51 mm (2 in.) or smaller to take full advantage of the density effects shown by Frohberg (2005). Additionally, a blower from a self propelled forage harvester is attached to the outlet of the stover chopper. The blower will receive stover from the chopper and propel it into a wagon for compaction or transport.

This thesis will discuss the design, development, and testing of a single pass, dual stream harvest system. The power required to operate the new stover chopper will be compared to that required for the existing residue chopper, and the power required by the blower will also be measured and analyzed. Analysis will show if there is a statistically significant difference in the power requirements of the choppers and blower based on multiple machinery configurations. The field capacities of the system will also be identified along with limitations of the system. Recommendations for further study will follow the conclusions drawn from testing.

Literature Review

The motivations for collecting corn stover are primarily based two distinct usage paths. The classical path has focused on stover as a livestock feed source while the more contemporary path views it as an industrial feedstock. Regardless of the intended use, both paths share the common challenge of harvesting the stover. The following literature review will illustrate the methods that have previously been employed to collect corn stover. In addition, the types of choppers used to reduce the particle size of materials such as corn stover will be explored.

Early stover harvesters: Stover for feed

Some of the first mechanical corn stover harvesters collected the stover with the grain as much for convenience as for a desire to harvest stover. Corn binders were patented from the late 1800's to the 1950s in the United States as a method to mechanize corn grain harvest (Gray, 1898; Zickefoose, 1916; McKahin 1950). These devices would typically cut the corn plant at its base, accumulate a number of these similarly cut corn plants, tie them together in a bundle, and drop the bundles on the ground to be subsequently accumulated in bunches throughout the field or directly transported from the field. Eventually the bundles would be transported to a central location and fed into a corn shredder, such as that developed by Grossman (1927), to separate the ear from the stalk and chop the stalks. The chopped stalks and husks were then often used for livestock feed or bedding or disposed of if unneeded.

An alternative harvest method available during the same time period involved picking the ears of corn and leaving the stalks in the field. In early years, this picking would have been done by hand, but attempts were quickly made to transition to mechanized corn picking (Stone, 1905; Snow, 1961). Though the corn stalks were left in the field, a portion of the stover was still harvested in the form of cobs.

Some farmers were not satisfied with passing up the opportunity to collect corn stalks for feed or bedding purposes. This sentiment was partially due to the United States cattle inventory ballooning during the first three quarters of the twentieth century (USDA, 2007). In response, individuals such as Rosenthal (1950) developed machines to pick ears of corn into one wagon and deliver chopped stalks to another. These machines never gained wide commercial acceptance, but that did not stop the quest to collect corn stover.

As combine harvesters became more popular, the act of collecting corn cobs by default when ear corn was harvested faded, but the theory of stover harvest did not. In the 1960's research was conducted by Ferlemann (1966) and Schroeder (1968) to develop a total corn harvesting machine by combining features of a John Deere Model 55 combine (Deere & Company, Moline, IL) with features of a John Deere Model 38 forage harvester (Deere & Company, Moline, IL). The result was a machine designed to harvest shelled corn grain and deposit it in the grain tank normally while also collecting and chopping the material exiting the rear of the combine to be used as livestock feed. The finished machine was reported to function properly but with marginal reliability (Schroeder,1968).

In more recent years, many farmers who desire to collect corn stover for feed or bedding purposes have elected to use multiple machinery trips through the field rather than collecting grain and stover simultaneously. Devices such as Hesston Corporation's (Hesston, KS) Stack-forming Machine (Lutz and Buller, 1979) or the currently popular large, round or rectangular balers have allowed farmers to collect corn stalks without interfering with the grain harvest operation. The downside to machines such as these is the need for additional field operations beyond the grain harvest. In addition, when the stover is deposited on the ground behind the combine it is at risk of being driven over by other equipment, and it gets contaminated with soil when collecting it from the ground. Further, the cobs are usually not recovered in any of these secondary operations.

Later stover harvesters: Stover for feed or industry

As societal preferences have shifted toward utilizing more renewable resources, corn stover and its components have received attention as potential industrial products. In response, additional machinery has been developed to harvest corn stover. Specifically, Flamme (1999) and Stukenholtz and Stukenholtz (2002) developed machines to separately collect corn cobs as a combine was harvesting grain. The grain was separated from the cob and other chaff with sieves and fans, and the cobs were separated from the chaff by using air flow from fans. Devices have also been developed to allow the collection of a corn cob and corn grain mixture (McBroom 1986). However, harvesting the mixture of cobs and grain will require an additional process to separate them before either can be used independently.

Interest is not lacking in the area of whole corn plant harvest for industrial uses either. Tuetken (2002) developed several such systems at Iowa State University with the stated goal of harvesting independent streams of both corn grain and stover in a single pass through the field. One such system used an International Harvester 1460 Axial Flow combine (International Harvester Company, Chicago, IL) with a John Deere 653A row crop head (Deere & Company, Moline, IL) and a Hesston 10 Stakhand (Hesston, KS) to collect stover. All of the material discharged from the back of the combine was delivered to the modified flail pickup on the Stakhand without ever contacting the ground. The benefits of this system were that it was a single-pass operation, and soil contamination was avoided by not depositing the stover on the ground. On the downside, in order to compress the stover in the Stakhand as intended, the combine had to stop moving and wait for the compression to take place.

Another device developed by Tuetken (2002) was named the “stover caddy.” It was again an effort to use an existing combine as the basis for the design with a stover collection device added to the rear of the combine. The caddy consisted of an upright silo forage blower mounted on a framework that was pinned to the rear axle of the combine at two locations. The framework was supported by caster wheels and would remain directly in line with the combine at all times. As a result, the combine chopper would discharge material into the blower which would then propel the stover into a trailer. Testing showed that plugging was a problem when material did not feed uniformly into the blower. Also, wind had a significant impact on the effectiveness of the system at the transition between the chopper and blower and at the outlet of the blower, especially with dry stover.

Shinners et al. (2005) at the University of Wisconsin has also developed corn stover harvesting devices using a John Deere 9760 STS combine (Deere & Company, Moline, IL) as the base machine. One version employed a John Deere model 666R whole-plant corn head (Deere & Company, Moline, IL) which was normally intended for use with a forage harvester. The head would cut the stalk and pull the entire corn plant into the combine to be processed. A flail chopper, blower, and spout were added to the rear of the combine to reduce the size of the harvested stover and deliver the material to a wagon. The downside to using a flail chopper was the high power requirement and lack of uniformity in terms of particle size due to the inability to orient the stover ideally for the chopper. Shinners et al. (2005) also identified the need to do a better job of aligning and metering stover into a cutting mechanism in order to achieve higher density output.

A second configuration was developed by Shinners et al. (2006) which consisted of a modified Slavutich model KMM-6 ear-snapper corn head (JSC Khersonsky Kombayny – Khereson, Ukraine) mounted on a John Deere 9750 STS combine (Deere & Company, Moline, IL). This head was designed to snap the ears from the stalks and feed them into the combine in the conventional manner. In addition, it had a knife rotor mounted below the snapping rolls designed to cut the stalks and feed them into an auger mounted behind the knife rotor. The auger would then convey the stalks to the end of the head and feed them into a chopper and blower to reduce the size of the stalks and blow them into a wagon. The main advantage of this system was that it eliminated the need to feed all of the stalk material through the combine, but it did not allow for the collection of the cobs, husks, and top of the stalk that was fed through the combine. Unless a second stover collection device was installed at the rear of the combine, the cobs, husks, and top of the stalk would be lost.

Chopper types and characteristics

Most modern combines rely on a residue chopper to reduce the size of the residue being discharged from the separation mechanism within the combine. In many cases the chopper also serves as a spreader to distribute the stover across the width of the combine head. The widely accepted chopper style to use for this application is a flail chopper with knives pinned to the periphery of a rotor. The knives impact the stover to break it and impart energy to distribute it across the ground. Many patents have been issued for variations of this general design (Adams, 1955; Redekop and Redekop, 1996). Though the flail chopper is a simple and largely effective concept, it has some distinct drawbacks. First, evidence has shown that flail choppers tend to require large quantities of power to operate (Srivastava et al., 2006). Second, when randomly oriented material is fed into a flail chopper, as when used on a combine, the output from the chopper is not uniformly sized. Because these choppers typically only provide cutting action in a single plane, any material oriented parallel to that plane is not cut as intended. While this lack of uniformity may be acceptable when using these choppers to size and spread crop residue on a field, applications needing more precise cutting must find other alternatives.

A second chopper type commonly used for corn stover size reduction is the shear type chopper. Choppers of this type are commonly found in forage harvesters where the material to be chopped is oriented in a predictable manner and is fed into the chopper by feed rolls that control the orientation and feed rate of the material. As the material is fed into the chopper it is sheared between knives affixed to the perimeter of a rotor and a stationary shear bar. Again, this general design is widely used on forage harvesters and various versions of it have been patented (Waldrop, 1968; Raisbeck et al., 1977). Though this type of chopper requires less power to operate than a flail chopper (Srivastava et al., 2006), it too has some drawbacks. To effectively control the length of cut a shear chopper produces, the material to be cut must be fed into the chopper radially and at a fixed feed rate. Usually feed rolls are required to achieve this precision.

The stover harvesting machines mentioned above have been produced in response to a desire to collect corn stover. Though certain features of each have been effective, none have proven to be the ideal machine. By combining the best features of the single-pass, combine-based, stover harvesters with the best features of the shear type chopper, this project intends to create a stover harvesting machine that will improve on the previous attempts.

Objectives

The ultimate goal of this research is to develop a machine that will harvest corn grain and stover in a single pass through the field. Ideally, the machine developed will perform some sort of preprocessing of the stover in order to make it more feasible to transport or more suitable for final processing. In support of that goal the following specific objectives have been established.

- Develop, design, and build a new residue chopper for a John Deere STS combine
- Mount a forage blower on the back of the combine to convey stover from the combine chopper to a transportation device
- Field test the conventional residue chopper and the new residue chopper along with the blower system
- Analyze and compare overall power requirements for each configuration in the test procedure
- Analyze and compare power requirements per unit dry matter processed for each configuration in the test procedure
- Identify field capacities and limitations of the system

Equipment Design and Development

The concept of designing a single-pass harvester to collect both corn grain and stover required many issues to be considered in the process. Early on in this study, it was decided that a strategy of utilizing a farmer's existing line of machinery and designing attachments to perform additional desired operations would be an economical way for farmers to collect stover. With this strategy in mind, the combine harvester was selected as the base unit on which attachments would be mounted. Specifically, a John Deere 9750 STS combine was used as the testing platform for corn stover harvest attachments.

The focus of this paper will be on the development, testing, and analysis of a new chopper to be mounted at the rear of the combine in place of the factory supplied flail style residue chopper. In conjunction with the chopper, a particle accelerator or silage blower off of a self-propelled forage harvester was mounted behind the chopper. The material discharged from the chopper was to be fed into the blower and from there into a truck or wagon. The goal of developing an alternative chopper was based on two main issues:

- Reducing the power required to chop the stover
- Easing the task of increasing stover density for transport by cutting stover into uniform, small particles of 51 mm (2 in.) nominal size

Design Theory

A major focus of the development of an alternative chopper centered on minimizing the power required to perform the stover chopping, therefore designs that met this goal in theory drew most of the attention. The residue chopper supplied by the manufacturer was a hammer mill or flail style chopper that relied on impact from the swinging hammers within it to break the stover into smaller pieces, as seen in Figure 1. On the other hand, shear choppers utilize a moving knife blade that passes in close proximity to a stationary knife or countershear, as seen in Figure 2, to cut material. The countershear serves to support the material being cut while the knife slices through it. In terms of relative power requirements, a flail chopper requires significantly more power than a shear chopper because impact cutting requires more power than cutting with a countershear and because a large quantity of air is pumped by the flail chopper (Srivastava et al., 2006). The distinct advantage of a shear chopper over a flail chopper in terms of minimizing power requirements guided the design toward using some form of a shear chopper.

