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Final Report

Research Report

Investigation into Converting a Combine Grain-loss Signal into a Grain-loss Rate

For:
Ministry of Agriculture
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PAMI
Innovative Solutions
for Agriculture and Beyond

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Investigation into Converting a Combine Grain-loss Signal into a Grain-loss Rate

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1. Executive Summary

This study investigates the feasibility of converting a combine's loss sensor signal into a grain loss rate. In general, all brands of loss sensors and monitors have been slowly improving over time but still do not directly correlate actual grain loss to the grain loss signal. Therefore, there is a need for a real-time indication of actual grain loss, in a quantitative format (e.g., bushels/acre or dollars/acre), to help operators realize the impact of harvest loss, while also allowing them to decide what level of loss they are willing to accept under the conditions in which they are harvesting.

The main objective of this project was to correlate existing harvester loss sensor data with actual grain loss by putting the harvester loss signal and the actual grain loss rate in relation. Further project objectives were to determine if existing technology is adequate to support a grain loss rate, optimize the harvest loss sensor, and to decrease harvest losses across all Saskatchewan crops through improved harvest loss feedback.

Field testing was completed using the Prairie Agricultural Machinery Institute's (PAMI's) combine test equipment to collect both actual grain loss and the loss sensor signal from a combine in three crops (peas, wheat, and canola). The loss data was collected over a range of feed rates to create loss curves, and the relationship between the grain loss curve and loss sensor signal curve was then graphically compared through the use of relationship equations. Finally, a review of other sensing technologies was completed to determine if other technologies would be able to provide a more accurate grain loss measurement.

The correlation between the actual grain loss and loss sensor data using existing sensing technology in the separator area proved to be relatively strong when testing in large grain crops but generally underestimated grain loss. The correlation of the cleaning shoe data was not as strong and progressively worsened as grain size was reduced. For both the separator and cleaning shoe, the grain loss correlation was dependent on feed rate, and underestimated grain loss as feed rate increased in most cases. Relationship equations were produced to achieve a grain loss rate using feed rate and the loss sensor signal (seed impacts per acre). These relationship equations however are dependent on actual feed rate which isn't currently measured by combines, and require more research to fully understand their dependency on crop conditions, combine settings, and combine make and model.

Therefore, it can be concluded that the ability for existing loss sensing technology to provide an actual grain loss rate is limited; though the correlation to actual loss wasn't consistent, for most conditions, the grain loss monitor system tested did provide a reliable indication of when actual loss was increasing or decreasing. In large grain crops,

a grain loss rate could likely be determined through the use of relationship equations and correction factors. However, in small grain crops, design improvements would need to be made to the grain loss sensor system, especially on the cleaning shoe loss sensor, to accurately indicate actual grain loss rate.

Other sensing technologies that rely on various sensors including photoelectric, ultrasonic, microwave, microphone, and accelerometer were found to show potential in detecting grain loss; however, further research is required to determine their full capabilities for this application.

2. Introduction

Today, technology is playing a larger role on the farm than ever before throughout all aspects of farming but especially through real-time sensor data collection. This implementation of data collection can currently be seen in many areas of agriculture from the use of soil mapping using sonar-based imagery, to GPS sectional control on sprayers and seeders, to grain yield and grain moisture data on combines. Not only can this information be collected, but with today's technology, it can be wirelessly sent to mobile devices such as phones, tablets, and computers to be analysed anywhere at any time. All this information and data can then be used by the farm manager to make better economic decisions throughout all agricultural operations. It can also be used to assist young farmers or less experienced workers by providing continuous feedback on various tasks during farming operations.

This report investigates the feasibility of improving one specific sensing technology found on combines; the grain loss sensor. In general, grain loss monitoring technology for combines has experienced minimal advancement since being introduced into the market around 1975.

Grain loss monitoring systems typically consist of piezoelectric sensors placed at the rear of the separator and cleaning systems that count the seeds that strike the sensor pad (considered loss seeds). The sensor signal feedback to the operator is typically in the form of a bar graph without a unit of measurement displayed on the combine monitor. Without a unit of measurement, the indication on the monitor is meaningless unless the operator calibrates the indication to an actual loss amount on the ground.

Quantifying the loss on the ground requires the operator to get out the combine and manually check for losses, which many operators are not doing because they do not know how to properly collect and quantify the loss and/or they do not see value in taking the time to check, slowing down the harvest operation. Without a good calibration, the operator does not know if five bars on a given loss monitor is an indication of 1 bu/ac (67 kg/ha) loss or 5 bu/ac (336 kg/ha) loss.

There is a need to improve the presentation of the grain loss sensor signal generated by combine harvesters from generic numbers or graphs to absolute grain loss in bushels/acre, dollars/acre, or other meaningful loss units. Improvement in this area would provide the operator and/or farm manager with essential information when it comes to making economic decisions on the farm and managing grain loss during harvest. It would also act as a tool to help farmers optimize combine settings, minimizing grain loss, and effectively increase overall profits.

The main goals of this initial project are to explore the relationship between actual grain loss and sensed grain loss to determine if a meaningful relationship exists or could exist using other technology. It will also explore the limitations of current grain loss sensing technologies and possible solutions to these limitations. The research results gained through this preliminary project will support potential commercial development of an improved grain loss indication system in the future.

3. Methodology

The methodology used in this project can be broken down into three parts including lab testing, field testing, and data analysis. Lab testing was used in the initial stages of the project to better understand existing loss sensing technology and how to properly record the output signal. The core of the data collection was performed via field testing, which involved using PAMI's test equipment to collect both actual grain loss and the loss sensor signal from a combine at various feed rates. The field testing produced data that could then be analyzed to determine the correlation between data sets using the methodology described in **Section 3.3**.

3.1 Lab Testing

Lab testing was performed on the test combine loss sensors (both the separator and cleaning shoe sensors) to determine how they react to grain kernel impacts of varying magnitude (size of seed) and frequency (number of seeds dropped per time period). This involved testing both sensors by physically dropping grain from a set distance to determine signal characteristics including amplitude, impact signal frequency (time of single seed impact to signal stabilization), and signal resolution. From these signal characteristics, the proper sampling frequency, gain setting, and filter frequency were determined.

3.1.1 Equipment and Apparatus

The lab testing included the following pieces of equipment:

- Sorensen 12 V DC power source.
- Data acquisition system (EDAQ).
- Lenovo T420 Laptop (including software programs Infield and TCE build 3.24).
- Alligator Technologies module USB programmable amplifier and high-pass filter.
- Fluke Oscilloscope.
- Loss sensors (separator and cleaning shoe) from test combine.

The power source was used to supply the loss sensor with a 12 V DC signal while performing the tests. The data acquisition system used together with the laptop and high-pass filter/amplifier module were used to record and analyze the loss sensor signal. This signal was recorded over two channels during testing, both the raw signal and the conditioned signal (amplified and filtered).

To confirm results obtained by the data acquisition system, an oscilloscope was also used during testing, which displayed the loss signal in real time. The lab testing equipment used when testing the separator and cleaning shoe loss sensors can be seen in **Figure 1** and **Figure 2**, respectively**.**

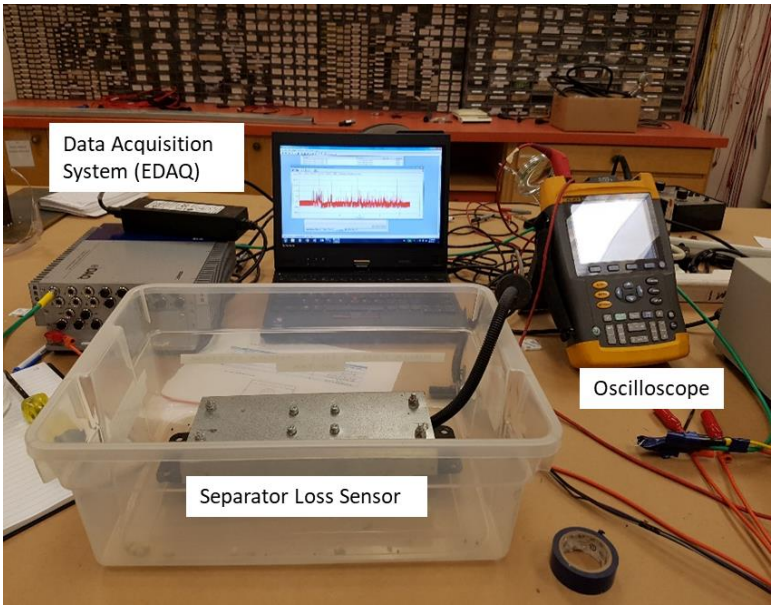

Figure 1. Lab testing of the separator loss sensor.

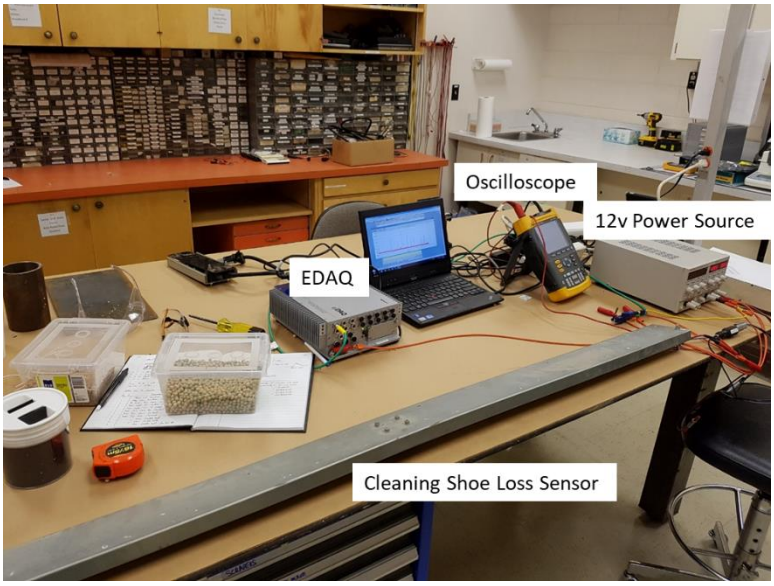

Figure 2. Lab testing of the cleaning shoe loss sensor.

The same sensing module was secured at the center of the cleaning shoe and separator sensors; however, as seen in **Figure 1** and **Figure 2**, the cleaning shoe sensor covers the entire width of the cleaning shoe and therefore is much larger than the separator sensor. It should be noted that little was known about the specific technology being utilized in each sensing module but that it did involve converting a mechanical impact force to an electrical (analog) signal and therefore was likely working on a piezoelectric principle.

3.1.2 Procedure

Three different types of grain (canola, wheat, and peas) were used to determine how grain size affects the sensor signal characteristics. The number of grain kernels dropped on the sensor at a given time was also varied from a single kernel to multiple kernels to simulate varying amounts of loss. The tests on the separator sensor were performed in a flat position to simulate the relative contact angle or seeds striking the sensor perpendicularly as would be the case in the separator area. The cleaning shoe sensor was tested at an approximate 30 degree angle from horizontal to simulate the relative contact angle as would be the case when installed in the combine.

The following procedure was used for each grain type:

- Set the power source to 12 V and 3 mA.
- Place the sensor in position (flat or angled) inside plastic tub.
- Set gain and filter frequency on alligator module to appropriate values.
- Set the sampling frequency to 1,000 Hz.
- Using the laptop, start recording the sensor signal.
- Drop grain kernels from approximately 4 in (10.1 cm) above the sensor (single grain kernels were dropped by hand at approximately one-second intervals, multiple kernels were dropped by filling a piece of U-channel the length of the senor then slowly pouring them on top of the sensor).
- Repeat the above steps using the other sensor (separator or cleaning shoe).

3.2 Field Testing

PAMI worked with farmer cooperators in the Humboldt, Saskatchewan, area to conduct field testing in three different crops (peas, wheat, and canola) using a test combine and PAMI's combine testing equipment.

The goal was to collect actual grain loss, raw data from the separator and cleaning shoe loss sensors, as well as the indicated loss from the combine monitor. After data collection, both sets of loss sensing data could be compared to the actual grain loss. To record the conditioned combine signal, a camera was mounted to capture the monitor display during testing, while the raw loss sensor data was recorded using a data acquisition system (see **Section 3.2.1** for more details).

The field test plan included collecting three curves of loss data per crop, where each curve consists of six to eight data points. These data points of grain loss at a specific feed rate were plotted on a graph and a best-fit curve was overlaid. The field testing procedure used was very similar to that outlined in ANSI/ASAE S396.3 (Combine Capacity and Performance Test Procedure). Also, for each data point collected, the

grain loss indicated by the combine monitor was recorded, as well as the raw signal from the loss sensors.

3.2.1 Field Testing Equipment

The following equipment was used during field testing; some of the equipment is shown in **Figure 3**.

- Test combine (Case IH model 8240).
- 35 ft (10.7 m) MacDon FD75-S FlexDraper straight-cut header (used in peas).
- Case IH pickup header (used for wheat and canola).
- Data acquisition system.
    - eDAQ
    - Alligator Technologies module USB programmable amplifier and high-pass filter (three modules; one for each loss sensor)
    - Lenovo T420 laptop (with installed software programs Infield and TCE v3.24 build 659)
- Canon FS300 video camera.
- PAMI combine test equipment (collector and processor).
- Grain truck with load cells (to measure yield).
- Garmin 60 handheld GPS (to measure distance traveled for yield calculation).

Note, the Case IH combine was selected for testing based on availability. Though each combine make and model has differences in its grain loss sensing systems, in principle the technology is similar. It is reasonable to expect that results, limitations, and trends observed for this combine could extend to other makes and models.

Figure 3. Field testing equipment.

The rear of the test combine needed to be modified to allow collection of the discharged material via the collector (additional information on the collector is provided in **Section**

3.2.4). This required removing the crop residue spreaders and installing a hitch to the rear axle as well as diverters and shielding, as shown in **Figure 4**, to deflect the discharge of straw, chaff, and grain onto the collector belts.

Figure 4. Modifications to test combine.

The test combine was also outfitted with data acquisition equipment, to collect both the monitor display and raw loss sensor signal as seen in **Figure 5**.