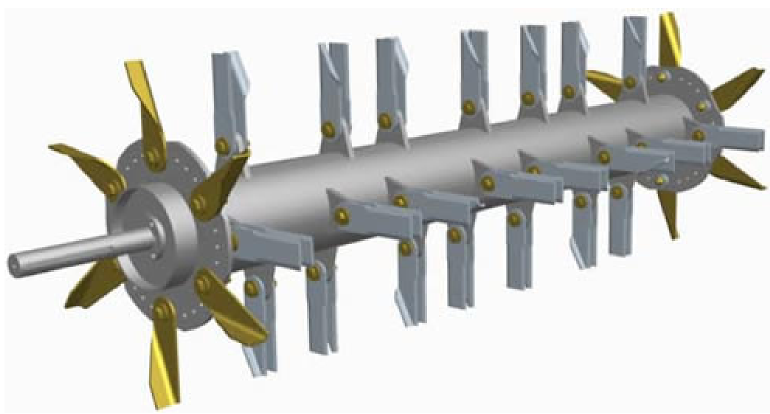


Figure 1: Typical example of a flail chopper rotor relying on swinging hammers for impact cutting (Anon, 2007)

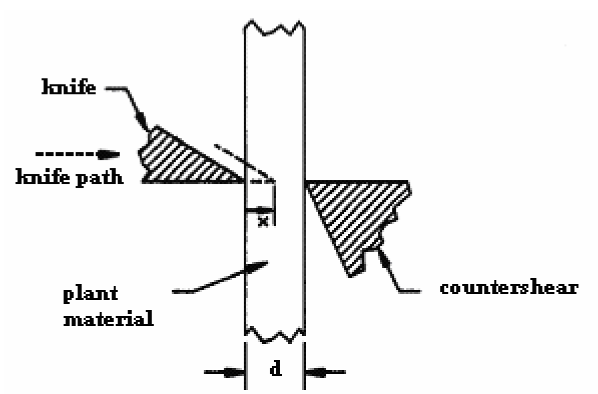


Figure 2: Principles of shear cutting (After, Srivastava et al., 2006)

Since stover density was also an important issue for stover harvest and transportation, it too influenced the design of the new chopper. Frohberg (2005) explored the effect of stover particle size on density and found that decreasing particle size resulted in a beneficial increase in density. However, chopping stover into pieces less than 51 mm (2 in.) in length resulted in negligible advantages for densification. Furthermore, the smaller the material length of cut, the more power required to achieve that length. The combination of these factors guided the design objectives for the new chopper to target a cut length of two inches.

A decision was made to pursue a shear chopper that would cut corn stover into two inch pieces, and different designs to achieve this cut length were considered. One readily available design was to use a chopper rotor similar to those used on self-propelled forage harvesters, as seen in Figure 3. Choppers of this type utilize shear cutting with knives mounted on the periphery of a rotating drum that pass in close proximity to a stationary countershear bar. Forage material is then gripped by feed rolls and fed into the chopper tangentially as seen in Figure 4. Because the material normally being fed into a forage harvester chopper consists of intact plants that can be consistently delivered to the cutterhead in a predictable and controlled orientation, the output of such a chopper is also quite predictable. Material gets chopped into pieces whose length is determined by the speed of the feed rolls, number of knives on the cutterhead, and rotational speed of the cutterhead. These systems provide good uniformity of cut length and relatively few pieces remain longer than the desired cut length.

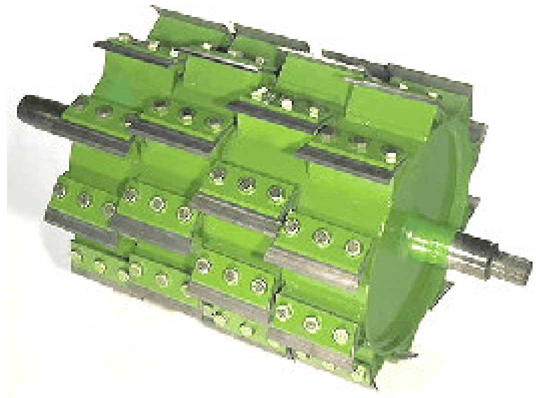


Figure 3: John Deere Dura-Drum™ cutterhead for self-propelled forage harvester (Deere & Company, Moline, IL)

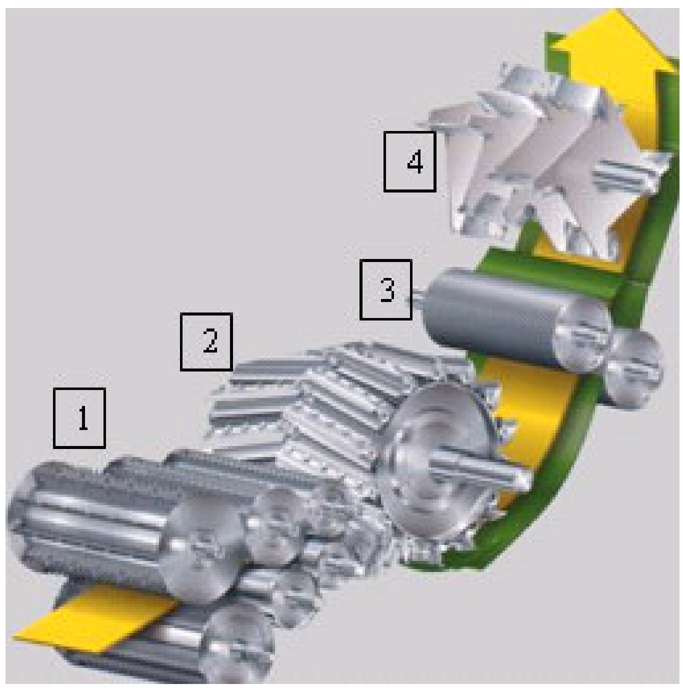


Figure 4: Krone forage harvester components showing (1) feed rolls, (2) cutterhead, (3) kernel processor, (4) blower, and material path through system (Krone NA, Inc., Memphis, TN)

The ability to achieve a consistent cut length with a forage harvester cutterhead brought that general design to the forefront of potential designs. However, there was a distinct drawback to using a forage harvester cutterhead for stover chopping. When corn stover exits the rear of a combine harvester, such as the John Deere 9750 STS used in this experiment, the plant is no longer intact or in a predictable orientation. The result is that material oriented parallel to the axis of the cutterhead would pass through the chopper without actually being cut to the desired size. In addition, the material exiting the combine is airborne and not positively controlled by feed rolls. Adding such feed rolls would inhibit the grain cleaning system on the combine by limiting airflow and would significantly increase the complexity of the system. As a result, an attempt was made to identify a design that would not require feed rolls but would still provide uniform cut length regardless of material orientation.

Specifications

Overall chopper rotor layout

The outcome of this pursuit to uniformly chop corn stover while minimizing the power requirement combined the beneficial characteristics of both shear and flail choppers. The selected design was a chopper that would simultaneously produce shear cutting in two perpendicular directions to ensure that all material that entered the chopper would exit in pieces two inches or smaller. The fundamental characteristics of the new chopper were based on the cutterhead design found on most self-propelled forage harvesters, with the addition of a second shear cutting axis perpendicular to the primary shear axis. That is, the chopper consisted of a series of knives affixed to the periphery of a rotating drum that would pass near a stationary countershear bar. In addition, another set of knives, mounted perpendicular to the first set, protruded from the countershear bar support and was positioned to pass through gaps between the set of knives on the drum, to produce shear cutting in a second plane. Since shear was to occur in two planes the new chopper was called a double shear chopper. Figure 5 is a CAD drawing of one section of the new double shear chopper rotor. Figure 6 is a picture of the completed chopper mounted in the chopper housing.

The entire chopper rotor was comprised of seven sections identical to that shown in Figure 5. Each section had nine knife holders distributed uniformly on the perimeter with three removable knives per knife holder. The sections were mounted on a two inch hex shaft in order to make torque transmission and manufacturing easier. The hex shaft allowed the sections to be indexed at 60 degree increments. Each adjacent section was staggered 60 degrees from the next on the center shaft in an effort to spread the timing of

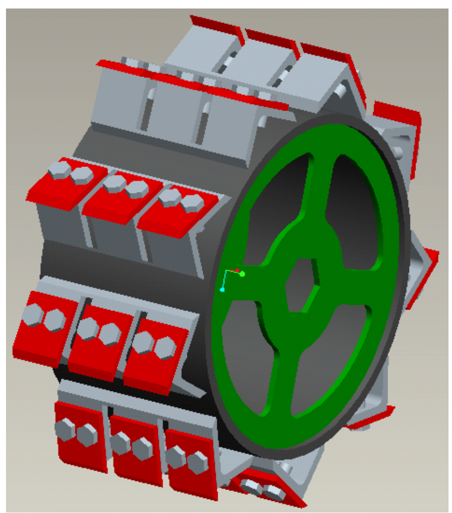


Figure 5: CAD image of double shear chopper rotor section

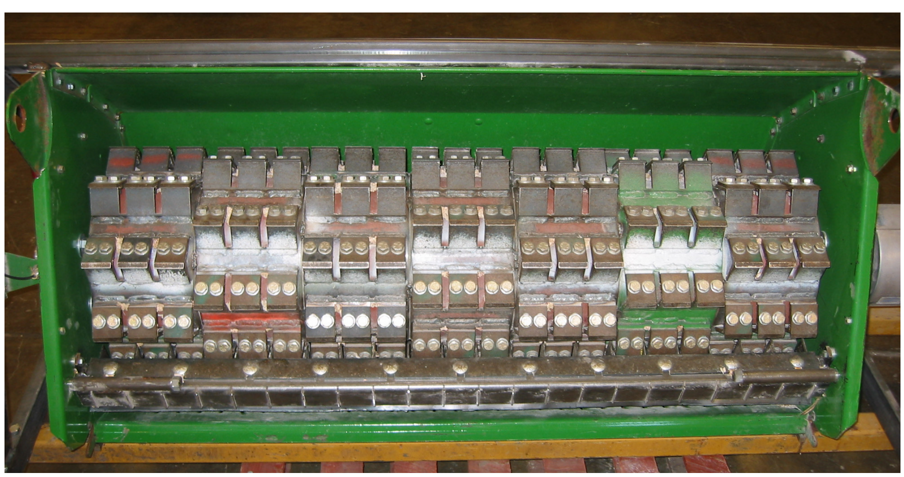


Figure 6: Completed double shear chopper mounted in housing

the cuts providing a distribution of the peak torque demand which would result in a more uniform power demand. In addition, this arrangement would avoid slugging the chopper. Each adjacent section on the center hex shaft was staggered in 60 degree increments, which resulted in the knife holders on adjacent sections being staggered by 20 degrees. Therefore, every 20 degrees of shaft rotation resulted in a cut. The chevron pattern created by this approach is visible in Figure 7.

Knife holder design and knives

The knife holder was a critical component in getting the double shear chopper to function as desired (Figure 8 a,b,c), and it simultaneously served two main functions. The first function of each knife holder was to hold three removable knives on the perimeter of the rotor drum. In the second function, the edges of the slots in the knife holder served as the countershear surfaces for the stationary knives attached to the main countershear bar. The dimensions of the knife holder were based on the nominal particle size desired from this chopper. The overall width of the holder was seven inches with two half-inch slots cut in the middle to allow for the stationary knives to pass through. The remaining portion of the holder consisted of three two-inch sections connected only by strips of steel that were left uncut when waterjet cutting the slots. By leaving the