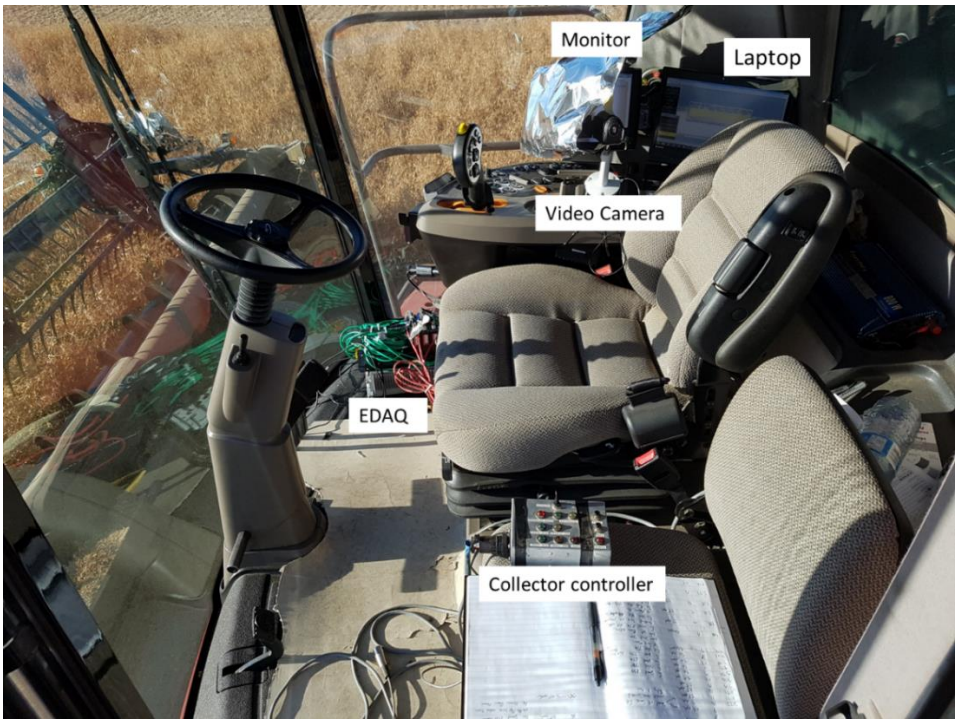

Figure 5. Test combine cab with data acquisition equipment labeled.

A custom run screen (**Figure 6**) was created within the monitor settings to display both average separator loss and cleaning shoe loss via bar graphs as well as a numerical value between 0 and 100, separator and cleaning shoe loss sensitivity, engine load, yield, and numerous combine setting values. A camera was mounted on the combine armrest to capture the grain loss monitor display during each of the tests.

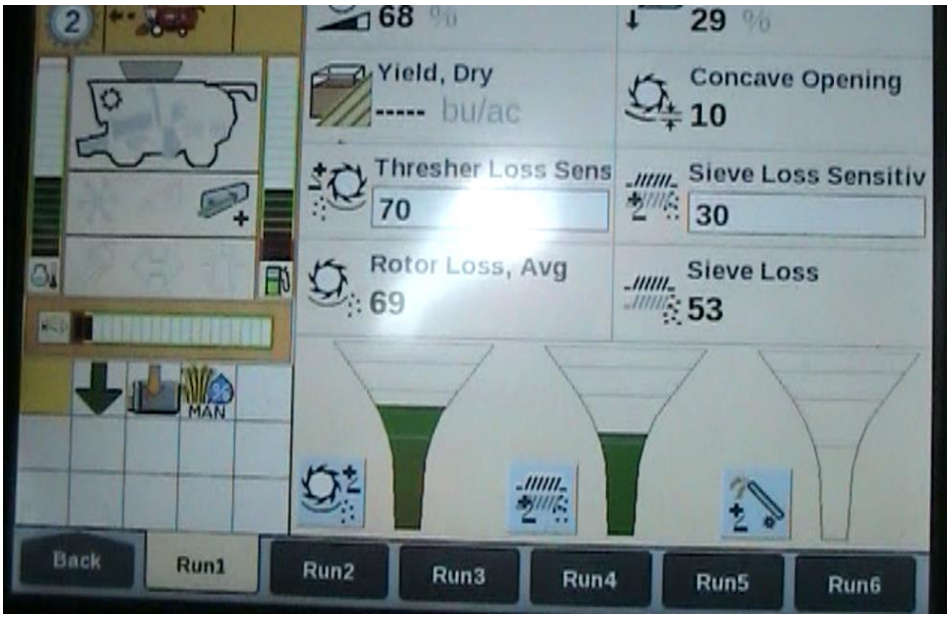

Figure 6. Monitor display captured during each test.

The loss signal coming from each loss sensor was split via a Y connection. This allowed the raw loss signal to be recorded directly from the loss sensors without interrupting the signal going to the loss monitor in the cab. Shielded wire was then routed to this wiring harness from the data acquisition system located in the cab, so the loss sensor signal could be recorded.

On this specific combine, there were three total grain loss sensors, two small sensors located on each side of the rotor at the rear of the separation area and one large sensor extending the full width of the cleaning shoe, located immediately behind the top sieve.

The location of both the cleaning shoe loss sensor and separator loss sensor can be seen in **Figure 7**.

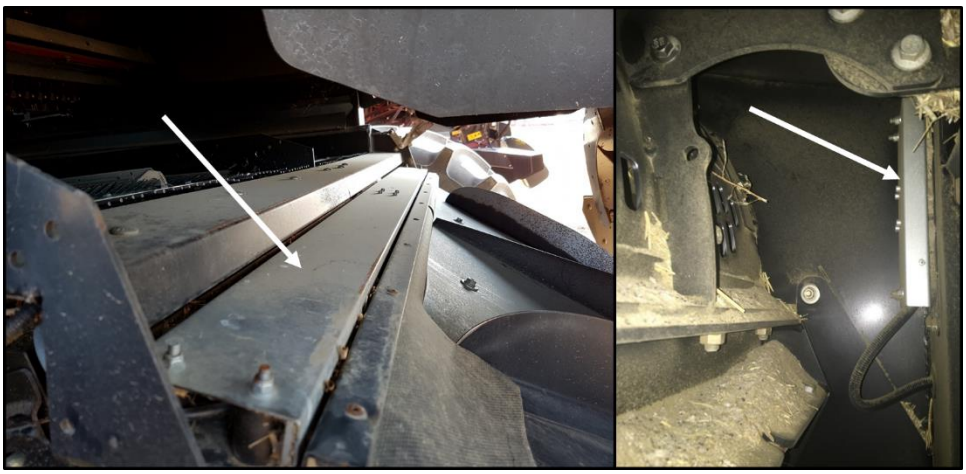

Figure 7. Cleaning shoe loss sensor (left) and separator loss sensor (right).

The placement of the loss sensors indicates any seeds that impact the cleaning shoe loss sensor are lost seeds, as they are past the cleaning area with no chance of being retrieved. However, seeds that impact the separator loss sensor are not lost as the sensor is located on the outside of the rotor housing at the rear-most section of the separator area. The separator loss sensor is still effective in theory because the number of impacts experienced by the sensor is representative of the amount of grain still within the separating area at the rear of the rotor. The grain still present at the rear of the separator can be considered lost as it will follow the straw into the chopper and eventually through the spreaders.

3.2.2 Data Acquisition System Verification

When testing sensitive electrical components such as loss sensors, extra steps and care is needed to ensure the signal is not adversely affected by the equipment used to measure the signal. In this instance, the sensor signal was recorded before and after installing the data acquisition equipment using the combine monitor diagnostic window.

In doing so, it could be verified that the signal displayed by the monitor was not affected by the additional data acquisition system required to record the raw loss sensor signal.

The signals sent to the combine monitor by the loss sensors were quantified when no seed impacts were occurring and when the sensors were lightly tapped with a screwdriver. The measurements were performed with and without the data acquisition system hooked up.

Figure 8 shows a picture of both cleaning shoe loss sensor signal graphs created in the diagnostic window of the combine monitor before and after installation of the data acquisition equipment. As shown, the sensor was reading 7.9 V when experiencing no impacts and 0.1 V when subjected to an impact for both sensors.

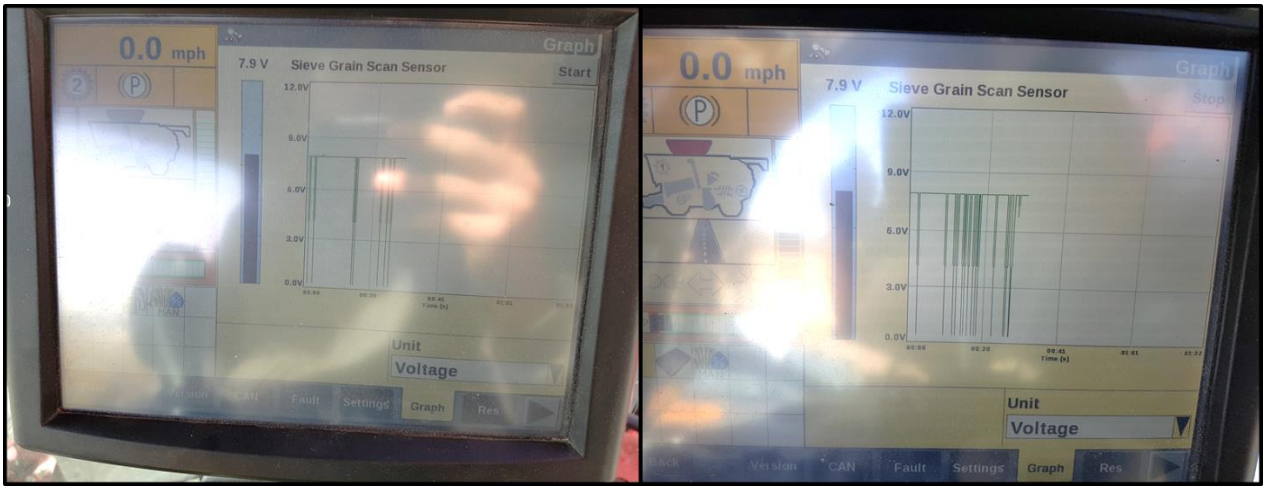

Figure 8. Cleaning shoe sensor verification, before (left) and after (right) installing the data acquisition system.

The data acquisition system installed to log the loss sensor data was also verified at the beginning of each test day; this was accomplished by dropping grain kernels onto the sensors while recording the loss data. The data was analysed and the gain and filter frequency settings confirmed.

3.2.3 Combine Setting Procedure

The test combine was set for each crop condition. The combine was initially set to the manufacturer's recommended settings (obtained from operators manual), then data to generate a few test points on the loss curve was collected to further optimize the combine settings by monitoring grain loss associated with the separator and cleaning shoe, as well as the grain tank sample (amount of chaff in sample). If the grain loss was found to be higher than acceptable levels, then setting changes were made accordingly.

These optimum settings were used for one curve of testing, but were generally changed in the second and/or third curves to obtain the desired amounts of loss on the cleaning

shoe and separator system. This ensured the loss sensors, specifically the cleaning shoe sensor, was exposed to unique loss scenarios. This included sluffing, where a thick layer of material (grain, straw and chaff) moves across the upper sieve, generally due to inadequate airflow or sieve gap, resulting in high grain loss. This could adversely affect loss sensor readings as the resolution of the sensor may not be sufficient to accurately detect such high loss rates. Additionally, the thick layer of material other than grain (MOG) and grain could build up on the sensor and prevent grain kernels from effectively impacting the sensor. Blowover is another important loss scenario where grain kernels are blown over the cleaning shoe area, mainly due to excessive fan speed. In this scenario, it is likely that many of the grain kernels would be blown over the cleaning shoe loss sensor (as it is immediately behind the top sieve), resulting in a lower sensed loss value when compared to actual grain loss.

Prior to testing, the loss monitor was also calibrated, so the loss bar graphs were in the “green” at approximately 1 bu/ac (67 kg/ha). This was accomplished by adjusting the sensitivities between both the cleaning shoe and separator loss sensors until the monitor indicated the desired levels of loss compared to actual grain loss.

3.2.4 Combine Grain Loss Testing Procedure

PAMI’s grain loss testing equipment consists of a collector and processor, which when used together, can collect the discharged material from the rear of the combine over a set distance and separate the grain loss from the MOG.

More specifically, the collector is towed behind the test combine and collects all material discharged from the rear of the combine. The combine harvests for at least 20 seconds to reach a steady state (in accordance with ASAE 396.3) at a given feed rate. During this time, material from the combine’s separator is conveyed on the top “straw belt”, while material from the cleaning shoe is conveyed on the lower “chaff belt” of the collector.

When the operator begins the test process, the collector travels a distance equivalent to one half rotation of its belts (25.3 ft [7.7 m]) before the collection and feed belts stop and the hitch extends away from the discharge area of the combine. The operator then stops the test combine and the material on each collection belt is weighed. The material on each belt consists of MOG and grain loss. These weights, the time it took for a collection, belt length, and belt speed to ground speed ratio are recorded into the loss spreadsheet along with known values of crop yield (calculated by weighing the grain harvested over a set distance) and header width.

Once the belt gross weights have been recorded, the chaff belt is unloaded into the processor, which recleans and, as necessary, rethreshes the crop material from the belt. Through a pneumatic retrieval system, the free grain and previously unthreshed grain are delivered to the cab of the processor. The grain loss is then weighed and recorded

as free grain and unthreshed grain loss. The reclean procedure is then repeated for the straw belt. Once both belts are empty, a tare weight is taken to get a net MOG weight for the collection.

The top belt of the collector can be seen unloading into the processor during a test in **Figure 9**.

Figure 9. Collector top belt being unloaded into processor.

3.2.5 Data Logging Procedure

During the first field testing in peas, the data acquisition equipment was set to the optimum settings found during lab testing. These settings, specifically the gain and high-pass filter frequency were initially 200 and 300 Hz, respectively. Upon testing these settings in crop, it was found that the sensor signal was consistently reaching the maximum voltage of 10 V and the signal-to-noise ratio was relatively low. The gain setting was therefore reduced to two with the same high-pass filter frequency and sampling frequency of 300 Hz and 1,000 Hz, respectively.

For each of the test collections described in **Section 3.2.4**, the operator began recording using the data acquisition equipment at the beginning of the test and stopped recording once the test was completed, which resulted in a set of data for each individual test collection.

This data set included the raw loss sensor signal, the loss monitor display data as well as time (in seconds, minutes, hours, and days), ground speed, GPS coordinates, and a test start signal (used to identify the start of the test point in the recorded data).

3.3 Data Analysis

Once all field testing was complete, the collected data was analysed to determine the relationship between sensed grain loss (loss sensor data and monitor data) and actual grain loss.

The loss signal displayed by the combine monitor could be compared graphically to the actual grain loss that had already been calculated by the combine computer system, and to a numerical value. The exact signal conditioning and calculations performed by the combine is unknown, but likely included some type of filtering and amplifying of the signal, a time-based average, calibration factors, as well as a set of conditions (voltage and/or frequency based) to determine if the impact experienced by the sensor was in fact a grain kernel.