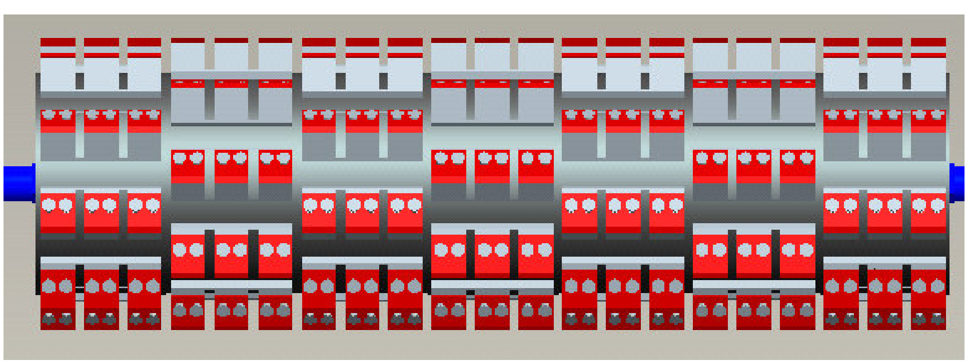
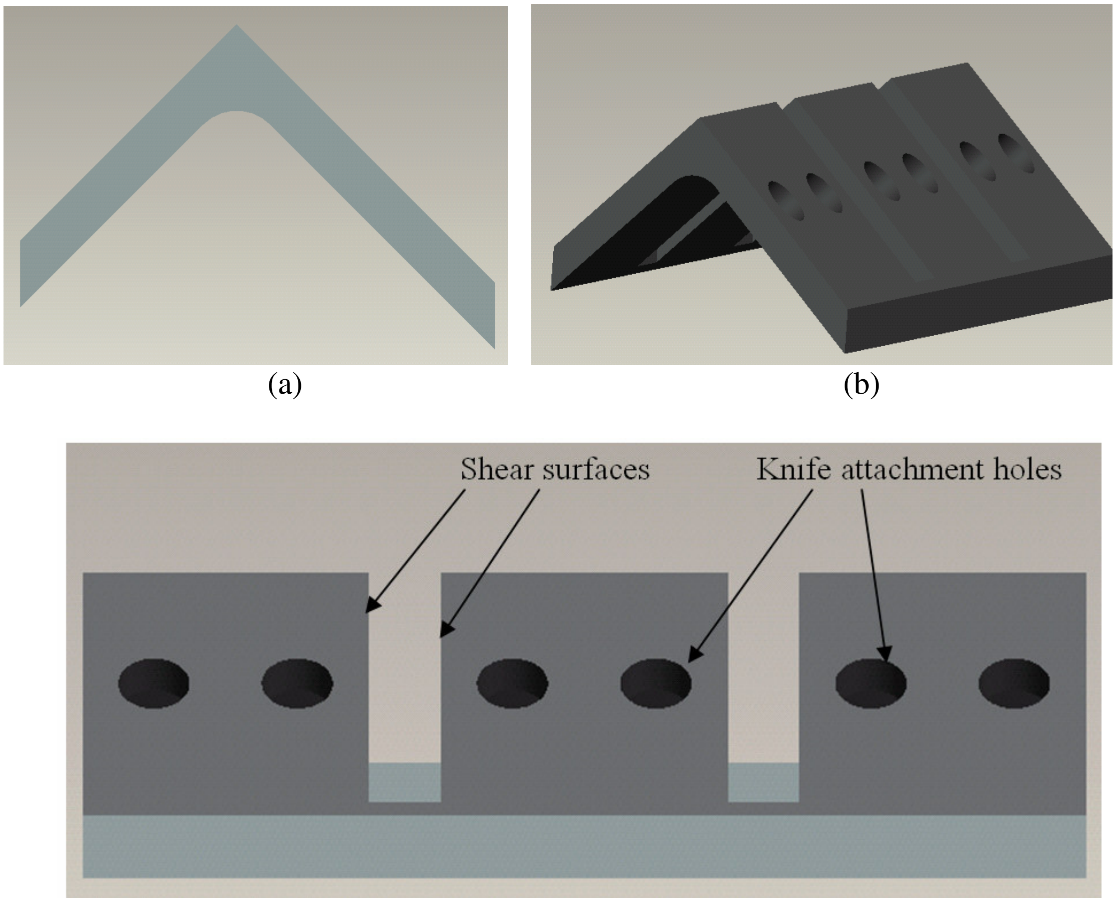


Figure 7: Stagger of adjacent sections on double shear chopper



(a) (b)

(c)

Figure 8: CAD image of knife holder sections showing (a) a cross section (b), orthogonal view, and (c) plan view showing longitudinal shear surfaces and knife attachment holes

strips intact, the half-inch spacing was maintained which resulted in an easier and more uniform manufacturing process. The knife holders were welded to the center tube using a jig to hold them in position during assembly.

The knives mounted to the rotor of the double shear chopper were designed to fit the needs of this particular application. They were made from hardened steel to prevent excessive wear during use, and they were cut using a waterjet cutting machine in order to avoid potentially negative heat effects during the cutting process. Each knife was 51 mm (2 in.) wide with two 12.7 mm (0.5 in.) slots cut into it to fasten it to the knife holder. The cutting edge was cut with a waterjet cutting machine to a 40 degree angle.

Rotor core

The center of the double shear chopper was made up of a round steel tube with steel plates welded in the center to transmit torque from the 51 mm (2 in.) hex shaft driving the device to the knife blades. A side view of a double shear chopper section illustrating the center plates, center tube, knife holders, and knives, is shown in Figure 9. The center tube had a 304.8 mm (12 in.) inside diameter and 9.53 mm (0.375 in.) wall to give an outside diameter of 323.9 mm (12.75 in.). The diameter at the tip of the knives was approximately 432 mm (17 in.). The center tube was largely selected because of its availability, but it provided an overall chopper diameter for the double shear chopper that fit comfortably within the housing of the original flail chopper. The original flail chopper was larger in diameter at about 584 mm (23 in.).

The center plates were made from 6.35 mm (0.25 in.) plate steel. They were cut with a waterjet cutting machine for convenience and timing issues, but other cutting methods would have been acceptable also. Two plates were used for each chopper

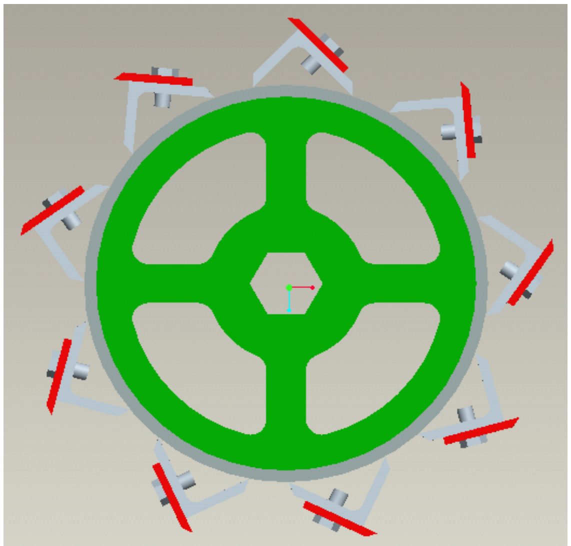


Figure 9: Side view CAD image of double shear chopper section design

section, and each was recessed 6.35 mm (0.25 in.) from the end of the tube. Four openings were cut in each plate to reduce the weight of the chopper and to allow access to the inside of the rotor. Original plans called for the plates to be welded to the center shaft so the openings would have provided access for that also. The final design dismissed the idea of welding to the center shaft. Instead, collars were made to slide over each end of the shaft and clamp to the shaft using a bolt. The seven rotor sections were then sandwiched between the two clamps and lightly welded together where the center tubes touched one another.

Chopper housing

The original intent of this project was to use an existing combine harvester with bolt-on attachments to harvest corn stover. In order to simplify that goal, it was determined that the double shear chopper would be mounted in a housing nearly identical to that of the original flail chopper. The only differences between the original housing and the housing for the double shear chopper were on the housing side panels. The design for the side panels was modified slightly to increase the thickness and remove some unnecessary bends. The original housing side panels, seen in Figure 10, were 3 mm (0.118 in.) thick. In order to support the additional weight of the double shear chopper, the new side panels were made 4.76 mm (0.1875 in.) thick. Since they were no longer needed, multiple bends in the original side panel were removed on the new iteration to simplify manufacturing. The new side panel, without the original bends, can be seen in Figure 11.

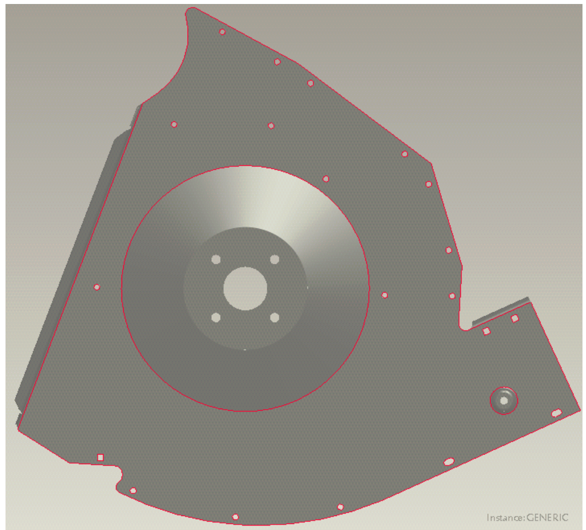


Figure 10: Side panel for original flail chopper housing (Deere & Company, Moline, IL)

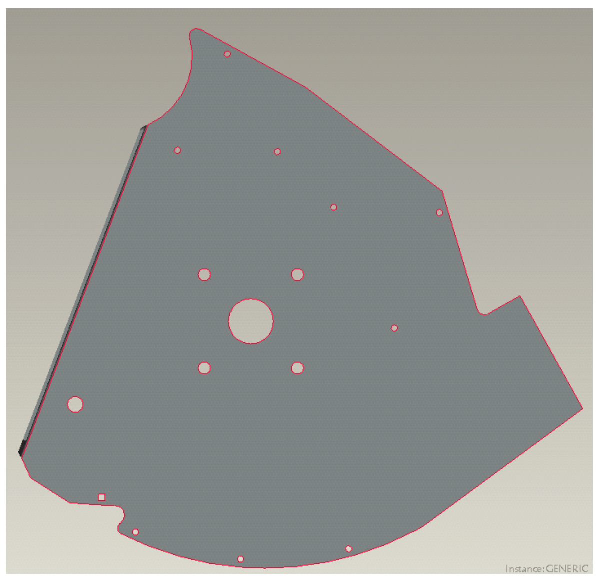


Figure 11: Side panel for double shear chopper housing (After, Deere & Company, Moline, IL)

Manufacturing and assembly

The task of manufacturing the double shear chopper was a challenge because of the need for high levels of precision to ensure that appropriate tolerances would be maintained between cutting surfaces and that the rotor would be balanced during operation. In order to accomplish this task, a jig was made to hold the components for each chopper section in position while welding them together (Figure 12). After each of

Figure 12: Jig for assembling double shear chopper sections

the seven chopper sections was welded together, it was checked for balance on the static balancing test stand shown in Figure 13. This stand simply consisted of a framework that would support a short section of 51 mm (2 in.) hex shaft that was slid through an assembled chopper section. Bearings on each end of the shaft reduced friction so that the heavy side of the chopper section would rotate to the bottom. By checking each section for balance, slight modifications could be made to the assembly procedure before the next section was assembled to try to improve the balance. None of the sections were out of balance far enough to justify drastic changes in the manufacturing process.

After the seven chopper sections were welded they were all slid onto the 51 mm (2 in.) hex shaft being used to drive the double shear chopper. As mentioned previously, each section was staggered 60 degrees from adjacent sections to spread the timing of the cuts in order to distribute the chopper power requirement more uniformly and avoid slugging the chopper. Lock collars were used to hold the sections in position on the shaft, and then the individual sections were welded to one another to give the chopper more rigidity and decrease the likelihood of the sections moving inadvertently. The

Figure 13: Balancing test stand for double shear chopper sections

entire rotor was also checked for balance on a stand similar to that seen in Figure 13. Additional steel was welded on the light spots of the rotor to balance it.

Countershear bar

One of the most noticeable differences between a flail chopper and a shear chopper is that a shear chopper needs a countershear bar to support the material being cut, as discussed previously. In the case of the double shear chopper, countershear surfaces were needed for two sets of knives rather than just one set. For the knives mounted on the double shear chopper rotor, a piece of 6.35 mm by 41.28 mm (0.25 in. by 1.63 in.) hardened steel mounted to a support tube served as the primary countershear parallel to the chopper axis. The second set of knives was positioned to cut material in a plane perpendicular to the first set. These knives were mounted in the support tube for the main countershear. The countershear surfaces for the second set of knives were actually the knife holders on the perimeter of the chopper rotor. The second set of knives would pass through the slots cut into the knife holders. The edges of the slots were close enough to the knives to act as shear surfaces. The components of the countershear bar including the main countershear surface, the secondary knives, the support tube, and the mounting points are shown in Figure 14, with the overall view of the countershear bar shown in Figure 15. The countershear bar was attached to the chopper housing side panels with a bolt and bushing to allow the bar to be rotationally adjusted for proper clearance with respect to the rotor. An additional mounting tab was positioned on either end of the support bar to clamp the bar in position once properly adjusted. The bolt clamping the bar passed through a slot in the housing side panels to accommodate any adjustments. The clamping bolt also acted as a shear bolt that would break and allow the countershear bar to rotate away from the chopper rotor if an obstruction was present.