The signal recorded directly from the loss sensors required some secondary analysis to convert it to a numerical value. The following procedure was used to analyse the loss sensor signal output:

- The loss sensor signal was recorded at 1,000 Hz and was initially saved as an SIE file. This file was later converted to a text file and then copied into a Microsoft Excel workbook.
- The number of grain kernel impacts were counted during each test period, where the test period indicates the time it takes the collector to travel one half rotation of the collector belts. Since ground speed varied for each test, but the distance traveled stayed constant at 25.3 ft (7.7m), the duration of each test varied.
- A condition was used to sum all the sensor signal data points that exceeded 2 V during the test duration. This voltage condition was chosen by knowing the minimum voltage produced by a grain kernel (from initial field tests) and by assuming all other MOG is less dense, thereby creating a smaller output voltage when impacting the sensor. It was also confirmed through lab testing that the sampling frequency of 1,000 Hz resulted in a single data point above 2 V per grain kernel impact.
- The number of impacts experienced by the separator loss sensors were averaged between the left and right separator sensors while the cleaning shoe loss sensor value was taken directly.
- Both the sensed loss signals (monitor data and loss sensor data) and the actual grain loss for the separator and cleaning systems were then graphed to create loss curves. The equations associated with these best fit loss curves were then determined.
- The relationship equation between the sensed grain loss and actual grain loss was then produced.

4. Results and Discussion

The project results are grouped in three main sections: optimum combine settings, the results from the initial lab testing performed on the loss sensors, and the core results obtained from field testing. The optimum combine settings were determined prior to test collections in each of the three crop types and was used to ensure the combine was set reasonably for the crop conditions. The lab test results included the loss sensor characteristics for each grain type including frequency and amplitude of impact, as well as the filtering frequencies and gain setting needed to record the signal. The data collected during field testing was used to correlate the loss monitor data and the direct loss sensor data to actual grain loss.

4.1 Optimum Combine Settings

Manufacturer recommended combine settings were initially used in each crop but were then optimized to the specific crop conditions experienced. Optimization was completed by making adjustments to combine settings and observing changes to cleaning shoe and separator grain loss, grain tank sample composition (amount of chaff) and capacity (loss rate at a given feed rate). The optimum combine settings used in each crop are summarized in **Table 1.**

Table 1. Optimum combine settings.

Crop	Vane Position	Rotor Speed (rpm)	Concave Clearance, in (mm)	Chaffer Gap, in (mm)	Bottom Sieve Gap, in (mm)	Fan Speed (rpm)
Peas	Mid	500	0.87 (22)	0.55 (14)	0.47 (12)	830
Wheat	Slow	1050	0.12 (3)	0.79 (20)	0.31 (8)	975
Canola	Slow	600	0.71 (18)	0.55 (14)	0.40 (10)	600

The concave (positions 1 and 2) and separator grate (positions 3 and 4) configurations used can be seen in **Table 2**. The module position number indicates where each module was placed in relation to the rotor, starting at the front of the rotor (position 1) to the rearmost section of the rotor (position 4). Note, the left and right module sections were the same for each position.

Table 2. Concave and grate configurations.

Crop	Concave Area		Grate Area	
	Position 1	Position 2	Position 3	Position 4
Peas	Large wire	Large wire	Slotted	Slotted
Wheat	Blank out plates	Small skip wire	Large wire	Large wire
Canola	Small wire	Small skip wire	Large wire	Large wire

4.2 Lab Test Results

The raw data collected from the lab tests was graphed using Infield, so the signal characteristics could be observed. High levels of noise and relatively low signal voltage were found when no gain or filtering mechanisms were used. Therefore, a high-pass filter and amplifier were introduced to increase the signal to noise ratio. A gain setting of 200 and a high-pass filter setting of 300 Hz was found to give the best results throughout all grain kernel types. The resulting signal impact frequencies and amplitudes seen from each grain kernel type can be seen in **Table 3**.

Table 3. Lab testing results (gain 200, filter frequency 300 Hz).

Grain Type	Impact Frequency (Hz)	Signal Amplitude (mV)
Peas	300 to 350	200 to 1000
Wheat	330 to 400	100 to 500
Canola	330 to 400	100 to 200

The noise-to-signal ratio was found to range from 3 in canola to 6 in wheat and 20 in peas. The vast majority of noise had a frequency of 60 Hz, which could have been caused by nearby electronics in the lab or the logging equipment itself. When subjecting the loss sensors to multiple grain kernels at once, simulating high grain loss, it was found that sensor resolution may be a limiting factor (especially with small grains such as canola). When multiple grain kernels simultaneously impact the loss sensor, the sensor may only record a single impact. This would occur in higher frequencies during high loss scenarios and in smaller grain crops (higher number of seeds per volumetric unit of loss). The graphs of raw test data from Infield including both single and multiple-grain impact tests can be found in **Figure A-1** to **Figure A-6** in **Appendix A**.

From the impact frequencies, it was confirmed that the sampling rate of 1,000 Hz was sufficient to capture a seed impact. Also, initial gain and filter settings to be used when field testing were determined.

4.3 Field Test Results

The field tests resulted in data from three crops including peas, wheat and canola. Within each of these crops, three results were compared: actual grain loss, the conditioned signal from the combine monitor, and the loss signal directly from the loss sensors. The grain loss data was collected and analysed seperately between the separator and cleaning area and a set of graphs was created for each.

4.3.1 Crop Conditions

Field testing first took place on August 27, 2017, in peas 15 miles (24 km) north of Humboldt. Field testing in wheat and canola followed from September 28 to 30, 2017, twenty miles (32 km) east of Humboldt. All testing was completed between 1:00 and 6:00 p.m. to ensure crop condition remained as consistent as possible during testing.

The field peas were combined (straight cut) during sunny warm conditions between 75 and 79°F (24 and 26°C) and had a 15% moisture content and an average yield of 68 bu/ac (4,573 kg/ha). The wheat and canola were swathed and combined during relatively warm days between 68 and 72°F (20 and 22 °C). The wheat was harvested tough at 18% moisture due to poor weather in the latter half of September and yielded on average 75 bu/ac (5,044 kg/ha). Finally, the canola was harvested at 10% moisture and yielded on average 55 bu/ac (3,699 kg/ha).

To ensure consistency between tests, auto-header height was used when harvesting all crops. The location of tests within each field were also selected so tests were being conducted in the most uniform areas.

4.3.2 Raw Loss Sensor Data

Initially, the same settings used during lab testing were applied to the data logging equipment; however, due to the difference in impedance load between the two systems, the gain setting was reduced to improve signal quality.

The following settings were used when recording the loss sensor signal during field testing:

- Sampling frequency: 1,000 Hz
- High pass filter frequency: 300 Hz
- Gain setting: 2

Portions of raw data from field testing were graphed to show the signal characteristics associated with the dynamics of the combine as well as grain kernel size. The full set of data was graphed during a representative test in each crop (peas, wheat, and canola), which can be seen in **Appendix B**, **Figure B-1**, **Figure B-3**, and **Figure B-5**, respectively. In order to better observe the grain kernel impacts, a five-second snapshot of the three sets of data was also graphed. These graphs for peas, wheat, and canola

can be seen in **Appendix B**, **Figure B-2**, **Figure B-4**, and **Figure B-6**, respectively. The graphs show the majority of impacts are well above the cut off voltage of 2 volts, set to indicate a grain impact. Also, the signal quality was good with a high signal-to-noise ratio across all sensors.

As seen from the raw data graphs, there was a larger concentration of impacts on the right separator sensor compared to the left separator sensor in small grains (wheat and canola) but not in the larger grains (peas). This phenomenon could be caused by the direction of the rotor rotation and the way it interacts with the grain kernels. As the average number of impacts is taken between the separator sensors, the resulting value could still be correlated to actual grain loss on the separator system.

The raw data also shows a direct relationship between the oscillation of the cleaning shoe (5 Hz) and the grain kernel impacts observed on the cleaning shoe loss sensor, especially in small grain (**Figure B-3** to **Figure B-6**). It is thought that the cleaning shoe sensor must be impacted by a large number of grain kernels when the cleaning shoe (and loss sensor) moves up and rearwards of the combine and very little or no impact when it moves down and towards the combine. This oscillating pattern is enhanced by the nature of smaller seed size, meaning more seeds per unit of loss and thus more impacts. The ossilation also effectively decreased the cleaning shoe sensor accuracy as the sensor was only subjected to grain kernel impacts approximately 60 percent of the time. Therefore, the sensor would require a higher resolution to acurately differenciate between grain loss amounts when subjected to an oscillation as well as high loss scenarios (particularly in small grains).

4.3.3 Sensed and Actual Grain Loss Curves

Once the raw sensor data was analysed, each test point could be graphed to create two loss curves, one for the separator area and one for the cleaning shoe. These loss curves were then plotted alongside the actual grain loss curve as well as the loss monitor curve, resulting in three loss curves each for the separator and cleaning systems.

The loss curve produced in each crop using optimum combine settings was used in the bulk of the anlaysis to form a correlation between the loss data and actual grain loss. Some supporting loss curves were also produced using varying combine settings to observe their effect. The following analysis shows the results associated with field testing in peas. Rather than showing the repeated analysis for wheat and canola, the results are discussed and the supporting figures can be found in **Appendix C**. Also, the tabulated data associated with each loss point for all loss curves can be found in **Appendix F**.

Figure 10 and **Figure 11** show the actual and sensed loss (monitor and direct loss sensor data) associated with the separator when field testing in peas. The separator and cleaning shoe loss sensor senitivities were set using the combine monitor to 84 and 16, respectively.

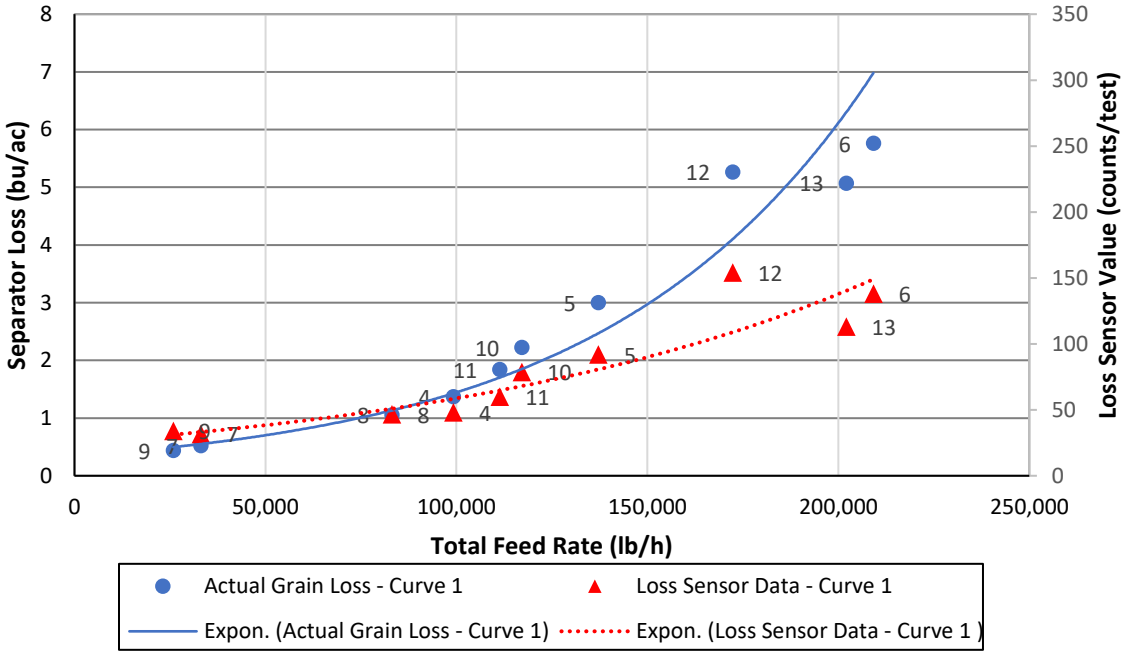

Figure 10. Actual grain loss and loss sensor curves on separator area in peas.

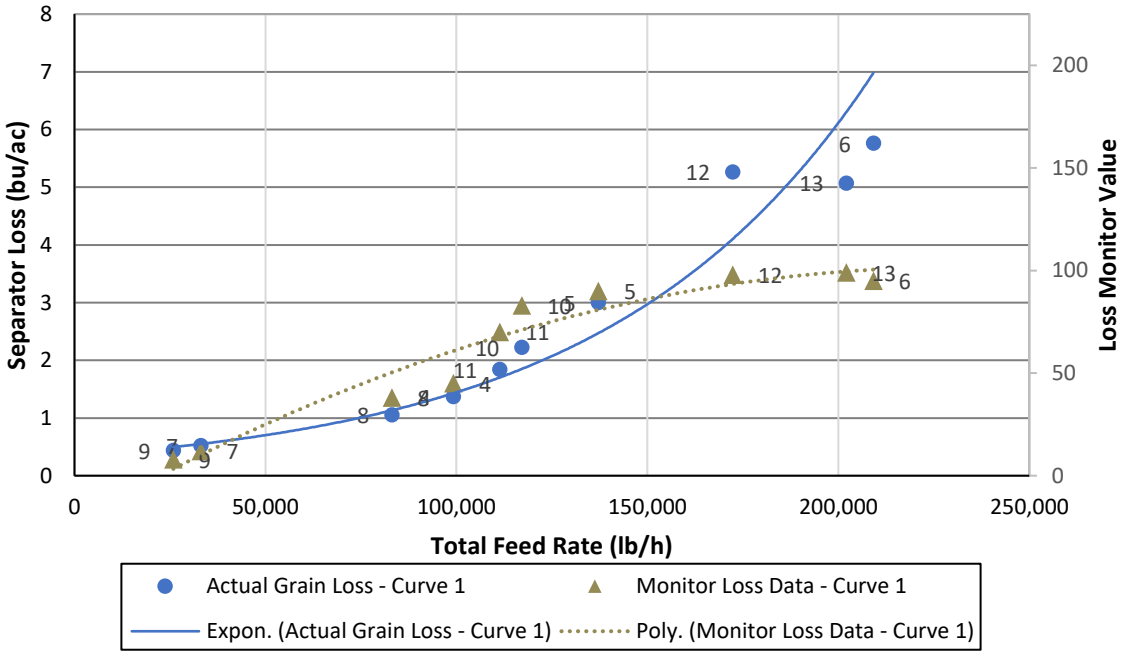

Figure 11. Actual grain loss and monitor loss curves on separator area in peas.

Both the sensed loss curves underestimate grain loss as feed rate increased. It is also important to note the monitor loss data reached a maximum of 100 at approximately 170,000 lb/h (77.1 tonnes/h) and remained close to maximum as feed rate was increased. This shows the range of the combine loss monitor at a given sensor sensitivity. A lower loss sensitivity might have helped at higher feed rates and losses, but would have detrimental effects at low feed rates and lower losses.