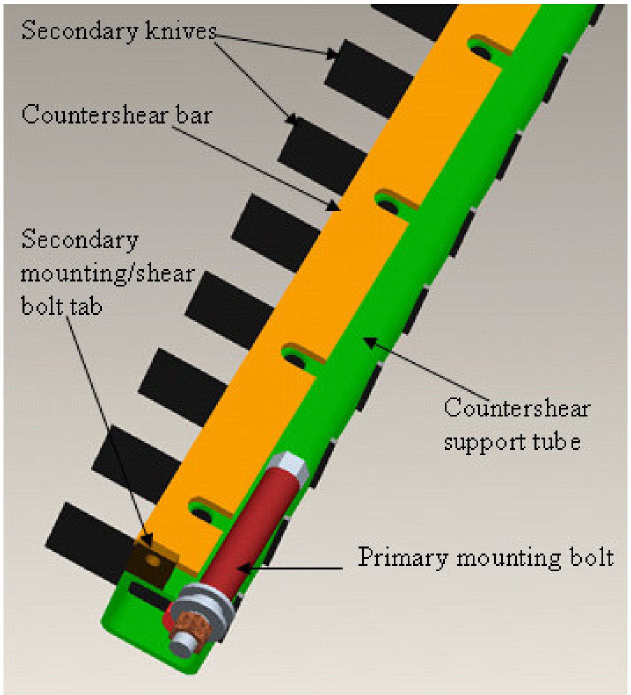


Figure 14: Components of countershear bar

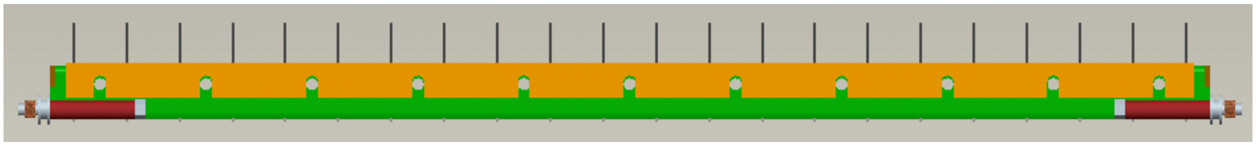


Figure 15: Overall view of countershear bar and secondary knives

Blower and transition

In order to achieve the goal of single pass corn stover harvest, the material being discharged from the chopper needed to be transferred to a storage or transport container. To accomplish that task, a forage blower from a John Deere 7500 self-propelled forage harvester (Deere & Company, Moline, IL) was mounted on a framework extending from the rear of the combine as seen in Figure 16. A sheet metal transition was fabricated to extend from the outlet of the chopper to the inlet of the forage harvester blower. This transition was designed with multiple functions in mind. First, it could be positioned such that it formed an enclosed pathway to transition the material from the chopper to the blower. Alternatively, it could be used as a spreader to distribute corn stover on the ground when collection was not desired. On the bottom side of the transition, the factory-supplied deflector fins were mounted such that when the transition was pivoted to the open position, the chopper would accelerate the stover along the deflectors and spread the material on the ground. When the transition was pivoted to the closed position, the stover from the chopper was guided to the blower. This feature would allow the combine to continue grain harvest even if a stover storage or transportation container was not available at the time.

Drive system

The original chopper drive system for a 9750 STS combine was a belt drive system. For research purposes, the belt drive system was replaced with a hydraulic drive system in order to take advantage of the convenience of being able to adjust speed more easily and measure the power requirement of the chopper with the aid of pressure sensors in the hydraulic lines. Hydraulic power was provided by mounting two additional pumps on the combine engine. One of the pumps was used exclusively for driving the chopper,

Figure 16: Image of forage blower and multi-function sheet metal transition

and the other was attached to a valve stack to provide hydraulic capability to run the motor on the forage blower as well as auxiliary hydraulic outlets. No major modifications were done to the original belt drive system so the hydraulic motor could be removed and the system converted back to belt drive after all necessary data was collected. The pump used for the chopper was a Sauer-Danfoss Model 90L130 axial piston pump (Sauer-Danfoss, Inc., Lincolnshire, IL) with a displacement of 130 cm^3 per revolution (7.9 in^3/rev) while the pump used for the blower was a Sauer-Danfoss Model 4577445 axial piston pump with a displacement of 57 cm^3 per revolution (3.48 in^3/rev). The shear chopper used a Sauer-Danfoss Model 90M130 axial piston motor with a displacement of 130 cm^3 per revolution (7.9 in^3/rev). The flail chopper used a Sauer-Danfoss Model 90M75 axial piston motor with a displacement of 75 cm^3 per revolution (4.6 in^3/rev). The blower used a Marzocchi motor (Marzocchi Pompe, Bologna, Italy) with a displacement of 52 cm^3 per revolution (3.1 in^3/rev).

Combine Heads

Two different combine head types were used during this project to determine the impact of the head on harvest speed, biomass yield, and chopper and blower power requirement. The first head was a John Deere 653A row crop head (Figure 17), which generally would have been used to harvest crops such as soybeans, milo, or sunflowers rather than corn. This head had the capability of harvesting virtually all of the above ground corn plant material. It used gathering belts for each row unit to grasp the stalk and pull it toward the combine while holding it in an upright orientation (Figure 18). As the belts pulled the stalk closer to the combine, a set of knives would slice the stalk off at its base. The belts continued to carry the vertical stalks to the cross auger at the rear of the head where the belts released the stalks and the auger guided them into the combine feederhouse. This particular head was a six row model set for 762 mm (30 in.) rows. Previous experience running the 653A in corn revealed feeding problems with the head. That is, the corn plants would sometimes work free from the gathering belts, fall on the head points, and cause plugging issues. An additional problem was that the cross auger was designed with shallow flighting for crops producing less biomass than the corn for which it was currently being used. Again, some stalks would tend to accumulate on the head and eventually plug it. To combat the feeding problems, a reel was mounted on the head, and a new cross auger with deeper flighting and a smaller diameter center tube was installed. The reel would then help pull the corn stalks toward the combine and the aggressive auger would grab them more consistently and deliver them to the feederhouse.

The reel was a relatively simple design that consisted of two end supports, a round tube to serve as the center shaft of the actual reel, tines, and a hydraulic motor drive (Figure 19). The tines on this reel were positioned directly over the points so they

Figure 17: John Deere 653A row crop head with corn reel and modified auger tube section

Figure 18: Gathering belts on 653A head used to control corn plant during harvest

would not interfere with the stalks that were feeding in normally, but they would pull in stalks that were leaning or no longer being held by the gathering belts. The center shaft of the reel was operated at a height that would minimize interference with the stalks that were being fed into the head. In previous years, the reel was operated closer to the ground but that initiated additional problems by pushing the stalks forward and out of the

Figure 19: Corn reel in operation on 653A head during harvest

grip of the gathering belts. Operation of the reel farther above the gathering belts allowed the shaft to clear most of the stalks, and the tines were still able to pull the loose stalks into the head.

The original auger in the 653A had a 406 mm (16 in.) center tube and 102 mm (4 in.) flighting. The large center tube and shallow flighting limited the amount of open space around the auger. As a result, it was not very aggressive in terms of grabbing material and pulling it toward the feederhouse. A different auger with a 152 mm (6 in.) center tube and 229 mm (9 in.) flighting was acquired and installed in the head. The increased open area of this auger made it much more aggressive and better suited for the larger quantities of material encountered when harvesting entire corn plants. The original and new augers can be seen in Figure 20 and Figure 17 respectively.

The second head used for testing purposes was a John Deere 1293 12 row corn head (Deere & Company, Moline, IL) set to 762 mm (30 in.) rows (Figure 21). The 1293 was a conventional, unmodified head that was used to represent normal harvesting and provide a baseline to which the modifications could be compared.

Figure 20: Original auger with 406 mm (16 in.) center tube and 102 mm (4in.) flighting in 653A head

Figure 21: John Deere 1293 conventional corn head

Choppers

The other main variables in terms of equipment being tested were at the rear of the combine. Two choppers were evaluated in this study. The original flail chopper was being tested to represent normal harvesting and provide a baseline to which other modifications could be compared. In addition, the double shear chopper developed in this project was also studied to determine how it influenced the entire harvest system.

Methods and Analysis

In fulfillment of the objective to develop, design, and build a new residue chopper for a combine, the double shear chopper discussed in the Equipment Design and Development section was built. In addition, a forage blower from a John Deere 7500 self-propelled forage harvester was mounted on the rear of the combine. The next step was to test the performance of the completed system. More specifically, a series of system configurations were developed to test the effects of changing the features of the harvest system including the combine head, chopper, ground speed, and use of the blower.

Experimental design

This experiment was set up as a completely randomized design. Using the equipment described previously, each combination of head, chopper, presence or absence of blower, and ground speed were compiled to determine the configurations to be tested. Also, three repetitions of each configuration were run. A configuration was made by selecting one of two possible heads, one of two possible choppers, one of two possible blower settings, one of three possible ground speeds, and one of three possible repetitions for a total of 72 runs. Table 1 shows the components that were combined to produce all of the test run configurations.

Table 1: Design of experiments for field trials of different test configurations

Heads	Choppers	Blower	Ground Speed	Repetition
1293 conventional 12 row	conventional flail	with	1	1
653A row crop 6 row	double shear	without	2	2
			3	3

Due to logistical limitations, the test order could not be completely randomized. Because of the significant time required to switch between the two different choppers and the two different heads, it was not possible to switch these devices on a random basis. As a result, all of the tests with a given chopper and head were run in a group in a random order. At the conclusion of that set of tests the head was switched and the associated tests were again run in a random fashion. Next, the chopper was switched and the same strategy of completing all tests with one head and then the other was again followed. Within the chopper and head constraints listed above, the tests were run in a random order and the location of each test in the field was randomized

Site layout

All of the tests were run on a farm between Ames, IA, and Boone, IA, over a three day period. The field was nominally half of a mile long and approximately 168 m (550 ft.) wide. The rows of corn were planted in the long direction through the field, roughly north and south, and the field was divided perpendicular to the rows into six sections nominally 114 m (375 ft.) long. A plot consisted of either 6 or 12 rows, depending on the head to be used, in one of the 114 m (375 ft.) sections. Different combine configurations were randomly allocated to individual plots within the field.

The field used for this experiment was managed using commercially accepted production practices. The field was in its third year of continuous corn production and had been tilled the previous fall using an M&W ripper (M&W Gear, Gibson City, IL). Fertilizer was applied using variable rate technology and was incorporated into the soil using a John Deere Mulch Finisher (Deere & Company, Moline, IL). It was planted on April 15, 2006, to Pioneer 34N45 corn (Pioneer Hi-Bred International, Inc., Johnston, IA). This 110 day maturity hybrid had resistance to European corn borers and was glyphosate herbicide tolerant. It was also treated with Poncho 1250 seed-applied insecticide (Bayer CropScience, Research Triangle Park, NC).

Equipment

To facilitate the collection of data necessary to evaluate the performance of the single pass corn stover harvester, additional equipment was needed. The primary supplies required included the following:

- Laptop computer
- Data acquisition system
- Pressure sensors
- Magnetic pickup speed sensors
- Stover wagon with scale
- Grain trailer with scale
- Laboratory drying oven

The laptop computer was a standard Microsoft Windows based device (Microsoft Corporation, Redmond, WA) that was used to run a Microsoft Visual Basic program written to collect and store all desired data from the tests to be run. The computer also served as storage for the data files that were collected.

The data acquisition system included a Model USB-1208LS Personal Measurement Device (PMD) (Measurement Computing Corporation, Norton, MA). This device provided features including analog inputs and outputs, digital inputs and outputs, and an event counter. Using the PMD allowed the operator to control the speed of the stover chopper from the combine cab. It also permitted organized and efficient data collection.

Since four pressure sensors were used in the hydraulic system controlling the chopper and blower and two speed sensors were used to measure the speed of the chopper and blower, the PMD was essential to scan through these sensor readings and record them to data files on the laptop computer. The result was that a large amount of data could be captured and stored in a short period of time allowing for increased accuracy in measurements.

Pressure sensors were used in the stover harvest system being tested to determine the pressure drop across the hydraulic motors being used to run the chopper and the blower. For each motor, a pressure sensor was placed on both the high pressure and low pressure side of the motor. The output of theses sensors was sampled at 150 Hz by the PMD and stored in the data files for later reference. The sensors used were Model 2700 units from Precise Sensors, Inc. (Monrovia, CA). They had a working range of 0 to 34.5 MPa (0 to 5000 psig) and can be seen in Figure 22.

The actual speed of the chopper and blower were important for system performance calculations including the power required to operate each. To obtain these

Figure 22: Pressure sensor used on stover harvester

values, magnetic pickup speed sensors were installed on the chopper and blower to determine the speed of each. These sensors were mounted such that they just cleared a gear mounted on the chopper or blower shaft. As the shaft rotated, each tooth on the gear passed through the magnetic field of the sensor and induced a digital output pulse. The frequency of the pulses could then be related to the speed of the shaft. Again, the output cumulative counts were recorded by the PMD every second and stored in the data files for post processing.

It was also determined that the weight of the material being harvested would be beneficial for additional calculations including determining yield. To weigh the stover, a covered wagon was pulled behind the combine and the forage blower discharged the harvested stover into the wagon. The wagon used can be seen in Figure 23. The wagon was equipped with load cells to weigh the contents. At the end of each run, the weight of the stover in the wagon was recorded. Similarly, a grain trailer equipped with load cells was used to weigh the harvested grain. After each run the combine grain tank was unloaded into the grain trailer and the weight of its contents recorded.

Figure 23: Instrumented stover wagon with integrated load cells used for stover collection

Samples of the harvested corn grain and stover were taken to determine moisture content of the material for each configuration of equipment tested. The samples were then dried in a laboratory drying oven using ASAE Standards S358.2 (2003b) for the stover and S352.2 (2003a) for the grain.

Procedure

The testing procedure followed when evaluating the single pass stover harvester depended on which configuration was being tested at a given time. Some of the steps were not applicable for all of the configurations. The details of the test procedure will be discussed below.