The same graphs were created for the cleaning shoe and can be seen in **Figure 12** and **Figure 13**.

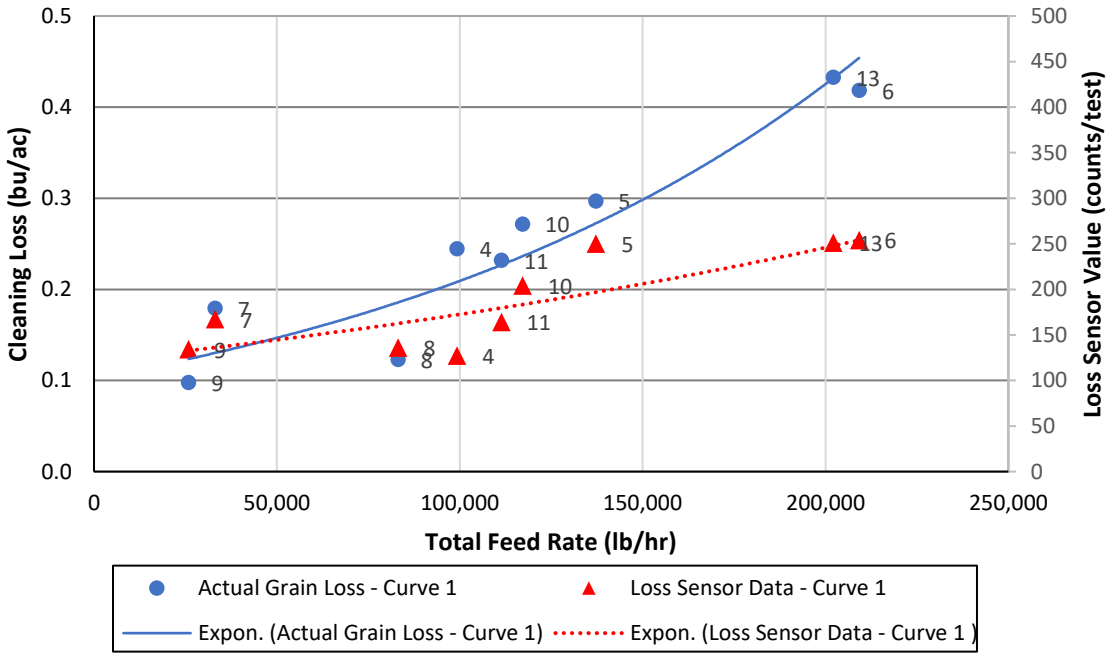

Figure 12. Actual grain loss and loss sensor curves on cleaning shoe in peas.

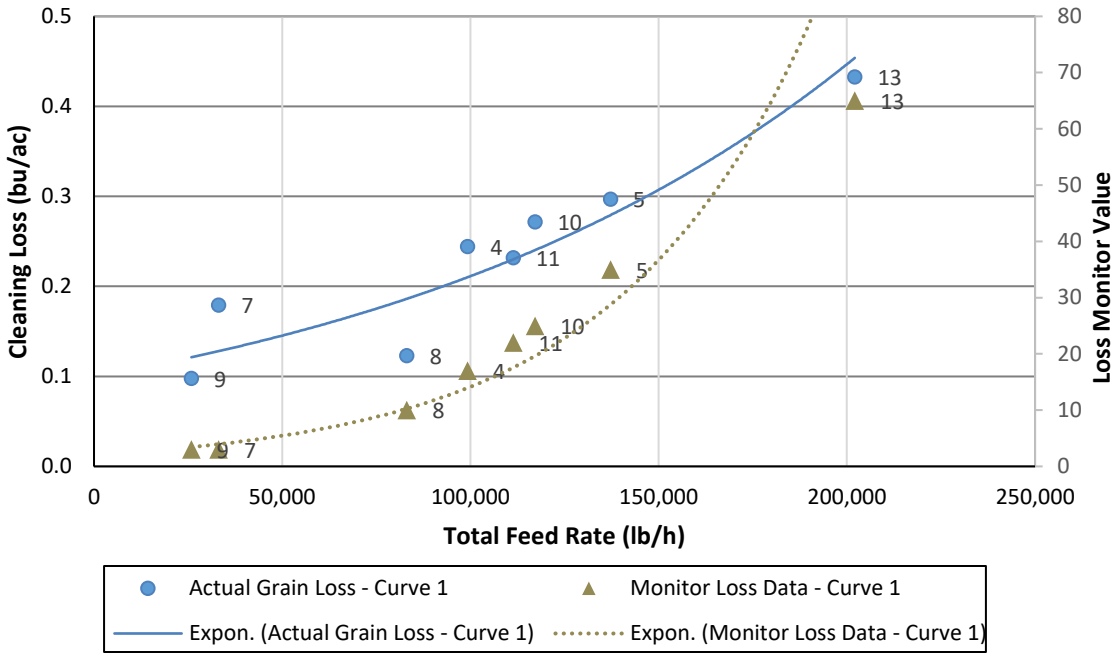

Figure 13. Actual grain loss and monitor loss curves on cleaning shoe in peas.

The loss sensor data slightly underestimates grain loss as feed rate increased, where the monitor loss data slightly overestimates grain loss as feed rate increased.

Similar curves using optimum combine settings were produced for wheat and canola and can be seen in **Appendix C**. In wheat as seen in **Figure C-5** and **Figure C-6**, both the sensed grain loss signals (monitor data and direct loss sensor data) again underestimated grain loss as feed rate increased on the separator area. On the cleaning shoe, the monitor data slightly overestimated grain loss with increased feed rate, while the direct loss sensor signal slightly underestimated grain loss as seen in **Figure C-7** and **Figure C-8**.

In canola, the sensed loss on the separator (both monitor and loss sensor data) is shown to follow a polynomial curve seen in **Figure C-9** and **Figure C-10**, where it overestimates the grain loss at all feed rates except on the extremes of low and high feed rates. On the cleaning shoe, the monitor data follows the grain loss curve relatively well, while the loss sensor signal overestimates grain loss at low feed rates and underestimates grain loss at high feed rates as shown in **Figure C-11** and **Figure C-12**.

Loss curves were also produced in each crop using varying combine settings to produce high-loss scenarios on the cleaning shoe such as blow over and sluffing. The resulting data and graphs is included for canola (**Appendix D**) but excluded for wheat and peas as the grain loss was relatively insignificant from previous test collections. It is important to note that to achieve a high loss scenario on the cleaning shoe in peas fan speed had little effect and significant loss only occurred when the chaffer gap was greatly reduced.

In canola, as seen in **Figure D-4** in **Appendix D**, when the combine fan speed was increased 100 rpm over the optimum setting of 600 rpm, the loss monitor curve was unable to accurately detect grain loss. The monitor displayed an increase in grain loss as feed rate increased; however, the actual grain loss was opposite with decreasing loss with increased feed rate. This downward trending loss curve suggests grain loss was actually decreasing with increased feed rate during this collection. This is likely due to an insufficient layer of material on the cleaning shoe (apparent at low feed rates) in combination with the increased fan speed. It is important to note that the raw loss sensor signal followed the actual grain loss curve relatively closely during this test as shown in **Figure D-3**, suggesting significant conditioning was done by the combine computer system. Although the conditioning resulted in a poor indication of grain loss in this scenario, there were also conditions where the combine monitor resulted in a better indicator of grain loss when compared to the PAMI analyzed curve.