Once the equipment configuration to be tested was selected, the appropriate equipment was prepared. For tests requiring the use of the blower, the stover collection wagon was hitched to the combine, the transition structure between the chopper and blower was lowered into position, and the blower started. The combine operator then started the chopper and the combine mechanism, activated the data collection system, and harvested the plot. At the end of the plot, the data collection system was deactivated, and the grain was unloaded into the grain trailer, weighed, and a sample was taken for moisture determination. The stover collected in the trailing stover wagon was also weighed and sampled for moisture determination. For the tests not requiring the use of the blower, the stover wagon was not used, the transition structure between the chopper and the blower was raised into the spreading position, and the blower was not started. The stover was discharged directly from the chopper onto the ground so no stover was collected. The remainder of the procedure was the same as when the stover was collected with the exception of not weighing or sampling the stover at the end of the plot.

The type of combine head being used also influenced the testing procedure in terms of the ground speed at which the combine was operated. The 1293 conventional 12 row corn head was to be tested at 1.61, 2.41, and 3.22 km/h (1, 1.5, and 2 mi/h) while the 653A row crop 6 row head was to be tested at 1.61, 3.22, and 4.02 km/h (1, 2, and 2.5 mph). The combine settings were unchanged during the tests. The sieves and chaffer were set according to the operator's manual and never changed. The fan speed was maintained at 1300 rpm for all tests, the rotor was set between 300 and 350 rpm, and the concave was set to 25 according to the manual. Based on preliminary experimentation, for the tests using the 653A head and the shear chopper, the rotor speed was increased to between 450 and 500 rpm and the concave clearance was decreased to a setting of 10 in an effort to break the stalks as they passed through the rotor to improve stover flow into the shear chopper. Cut height as indicated on the header height display was maintained constant for all tests.

After the field tests were run and samples were collected from the harvested stover and grain, it was necessary to dry the samples to determine the moisture content of each. The samples were oven dried according to ASAE Standard S358.2 (2003b) for the stover and S352.2 (2003a) for the grain. The wet weight of the samples was recorded, the samples were then dried, and the dry weight was recorded. The change in weight was considered to be entirely due to evaporation of water, and the samples were considered to have no water in them when dry. The wet basis moisture content for the sample was then calculated based on the amount of water that had evaporated divided by the wet weight of the sample.

The goal of conducting the performance tests with the single pass stover harvester was to observe the effectiveness of the modifications to the base combine harvester. The information recorded and subsequent material tests provided the information required to facilitate that goal. The data collected and its intended use will be discussed below.

In addition to the overall power required for the chopper and blower, the power requirement per unit dry matter for each configuration was desired. To determine the quantity of dry matter flowing through the machine the weight of grain and stover collected during each run was recorded, and samples of each were taken to perform moisture tests. The moisture information and material weight information was used to determine the weight of dry matter passing through the system.

Separate from the data collected during the test runs, it was also critical to know the dimensions of the plots to determine the yield of each per unit area. By calculating the yield per unit area, the test field could be compared to other fields to verify that it was representative of a typical corn field. This information was also used when determining the field capacity of the system. The yield per unit area could be combined with the area harvested per unit time to give the capacity of the harvester over a given amount of time.

Data Analysis

The information contained in this section will explain the ways in which collected data was used to calculate desired quantities when analyzing the data. It will also explain the general strategies that were used to evaluate the results of the tests.

The power requirements for the chopper and blower were of particular interest in this study. The torque and speed needed to be known before doing the final power calculation, however. The torque on the motor was calculated by equation **(1)**.

$$T = \frac{\Delta p * D_m}{2 * \pi} \qquad (1)$$

where: T = motor torque (N·m)

Δp = pressure drop across motor (MPa)

D_m = motor displacement (cm^3/rev)

The speed of the motor was determined through the use of the magnetic pickup speed sensors discussed earlier, the pressure drop was the difference between the calibrated pressure readings on the high and low pressure sides of the motor, and the displacement of the motors can be seen in Table 2. The speeds and pressure drops used for calculation purposes were the averages of the data values recorded during each test. That is, the data values recorded every second were averages of the 150 samples taken per second. An average pressure and speed to be used in calculations was found by averaging the one-second readings over the time the test was being run. The result was then a single value for pressure drop that was used to calculate a single value for torque for each run. The speed value was then combined with the torque to determine an average power for the run using equation **(2)**.

$$P = \frac{2 * \pi * T * N}{60{,}000} \tag{2}$$

where: P = power required to operate the chopper or blower (kW)

T = torque on the device (N·m)

N = motor speed (rpm)

Table 2: Pump and motor displacements specifications (cm^3/rev)

	Pump	Motor
Shear Chopper	130	130
Flail Chopper	130	75
Blower	57	52

The moisture content (MC) of the grain and stover samples was also important to determine dry matter yields which ultimately allowed the calculation of the power requirements per unit dry matter. Equation **(3)** was used to calculate the moisture content of the samples on a wet basis (w.b.) as follows:

$$MC(w.b.\%) = \frac{Loss\ in\ Weight * 100}{Weight\ of\ Wet\ Sample} \qquad (3)$$

where the loss in weight is assumed to be due entirely to the evaporation of all of the water in the sample. Combining the moisture content of the sample with the weight of the material harvested from the plot allowed the calculation of dry matter yield for each plot as shown in equation **(4)**.

$$DM = \frac{(100 - MC\%_{w.b.})}{100} * harvested\ weight \qquad (4)$$

where: DM = weight of dry matter material harvested

harvested weight = weight of wet material as harvested

The dry matter weight was then be divided by the plot area to get the yield of the plot per unit area.

Calculations were also performed to determine the amount of land area that the single pass stover harvester could cover at the speeds tested in this study. The ground speed at which the machine was operated was multiplied by the width of the combine head to get an area harvested per unit time. The feedrate of dry matter material through the harvester was then calculated in equation **(5)** as follows:

$$Feedrate = \frac{weight\ of\ DM}{harvested\ area} * \frac{harvested\ area}{time} \qquad (5)$$

where feedrate is the weight of dry matter passing through the harvester over a given time period.

Finally, the specific power, or power required per unit dry matter harvested over a given time period, was calculated by using equation **(6)**:

$$P_S = \frac{Power}{Feedrate} \tag{6}$$

where P_S is the specific power and has general units of kilowatt hours per megagram. The specific power value provides a quantity that can be compared universally throughout this study regardless of the variables involved. Specific power values of this format for other chopping or blowing mechanisms could also reasonably be compared to the values obtained here.

Statistical Analysis

Statistical analysis was done using Statistical Analysis Systems software (SAS, 2003). The statistical significance of treatment effects was determined using the general linear model (GLM) procedure. Comparisons of head and chopper effects were made using orthogonal contrasts. Differences among treatment means were considered significant at $p \leq 0.05$.

Results

Testing of the single pass grain and stover harvesting system yielded quantitative and qualitative results. Both will be discussed here starting with observations of the system during testing and leading to the numerical values of the collected data.

Test Observations

Starting at the front end of the combine, the performance of the two types of heads used in this experiment was largely as expected. The 1293 conventional 12 row corn head effectively harvested the crop at any speed the rest of the machine was capable of running. The 653A row crop 6 row head was not originally designed to harvest corn. In previous years, it was found that the 653A row crop head limited the harvest capacity of the combine due to inadequate feeding of the crop material into the combine. To correct that problem a reel was added to the head to pull the stalks toward the combine and clear off the head's row dividing points in an attempt to avoid buildup of crop material on the head. Additionally, the original auger in the head was replaced with one that had a smaller diameter center tube and deeper flighting. The changes made to the 653A were highly effective in terms of improving crop flow into the combine and minimizing plugging issues at the head.

The combine feederhouse was the next step for the grain and stover entering the combine. When using the 1293 conventional corn head, the feederhouse kept pace with the material delivered by the head. This achievement was not unexpected because the 9750 STS combine was commercially designed to operate with the 1293 head, and a conventional corn head of this type was engineered to minimize the amount of plant material brought into the combine with the grain. However, when the 653A row crop head was used, up to three times as much stover was being harvested on a per unit area basis. The stover being harvested also consisted of longer stalks that included the tougher and wetter lower portion of the corn plant. This combination of factors resulted in the combine feederhouse occasionally plugging or recycling the stover back out into the head. Further analysis has led to the belief that increasing the aggressiveness of the feed accelerator located immediately behind the feederhouse would improve crop flow from the feederhouse to the combine rotor. The feed accelerator used on a 9750 STS when harvesting rice is more aggressive than the one that was used during the stover harvesting tests. A rice feed accelerator has since been obtained to be used in future tests.

The grain separation and grain cleaning regions of the combine performed normally so there were no issues to report regarding them. The next area of interest was the stover chopper region. Soon after testing commenced on the first day, it became apparent that high ground speeds with the 653A head and the shear chopper would lead to plugging the combine immediately ahead of the chopper. Slower ground speeds were less of an issue, but still occasionally produced plugging with the previously mentioned head and chopper. Visual inspection indicated a likely cause of the feeding problem could be attributed to long pieces of stalk being discharged from the combine rotor and bridging across the inlet to the shear chopper. When one of these long stalks lodged itself across the inlet to the chopper, the stover following it would tend to build up there rather than feeding into the chopper. The problem would quickly compound until no material would feed into the chopper. Most of the time when such a plug formed it was necessary to shut the combine off and manually remove the obstruction. No convenient method was available to weigh the material manually removed from the combine so each plug resulted in a reduction of the collected stover and introduced error into subsequent calculations. The persistence of this plugging problem limited the scope of the original test plan that included tests at three ground speeds. The lowest two speeds were attainable, but the highest speed consistently resulted in plugging ahead of the chopper. As a result, the high speed runs could not be performed for the 653A with the shear chopper.

Based on preliminary tests, the potential feeding problem into the chopper was identified and was most prominent when using the 653A head with the shear chopper. In an attempt to counteract the feeding issue when using the 653A row crop head, the combine threshing system was set more aggressively to try to break the stalks into smaller pieces in the rotor so they would feed into the chopper easier. The speed of the rotor was increased from between 300 and 350 rpm to between 450 and 500 rpm. The concave clearance was also reduced from a setting of 25 to a setting of 10. These combine settings were maintained throughout all of the official test runs with the 653A head and the shear chopper. Though the adjustments did break the stalks more, there were still long stalks present to cause bridging and plugging in front of the chopper.

When an obstruction would start to form in front of the chopper, the airflow exiting from the grain cleaning system would also be obstructed. This air assisted the transfer of the stover from the chopper, through a transition structure, to the blower. As the airflow was limited, the stover being pushed through the transition and into the blower would slow and precipitate out of the air eventually causing an obstruction in the transition structure. Though there was no way to fully validate this theory during testing, the empirical results seemed to support the premise that an obstruction ahead of the chopper usually led to a subsequent obstruction in the transition structure rather than the opposite.

Beyond the obstructions that formed in the transition structure as a result of feeding issues into the chopper, the blower system performed well. Before field testing was performed, there was some concern that the blower being used might not perform well with dry material like some of the stover that would be harvested. The concern was based on the fact that the blower would have normally been operated in much higher moisture crops that would respond predictably to the impact of the blower paddles. However, the blower did generate enough airflow to create an air stream in which the dry particles traveled into the stover collection wagon.

Since the development, construction, and testing of a new stover chopper for the combine was of high importance for this project, the ability of that chopper to size the corn stover as desired was a characteristic to be explored. Visual analysis of the stover discharged from the shear chopper revealed multiple notable characteristics. First, most of the stalk material was cut into lengths 51 mm (2 in.) or less as intended. Second, the cobs were also consistently cut in to pieces 51 mm (2 in.) or smaller. Third, the husks that were discharged from the shear chopper were in much larger pieces than the remaining material and those pieces were larger than the desired 51 mm (2 in.) cut length. The cut characteristics of the stalk and cobs seem fairly easy to explain. That is, these two portions are relatively rigid and lend themselves to being sheared uniformly in a chopper such as this shear chopper. The husks, on the other hand, are not at all rigid. They are able to conform to the shape of their surroundings which enables them to pass through certain areas of the shear chopper without significant size reduction. Due to concerns about manufacturing tolerances when constructing the shear chopper, the gap between the knives on the chopper rotor was set at 12.7 mm (0.5 in.). The stationary blades mounted on the countershear bar were 3.18 mm (0.125 in.) thick leaving 4.76 mm

(0.1875 in.) on either side of the stationary knives through which the husks could pass by bending to fit the slot. Additionally, as one of the lightest portions of the stover stream, some of the husks may have bypassed the chopper rotor entirely by being carried in an air stream over the top of the chopper rotor. Both factors probably contributed to the issue.

In comparison to the conventional flail chopper that was also tested on the combine harvester, a few differences were noted in the performance of each. The flail chopper was less effective at uniformly reducing the size of the stalks and cobs, but it appeared to be more effective at reducing the size of the husks. This difference could be attributed to the higher speed at which the flail chopper operated and the indiscriminant manner in which it chopped material. The higher speeds in the flail cutting action meant the inertia of the husks aided in chopping them, whereas in the slower shear chopper, the husks had more time to flex and were less likely to tear on impact. Decreasing the clearance between the knives on the shear chopper rotor will likely improve the size reduction of the husks.

Numerical Results

The grain yield for the test field averaged 181.4 bushels per acre (15.5% MC) while the amount of stover harvested varied depending on the equipment configuration used to harvest it. As previously indicated, the combine head type was the major factor in determining the amount of stover collected. The specific stover yield and theoretical harvest rate for each configuration tested can be seen in Table 3. For the runs without the blower, the stover could not be collected so no yield data is provided. Test configurations for which data could not be collected, or was not collected for any reason, are indicated with dashes. The 1293 conventional corn head was able to harvest 1.1 to

Table 3: Stover moisture content, stover yield (dry basis) and harvest rate for different combine configurations, including two different headers (1293 corn head and 653A modified row crop head), two chopper configurations (conventional flail chopper and prototype double shear chopper), and two blower configurations (with blower, without blower)

Stover									
Head	Chopper	Blower	Nominal Speed		Avg. MC	DM Yield		DM Harvest Rate	
1293 or 653A	Flail or Shear	w/ or w/o	km/h	mi/h	% w.b.	Mg/ha	t/A	Mg/h	t/h
1293	Flail	w/	1.6	1.0	17.4	1.9	0.8	2.8	3.1
1293	Flail	w/	1.6	1.0	16.3	1.7	0.8	2.5	2.8
1293	Flail	w/	1.6	1.0	19.7	1.8	0.8	2.7	2.9
1293	Flail	w/	2.4	1.5	16.5	1.9	0.8	4.2	4.6
1293	Flail	w/	2.4	1.5	18.8	1.8	0.8	4.0	4.4
1293	Flail	w/	2.4	1.5	17.5	1.8	0.8	3.9	4.3
1293	Flail	w/	3.2	2.0	16.7	1.8	0.8	5.2	5.7
1293	Flail	w/	3.2	2.0	18.2	2.0	0.9	5.8	6.3
1293	Flail	w/	3.2	2.0	17.1	1.7	0.7	4.9	5.4
1293	Shear	w/	1.6	1.0	16.1	1.8	0.8	2.6	2.9
1293	Shear	w/	1.6	1.0	15.8	1.7	0.8	2.6	2.8
1293	Shear	w/	1.6	1.0	16.0	1.4	0.6	2.1	2.4
1293	Shear	w/	2.4	1.5	15.7	1.8	0.8	4.0	4.4
1293	Shear	w/	2.4	1.5	16.4	1.8	0.8	3.9	4.3
1293	Shear	w/	2.4	1.5	15.4	1.7	0.8	3.8	4.2
1293	Shear	w/	3.2	2.0	15.5	1.1	0.5	3.3	3.7
1293	Shear	w/	3.2	2.0	15.0	1.6	0.7	4.7	5.2
1293	Shear	w/	3.2	2.0	16.5	1.7	0.7	4.9	5.4
653A	Flail	w/	1.6	1.0	26.1	5.6	2.5	4.1	4.6
653A	Flail	w/	1.6	1.0	19.4	4.5	2.0	3.3	3.6
653A	Flail	w/	1.6	1.0	20.7	5.0	2.2	3.7	4.1
653A	Flail	w/	3.2	2.0	26.0	5.1	2.3	7.5	8.3
653A	Flail	w/	3.2	2.0	16.0	4.9	2.2	7.3	8.0
653A	Flail	w/	3.2	2.0	20.0	4.7	2.1	7.0	7.7
653A	Flail	w/	4.0	2.5	--[1]	--	--	--	--
653A	Flail	w/	4.0	2.5	--	--	--	--	--
653A	Flail	w/	4.0	2.5	--	--	--	--	--
653A	Shear	w/	1.6	1.0	16.1	3.9	1.7	2.9	3.2
653A	Shear	w/	1.6	1.0	30.3	2.7	1.2	2.0	2.2
653A	Shear	w/	1.6	1.0	--[2]	--	--	--	--
653A	Shear	w/	3.2	2.0	16.8	2.8	1.2	4.1	4.5
653A	Shear	w/	3.2	2.0	16.9	3.6	1.6	5.2	5.8
653A	Shear	w/	3.2	2.0	--[2]	--	--	--	--
653A	Shear	w/	4.0	2.5	18.7	3.7	1.6	6.8	7.5
653A	Shear	w/	4.0	2.5	--[1]	--	--	--	--
653A	Shear	w/	4.0	2.5	--	--	--	--	--

1 Excessive plugging for 4 km/h runs with 653A head. Runs could not be conducted.

2 Missing data

2.0 Mg/ha (0.5 to 0.9 t/A) of dry stover while the 653A was able to harvest 2.7 to 5.6 Mg/ha (1.2 to 2.5 t/A). Based on the nominal testing speeds and actual yields, the dry matter harvest rate for the 1293 head ranged from 2.1 to 5.8 Mg/h (2.4 to 6.3 t/h). The harvest rate for the 653A head ranged from 2.0 to 7.5 Mg/h (2.2 to 8.3 t/h).

The grain yield for the test field was also of note in order to show that conditions present in the test field were consistent with typical, commercial production systems. The corn grain yield for each machinery configuration tested is shown in Table 4. The dry matter grain yield ranged from 6.9 to 11.0 Mg/ha (3.1 to 4.9 t/A). The dry matter harvest rate depended on the head being used, due to the difference in number of rows harvested with each head, the ground speed, and the grain yield distribution throughout the field. For the 1293 12 row conventional head, the grain dry matter harvest rate ranged from 10.2 to 32.4 Mg/h (11.2 to 35.7 t/h). The grain harvest rate for the 653A 6 row head ranged from 5.1 to 18.8 Mg/h (5.7 to 20.7 t/h). The field average yield of 181.4 bushels per acre was slightly higher than the average yield for Boone County, IA, the county in which the test field was located, which was reported at 172.7 bushels per acre by the National Agricultural Statistics Service (USDA, 2006).

Determining the power required by the two different stover choppers and the forage blower was also of high importance for this study. The chopper power required for each test configuration was calculated and can be seen in Table 5. For the configurations in which the blower was not used, no stover was collected. As a result, the stover moisture for those particular tests was unknown and the specific power requirement could not be calculated. The overall power requirement for each run was known, however. The blower power requirements were also calculated for each configuration in which the blower was used, and they can be seen in Table 6.

Table 4: Grain moisture content, grain yield (15.5% and dry basis) and harvest rate for different combine configurations

Grain										
Head	**Chopper**	**Blower**	**Nominal Speed**		**Avg. MC**	**Adjusted Yield**	**Grain Yield (dry basis)**		**Grain Harvest Capacity**	
1293 or 653A	**Flail or Shear**	**w/ or w/o**	**km/h**	**mi/h**	**% w.b.**	**bu/A @ 15.5%**	**Mg/ha**	**t/A**	**Mg/h**	**t/h**
1293	Flail	w/	1.6	1.0	15.1	194.3	10.3	4.6	15.2	16.7
1293	Flail	w/	1.6	1.0	14.9	168.2	8.9	4.0	13.1	14.5
1293	Flail	w/	1.6	1.0	15.1	180.3	9.6	4.3	14.1	15.5
1293	Flail	w/	2.4	1.5	15.4	196.9	10.4	4.7	23.0	25.4
1293	Flail	w/	2.4	1.5	14.9	186.2	9.9	4.4	21.8	24.0
1293	Flail	w/	2.4	1.5	15.2	179.0	9.5	4.2	21.0	23.1
1293	Flail	w/	3.2	2.0	14.8	148.3	7.9	3.5	23.1	25.5
1293	Flail	w/	3.2	2.0	14.4	182.7	9.7	4.3	28.5	31.4
1293	Flail	w/	3.2	2.0	15.1	187.5	9.9	4.4	29.3	32.3
1293	Shear	w/	1.6	1.0	15.6	197.1	10.5	4.7	15.4	17.0
1293	Shear	w/	1.6	1.0	14.9	193.7	10.3	4.6	15.1	16.7
1293	Shear	w/	1.6	1.0	14.8	186.2	9.9	4.4	14.5	16.0
1293	Shear	w/	2.4	1.5	15.0	154.7	8.2	3.7	18.1	20.0
1293	Shear	w/	2.4	1.5	14.8	200.5	10.6	4.7	23.5	25.9
1293	Shear	w/	2.4	1.5	15.0	197.9	10.5	4.7	23.2	25.5
1293	Shear	w/	3.2	2.0	15.1	186.3	9.9	4.4	29.1	32.1
1293	Shear	w/	3.2	2.0	14.9	167.1	8.9	4.0	26.1	28.8
1293	Shear	w/	3.2	2.0	15.5	207.6	11.0	4.9	32.4	35.7
653A	Flail	w/	1.6	1.0	15.9	189.5	10.0	4.5	7.4	8.2
653A	Flail	w/	1.6	1.0	15.1	157.4	8.3	3.7	6.1	6.8
653A	Flail	w/	1.6	1.0	14.9	172.4	9.1	4.1	6.7	7.4
653A	Flail	w/	3.2	2.0	15.2	181.5	9.6	4.3	14.2	15.6
653A	Flail	w/	3.2	2.0	14.6	136.2	7.2	3.2	10.6	11.7
653A	Flail	w/	3.2	2.0	14.9	132.8	7.0	3.1	10.4	11.4
653A	Flail	w/	4.0	2.5	--[1]	--	--	--	--	--
653A	Flail	w/	4.0	2.5	--	--	--	--	--	--
653A	Flail	w/	4.0	2.5	--	--	--	--	--	--
653A	Shear	w/	1.6	1.0	15.7	207.6	11.0	4.9	8.1	8.9
653A	Shear	w/	1.6	1.0	15.7	205.8	10.9	4.9	8.0	8.9
653A	Shear	w/	1.6	1.0	--[2]	--	--	--	--	--
653A	Shear	w/	3.2	2.0	14.9	182.8	9.7	4.3	14.3	15.7
653A	Shear	w/	3.2	2.0	14.9	172.9	9.2	4.1	13.5	14.9
653A	Shear	w/	3.2	2.0	--[2]	--	--	--	--	--
653A	Shear	w/	4.0	2.5	15.0	192.3	10.2	4.5	18.8	20.7
653A	Shear	w/	4.0	2.5	--[1]	--	--	--	--	--
653A	Shear	w/	4.0	2.5	--	--	--	--	--	--

Table 4 (continued)

Grain										
Head	Chopper	Blower	Nominal Speed		Avg. MC	Adjusted Yield	Grain Yield (dry basis)		Grain Harvest Capacity	
1293 or 653A	Flail or Shear	w/ or w/o	km/h	mi/h	% w.b.	bu/A @ 15.5%	Mg/ha	t/A	Mg/h	t/h
1293	Flail	w/o	1.6	1.0	15.0	130.6	6.9	3.1	10.2	11.2
1293	Flail	w/o	1.6	1.0	15.4	191.4	10.2	4.5	14.9	16.5
1293	Flail	w/o	1.6	1.0	15.0	196.4	10.4	4.6	15.3	16.9
1293	Flail	w/o	2.4	1.5	15.0	165.9	8.8	3.9	19.4	21.4
1293	Flail	w/o	2.4	1.5	14.9	186.8	9.9	4.4	21.9	24.1
1293	Flail	w/o	2.4	1.5	15.3	163.7	8.7	3.9	19.2	21.1
1293	Flail	w/o	3.2	2.0	15.3	163.9	8.7	3.9	25.6	28.2
1293	Flail	w/o	3.2	2.0	15.1	204.2	10.8	4.8	31.9	35.1
1293	Flail	w/o	3.2	2.0	15.2	181.4	9.6	4.3	28.3	31.2
1293	Shear	w/o	1.6	1.0	14.9	190.9	10.1	4.5	14.9	16.4
1293	Shear	w/o	1.6	1.0	14.9	198.6	10.5	4.7	15.5	17.1
1293	Shear	w/o	1.6	1.0	15.2	188.1	10.0	4.4	14.7	16.2
1293	Shear	w/o	2.4	1.5	15.0	200.5	10.6	4.7	23.5	25.9
1293	Shear	w/o	2.4	1.5	14.8	186.2	9.9	4.4	21.8	24.0
1293	Shear	w/o	2.4	1.5	14.7	195.2	10.4	4.6	22.9	25.2
1293	Shear	w/o	3.2	2.0	14.9	172.1	9.1	4.1	26.9	29.6
1293	Shear	w/o	3.2	2.0	14.9	195.4	10.4	4.6	30.5	33.6
1293	Shear	w/o	3.2	2.0	15.4	191.6	10.2	4.5	29.9	33.0
653A	Flail	w/o	1.6	1.0	15.1	202.6	10.7	4.8	7.9	8.7
653A	Flail	w/o	1.6	1.0	15.1	183.8	9.7	4.3	7.2	7.9
653A	Flail	w/o	1.6	1.0	15.1	131.7	7.0	3.1	5.1	5.7
653A	Flail	w/o	3.2	2.0	15.2	163.1	8.7	3.9	12.7	14.0
653A	Flail	w/o	3.2	2.0	15.2	153.5	8.1	3.6	12.0	13.2
653A	Flail	w/o	3.2	2.0	14.8	145.3	7.7	3.4	11.3	12.5
653A	Flail	w/o	4.0	2.5	--[1]	--	--	--	--	--
653A	Flail	w/o	4.0	2.5	--	--	--	--	--	--
653A	Flail	w/o	4.0	2.5	--	--	--	--	--	--
653A	Shear	w/o	1.6	1.0	14.9	195.3	10.4	4.6	7.6	8.4
653A	Shear	w/o	1.6	1.0	15.7	152.5	8.1	3.6	6.0	6.6
653A	Shear	w/o	1.6	1.0	15.5	205.3	10.9	4.9	8.0	8.8
653A	Shear	w/o	3.2	2.0	15.2	175.5	9.3	4.2	13.7	15.1
653A	Shear	w/o	3.2	2.0	14.9	182.5	9.7	4.3	14.2	15.7
653A	Shear	w/o	3.2	2.0	15.3	181.3	9.6	4.3	14.2	15.6
653A	Shear	w/o	4.0	2.5	14.4	185.4	9.8	4.4	18.1	19.9
653A	Shear	w/o	4.0	2.5	--[1]	--	--	--	--	--
653A	Shear	w/o	4.0	2.5	--	--	--	--	--	--

1 Excessive plugging for 4 km/h runs with 653A head. Runs could not be conducted.

2 Missing data

Table 5: Chopper power requirements for different combine configurations, including two different headers (1293 corn head and 653A modified row crop head), two chopper configurations (conventional flail chopper and prototype double shear chopper), and two blower configurations (with blower, without blower)

Stover Chopper									
Head	**Chopper**	**Blower**	**Nominal Speed**		**Avg. MC**	**Power Requirement**		**Specific Power**	
1293 or 653A	**Flail or Shear**	**w/ or w/o**	**km/h**	**mi/h**	**% w.b.**	**kW**	**hp**	**kWh/Mg**	**hp h/t**
1293	Flail	w/	1.6	1.0	17.4	24.2	32.5	8.7	10.6
1293	Flail	w/	1.6	1.0	16.3	23.7	31.8	9.3	11.3
1293	Flail	w/	1.6	1.0	19.7	25.1	33.7	9.5	11.5
1293	Flail	w/	2.4	1.5	16.5	25.5	34.2	6.1	7.4
1293	Flail	w/	2.4	1.5	18.8	26.3	35.3	6.7	8.1
1293	Flail	w/	2.4	1.5	17.5	25.9	34.7	6.6	8.0
1293	Flail	w/	3.2	2.0	16.7	27.9	37.4	5.4	6.6
1293	Flail	w/	3.2	2.0	18.2	26.3	35.3	4.6	5.6
1293	Flail	w/	3.2	2.0	17.1	25.2	33.8	5.2	6.3
1293	Shear	w/	1.6	1.0	16.1	13.7	18.4	5.2	6.4
1293	Shear	w/	1.6	1.0	15.8	14.0	18.8	5.5	6.7
1293	Shear	w/	1.6	1.0	16.0	14.4	19.3	6.7	8.2
1293	Shear	w/	2.4	1.5	15.7	16.0	21.5	4.0	4.9
1293	Shear	w/	2.4	1.5	16.4	15.1	20.3	3.9	4.7
1293	Shear	w/	2.4	1.5	15.4	15.0	20.1	3.9	4.8
1293	Shear	w/	3.2	2.0	15.5	12.7	17.0	3.8	4.7
1293	Shear	w/	3.2	2.0	15.0	16.5	22.1	3.5	4.3
1293	Shear	w/	3.2	2.0	16.5	17.0	22.8	3.5	4.2
653A	Flail	w/	1.6	1.0	26.1	21.6	28.9	5.2	6.3
653A	Flail	w/	1.6	1.0	19.4	31.0	41.6	9.4	11.5
653A	Flail	w/	1.6	1.0	20.7	27.5	36.8	7.4	9.1
653A	Flail	w/	3.2	2.0	26.0	23.6	31.7	3.1	3.8
653A	Flail	w/	3.2	2.0	16.0	35.5	47.6	4.9	6.0
653A	Flail	w/	3.2	2.0	20.0	31.7	42.5	4.6	5.5
653A	Flail	w/	4.0	2.5	--[1]	--	--	--	--
653A	Flail	w/	4.0	2.5	--	--	--	--	--
653A	Flail	w/	4.0	2.5	--	--	--	--	--
653A	Shear	w/	1.6	1.0	16.1	15.6	20.9	5.5	6.6
653A	Shear	w/	1.6	1.0	30.3	13.2	17.7	6.7	8.1
653A	Shear	w/	1.6	1.0	--[2]	--	--	--	--
653A	Shear	w/	3.2	2.0	16.8	15.9	21.3	3.9	4.8
653A	Shear	w/	3.2	2.0	16.9	14.5	19.5	2.8	3.4
653A	Shear	w/	3.2	2.0	--[2]	--	--	--	--
653A	Shear	w/	4.0	2.5	18.7	15.4	20.6	2.3	2.8
653A	Shear	w/	4.0	2.5	--[1]	--	--	--	--
653A	Shear	w/	4.0	2.5	--	--	--	--	--

Table 5 (continued)

Stover Chopper									
Head	**Chopper**	**Blower**	**Nominal Speed**		**Avg. MC**	**Power Requirement**		**Specific Power**	
1293 or 653A	**Flail or Shear**	**w/ or w/o**	**km/h**	**mi/h**	**% w.b.**	**kW**	**hp**	**kWh/Mg**	**hp h/t**
1293	Flail	w/o	1.6	1.0	N/A	30.2	40.5	N/A	N/A
1293	Flail	w/o	1.6	1.0	N/A	28.2	37.8	N/A	N/A
1293	Flail	w/o	1.6	1.0	N/A	30.3	40.6	N/A	N/A
1293	Flail	w/o	2.4	1.5	N/A	32.5	43.6	N/A	N/A
1293	Flail	w/o	2.4	1.5	N/A	30.5	40.9	N/A	N/A
1293	Flail	w/o	2.4	1.5	N/A	29.2	39.2	N/A	N/A
1293	Flail	w/o	3.2	2.0	N/A	30.1	40.4	N/A	N/A
1293	Flail	w/o	3.2	2.0	N/A	32.2	43.1	N/A	N/A
1293	Flail	w/o	3.2	2.0	N/A	30.3	40.6	N/A	N/A
1293	Shear	w/o	1.6	1.0	N/A	13.7	18.3	N/A	N/A
1293	Shear	w/o	1.6	1.0	N/A	13.7	18.4	N/A	N/A
1293	Shear	w/o	1.6	1.0	N/A	13.4	18.0	N/A	N/A
1293	Shear	w/o	2.4	1.5	N/A	14.4	19.3	N/A	N/A
1293	Shear	w/o	2.4	1.5	N/A	15.3	20.5	N/A	N/A
1293	Shear	w/o	2.4	1.5	N/A	15.5	20.8	N/A	N/A
1293	Shear	w/o	3.2	2.0	N/A	16.9	22.6	N/A	N/A
1293	Shear	w/o	3.2	2.0	N/A	17.1	22.9	N/A	N/A
1293	Shear	w/o	3.2	2.0	N/A	17.2	23.1	N/A	N/A
653A	Flail	w/o	1.6	1.0	N/A	30.6	41.0	N/A	N/A
653A	Flail	w/o	1.6	1.0	N/A	33.3	44.6	N/A	N/A
653A	Flail	w/o	1.6	1.0	N/A	31.8	42.6	N/A	N/A
653A	Flail	w/o	3.2	2.0	N/A	29.3	39.3	N/A	N/A
653A	Flail	w/o	3.2	2.0	N/A	28.2	37.8	N/A	N/A
653A	Flail	w/o	3.2	2.0	N/A	35.1	47.1	N/A	N/A
653A	Flail	w/o	4.0	2.5	N/A	--[1]	--	N/A	N/A
653A	Flail	w/o	4.0	2.5	N/A	--	--	N/A	N/A
653A	Flail	w/o	4.0	2.5	N/A	--	--	N/A	N/A
653A	Shear	w/o	1.6	1.0	N/A	16.9	22.7	N/A	N/A
653A	Shear	w/o	1.6	1.0	N/A	13.6	18.2	N/A	N/A
653A	Shear	w/o	1.6	1.0	N/A	14.7	19.7	N/A	N/A
653A	Shear	w/o	3.2	2.0	N/A	15.1	20.2	N/A	N/A
653A	Shear	w/o	3.2	2.0	N/A	14.3	19.2	N/A	N/A
653A	Shear	w/o	3.2	2.0	N/A	16.5	22.1	N/A	N/A
653A	Shear	w/o	4.0	2.5	N/A	16.2	21.7	N/A	N/A
653A	Shear	w/o	4.0	2.5	N/A	--[1]	--	N/A	N/A
653A	Shear	w/o	4.0	2.5	N/A	--	--	N/A	N/A

1 Excessive plugging for 4 km/h runs with 653A head. Runs could not be conducted.

2 Missing data

Table 6: Blower power requirements for different combine configurations, including two different headers (1293 corn head and 653A modified row crop head) and two chopper configurations (conventional flail chopper and prototype double shear chopper)

Stover Blower									
Head	**Chopper**	**Blower**	**Nominal Speed**		**Avg. MC**	**Power Requirement**		**Specific Power**	
1293 or 653A	**Flail or Shear**	**w/ or w/o**	**km/h**	**mi/h**	**% w.b.**	**kW**	**hp**	**kWh/Mg**	**hp h/t**
1293	Flail	w/	1.6	1.0	17.4	6.1	8.2	2.2	2.7
1293	Flail	w/	1.6	1.0	16.3	5.9	7.9	2.3	2.8
1293	Flail	w/	1.6	1.0	19.7	6.2	8.3	2.3	2.8
1293	Flail	w/	2.4	1.5	16.5	7.2	9.6	1.7	2.1
1293	Flail	w/	2.4	1.5	18.8	7.1	9.5	1.8	2.2
1293	Flail	w/	2.4	1.5	17.5	7.7	10.3	1.9	2.4
1293	Flail	w/	3.2	2.0	16.7	8.4	11.2	1.6	2.0
1293	Flail	w/	3.2	2.0	18.2	7.8	10.5	1.4	1.7
1293	Flail	w/	3.2	2.0	17.1	7.7	10.3	1.6	1.9
1293	Shear	w/	1.6	1.0	16.1	8.8	11.8	3.4	4.1
1293	Shear	w/	1.6	1.0	15.8	9.0	12.1	3.5	4.3
1293	Shear	w/	1.6	1.0	16.0	7.7	10.3	3.6	4.4
1293	Shear	w/	2.4	1.5	15.7	8.4	11.2	2.1	2.5
1293	Shear	w/	2.4	1.5	16.4	9.5	12.7	2.4	3.0
1293	Shear	w/	2.4	1.5	15.4	10.0	13.4	2.6	3.2
1293	Shear	w/	3.2	2.0	15.5	7.8	10.4	2.3	2.8
1293	Shear	w/	3.2	2.0	15.0	10.0	13.4	2.1	2.6
1293	Shear	w/	3.2	2.0	16.5	11.7	15.7	2.4	2.9
653A	Flail	w/	1.6	1.0	26.1	7.5	10.1	1.8	2.2
653A	Flail	w/	1.6	1.0	19.4	5.9	7.9	1.8	2.2
653A	Flail	w/	1.6	1.0	20.7	6.9	9.3	1.9	2.3
653A	Flail	w/	3.2	2.0	26.0	11.0	14.7	1.5	1.8
653A	Flail	w/	3.2	2.0	16.0	9.1	12.2	1.3	1.5
653A	Flail	w/	3.2	2.0	20.0	7.9	10.6	1.1	1.4
653A	Flail	w/	4.0	2.5	--[1]	--	--	--	--
653A	Flail	w/	4.0	2.5	--	--	--	--	--
653A	Flail	w/	4.0	2.5	--	--	--	--	--
653A	Shear	w/	1.6	1.0	16.1	6.9	9.2	2.4	2.9
653A	Shear	w/	1.6	1.0	30.3	8.8	11.8	4.4	5.4
653A	Shear	w/	1.6	1.0	--[2]	--	--	--	--
653A	Shear	w/	3.2	2.0	16.8	6.8	9.1	1.7	2.0
653A	Shear	w/	3.2	2.0	16.9	7.5	10.1	1.4	1.8
653A	Shear	w/	3.2	2.0	--[2]	--	--	--	--
653A	Shear	w/	4.0	2.5	18.7	7.1	9.5	1.0	1.3
653A	Shear	w/	4.0	2.5	--[1]	--	--	--	--
653A	Shear	w/	4.0	2.5	--	--	--	--	--

1 Excessive plugging for 4 km/h runs with 653A head. Runs could not be conducted.

2 Missing data

Statistical analysis of the previously listed data was conducted to determine the significance of the differences between values. Murphy (2007) was consulted for assistance with the statistical analysis. Ten treatments were considered in the analysis, as seen in Table 7. The original experimental design called for two more treatments using the 635A head with each chopper at 4 km/h. Machinery limitations made it infeasible to collect accurate data for these high speed runs so they were eliminated from the analysis.

The p-value results of the tests for significance of the head type and chopper type on chopper power and blower power can be seen in Table 8. Differences among treatment means were considered to be significant at $p \leq 0.05$. The type of chopper used in the experiment was shown to significantly influence the chopper power both when the blower was running and not running. Chopper type also influenced the blower power. The type of head used in the experiment did not produce a difference in the power requirement of the chopper or blower.

The power required to operate the chopper and blower under various feedrate conditions was analyzed for each chopper type and head type. A graph of the chopper power requirement versus feedrate can be seen in Figure 24. This graph shows that the

Table 7: Statistical treatments analyzed to determine significant differences

Treatment	Head	Chopper	Speed (km/h)
1	1293	Flail	1.6
2	1293	Flail	2.4
3	1293	Flail	3.2
4	1293	Shear	1.6
5	1293	Shear	2.4
6	1293	Shear	3.2
7	653A	Flail	1.6
8	653A	Flail	3.2
9	653A	Shear	1.6
10	653A	Shear	3.2

Table 8: Statistical results for tests of parameter significance

Effect on chopper power with blower operating	
Parameter	**p-value**
Effect of head	0.2275
Effect of chopper	<0.0001 ***
Effect on blower power with blower operating	
Parameter	**p-value**
Effect of head	0.3497
Effect of chopper	0.0165 *
Effect on chopper power with blower not operating	
Parameter	**p-value**
Effect of head	0.4425
Effect of chopper	<0.0001 ***
* significant at 0.05 level ** significant at 0.01 level *** significant at 0.001 level	

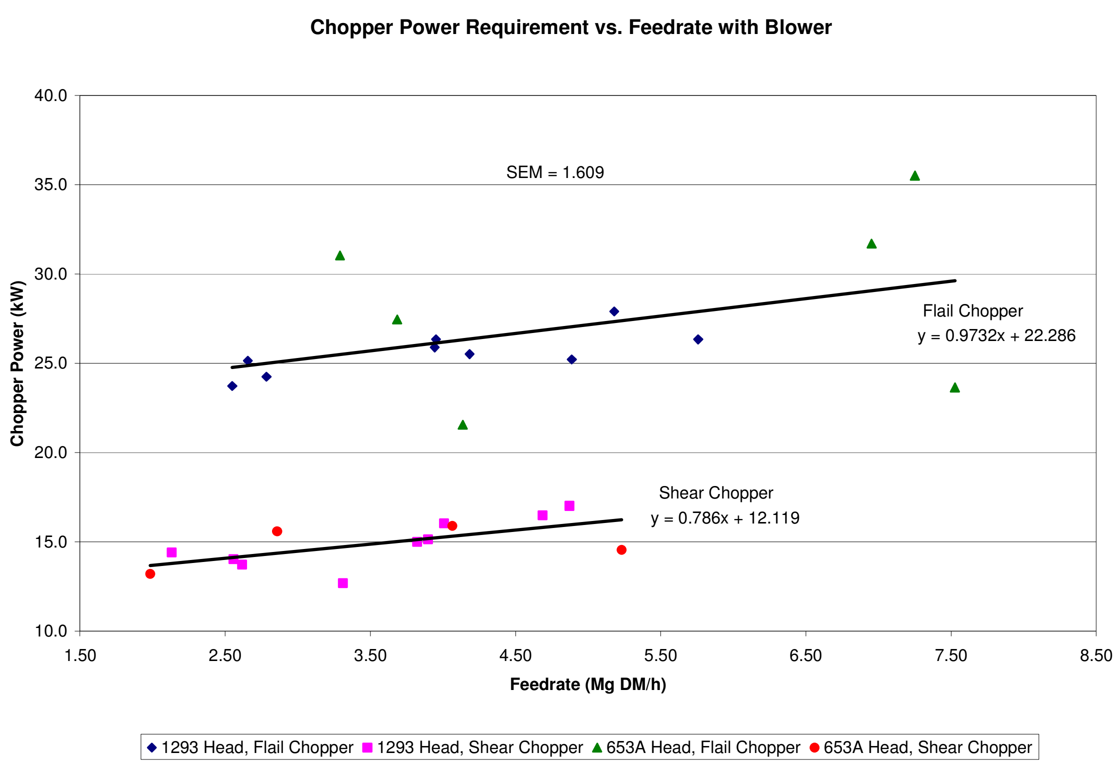


Figure 24: Chopper power requirement versus feedrate, with blower operating, for four test configurations

points representing the shear chopper fall along a common trendline regardless of the head type being used. The same trend holds for the flail chopper, and the distinct distance between the two trendlines supports the statistical evidence that the effect of the chopper type is significant in determining chopper power requirement with the shear chopper requiring approximately 12 kW less power than the flail chopper. A graph of blower power requirement versus feedrate can be seen in Figure 25. The data points for the flail chopper fall along a common trendline regardless of the head type used. When the shear chopper was used with the 1293 head, the resulting trendline of the blower power requirement data points nearly paralleled those of the flail chopper, but they were offset by about 2.5 kW higher power requirement when the shear chopper was in use. The lower power consumption of the blower when the flail chopper is being used can

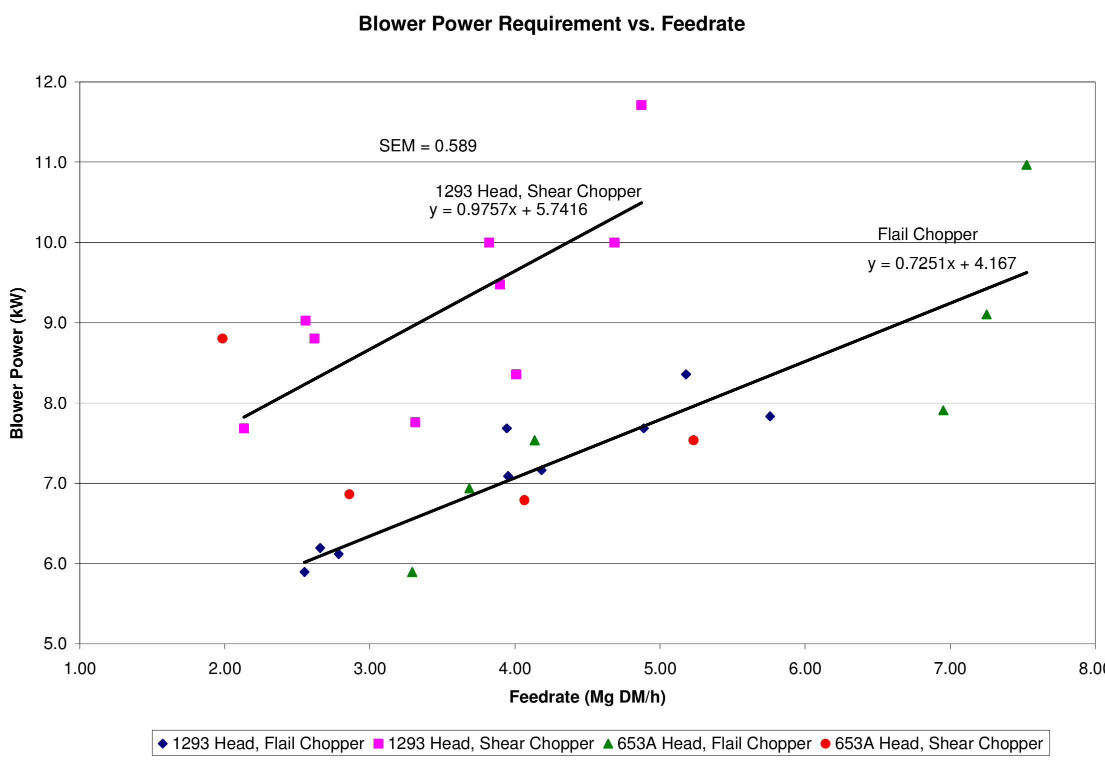


Figure 25: Blower power requirement versus feedrate for four test configurations

likely be explained by the higher airflow that the flail chopper provides over the shear chopper. This extra airflow reduces the power requirement of the blower because the blower no longer has to generate as much airflow itself. The combination of the 653A head and the shear chopper shows no distinct trend. Very limited data is available from which to draw conclusions because this equipment configuration was only tested at two speeds due to the infeasibility of operating the harvester at a faster ground speed. In addition, no data was collected for one of the repetitions in each of the tested speed levels. The result is that the experimental error contained within the small number of data points seems to dominate this portion of the data so no conclusion will be drawn based on that information.

Conclusions and recommendations for further study

Conclusions

To fulfill the concept of the single pass, dual stream corn grain and stover harvester, a new shear style chopper was developed and built to replace the existing residue chopper on a John Deere STS combine. A forage blower was successfully mounted at the outlet of the chopper to convey the stover from the chopper to a transport device. The entire system was then successfully field tested, and it proved the feasibility of the concept of the single pass harvester.

Several overall conclusions can be drawn from the results of this experiment and are detailed as follows.

1. The 653A row crop head can effectively harvest two to three times as much dry stover per unit area as the 1293 conventional corn head.
2. The maximum operating speed the system was capable of handling when the 653A head and the shear chopper were used was approximately 3.22 km/h (2 mi/h). When the flail chopper was used with the 653A head, stover feed into the chopper was less of a problem than with the shear chopper so a slight increase in speed was achievable. Plugging at the feederhouse and chopper limited this combination to approximately 4.02 km/h (2.5 mi/h) for the maximum speed. The 1293 head with the flail chopper represented the commercially available configuration that was tested. This machinery combination was capable of running at least 6.44 km/h (4 mi/h). The 1293 head with the shear chopper could not consistently operate at that speed because of feed problems into the chopper. The maximum reliable speed for that combination was approximately 4.02 km/h

(2.5 mi/h). The maximum stover feedrate seen by the shear chopper was 5.23 Mg/h (5.8 t/h) and by the flail chopper was 7.53 Mg/h (8.3 t/h). The maximum capacity of the blower was not challenged in these tests so it was not a limiting factor.

3. Modifications to the geometry at the inlet of the shear chopper are necessary to improve crop flow from the combine to the chopper to achieve faster operating speeds.
4. The type of chopper used has a statistically significant effect on chopper power and blower power requirements.
5. The type of head used does not have a statistically significant effect on chopper or blower power requirements.
6. The shear chopper developed for this project uses less power than the conventional flail chopper commercially available on combine harvesters.
7. The blower mounted to the rear of the combine requires less power when used in conjunction with the flail chopper than with the shear chopper.

Future Recommendations

The shear chopper was entirely capable of processing the large amounts of stover that the 9750 STS harvested so efforts should be made to improve on the shortcomings of the chopper. The main limitation to fully testing the chopper's abilities was plugging ahead of the shear chopper inlet. Some potential alternatives to alleviate that problem include:

- Dropping the axis of the rotor down so the stover will fall into it more effectively

- Adding an agitator in front of the stover chopper to break up any plugs that start to form
- Modifying the geometry of the deflector plate in front of the chopper inlet to avoid stalling stover before it gets to the chopper

Crop flow issues at the front of the combine should also be addressed. While the 653A row crop head performed much better with significantly fewer plugs after the new auger was added, a head specifically designed to harvest whole corn plants would probably feed material into the combine more smoothly. A forage harvester head would be one such possibility. Further, there were occasions when whole corn plants would be pulled into the feederhouse and then carried back out into the head rather than being fed into the rotor. Adding the more aggressive feed accelerator typically used for rice may improve performance.

The addition of large amounts of MOG (material other than grain) into the combine threshing and cleaning systems significantly affects the performance of these systems. It may be beneficial to conduct research directed at determining how to optimize the combine settings to accommodate the increase in MOG. The goal of such research would be to determine how the additional material affects the systems and what the best response is in terms of changing system settings.

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