To create a sluffing scenario on the cleaning shoe, the chaffer gap was reduced by 0.12 in (3 mm) from the optimum setting of 0.55 in (14 mm). Note, this reduction in chaffer gap may not have been a significant enough change to truly cause sluffing; however, the overall grain loss trend would be similar. The effect this had on cleaning shoe loss displayed by the monitor and direct output from the loss sensors can be seen in **Figure D-7** and **Figure D-8**, respectively. Both figures show a very poor correlation, where the sensed grain loss curves generally overestimate grain loss over the entire feed rate range. The accompanying separator loss curves are also included in **Appendix D** and show a relatively strong correlation to actual grain loss (as was the case with optimum cleaning shoe settings).

4.3.4 Grain Loss Relationship

Initially it was thought that the number of impacts experienced by the grain loss sensors would be directly proportional to the amount of actual grain loss. However, after observing the loss curves, it is apparent the relationship is not directly proportional, but dependent on feed rate. Therefore, to further investigate the relationship feed rate has on the number of grain kernel impacts experienced by the separator and cleaning shoe loss sensors, the number of impacts per bushel of loss was calculated over the range of total feed rates.

Figure 14 and **Figure 15** show this relationship on the separator and cleaning shoe, respectively, while harvesting peas. Similarly, **Figure E-3** and **Figure E-4** in **Appendix E** show the same relationship found in wheat, while **Figure E-5** and **Figure E-6** show the same relationship in canola. The supporting calculations used to achieve these relationship curves can also be found in **Appendix E**.

This provided a relationship that could be used to predict the amount of grain loss at a given feed rate by using the loss sensor data.

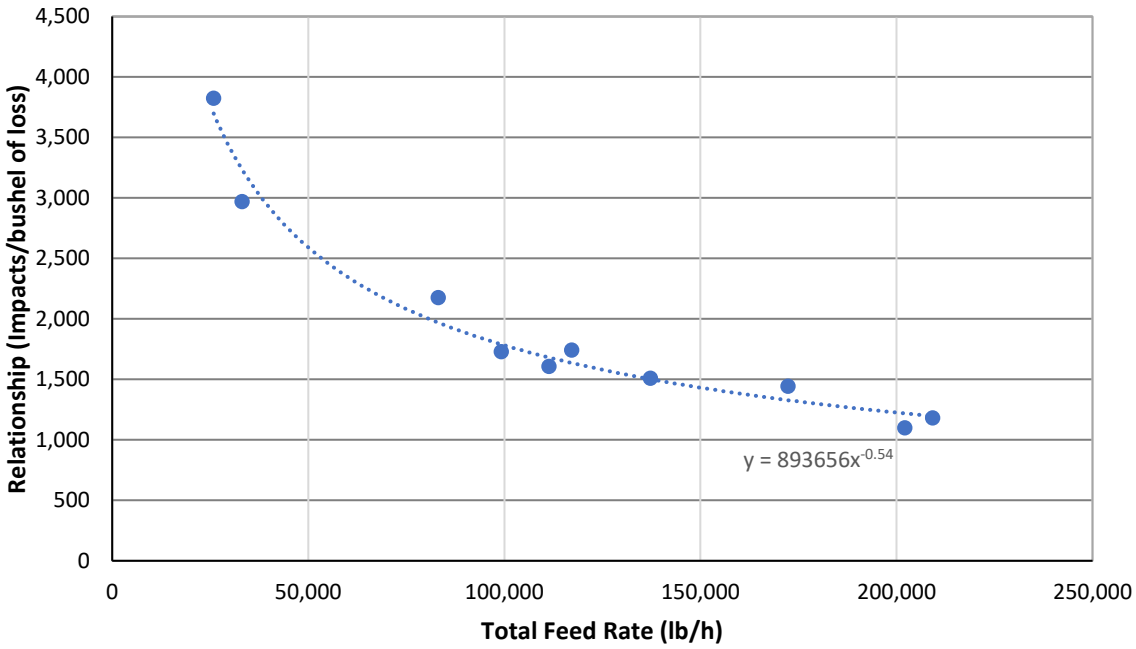

Figure 14. Grain loss relationship on separator area in peas.

As **Figure 14** suggests, the number of impacts per bushel of loss decreases with increased feed rate creating a downward sloping curve. It is important to note the significant change in the number of impacts required to make up one bushel of loss as the curve is reduced by approximately a factor of four over the range of feed rates. In other words, at low feed rates (25,000 lb/h or 11.3 tonnes/h) almost 4,000 impacts on the sensor signify one bushel of lost peas while at high feed rates (200,000 lb/h or 90.7 tonnes/h) only about 1,000 impacts indicate one bushel of loss.

The same type of relationship in peas can be seen with the cleaning shoe sensor but with a lower rate of change across feed rates, as seen in **Figure 15**.

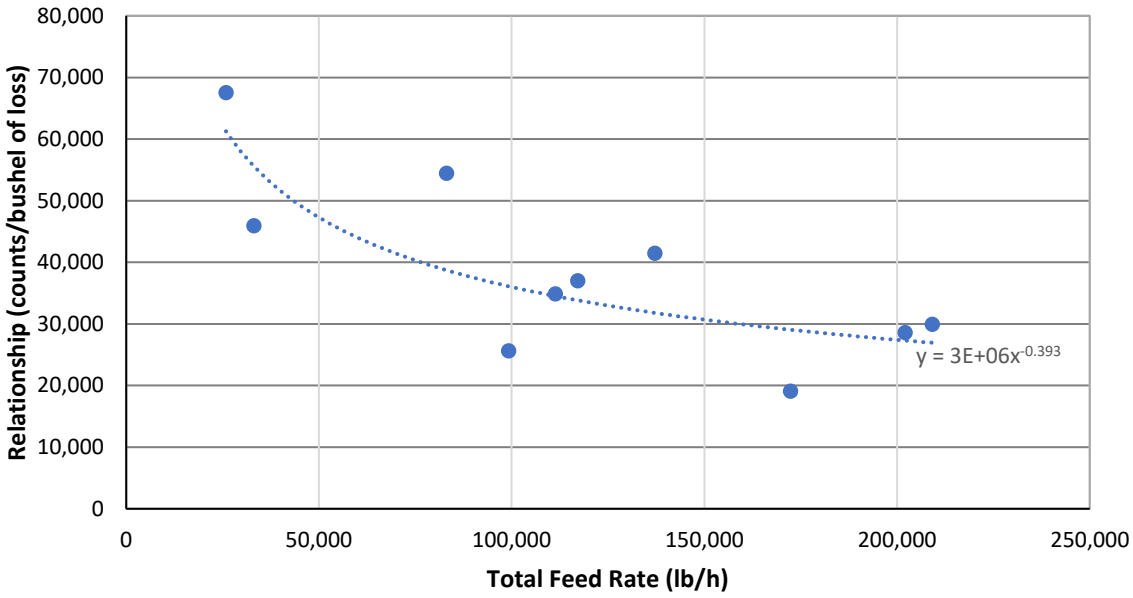

Figure 15. Cleaning shoe grain loss relationship in peas.

In wheat the grain loss relationship on the separator again produced a downward sloping curve signifying a reduced number of grain kernel impacts per bushel of loss, while the cleaning shoe grain loss relationship shows a slight increase in grain kernel impacts per bushel of loss before decreasing at higher feed rates.

In canola, the separator again had a dominantly downward sloping curve, while the number of impacts per bushel of loss on the cleaning shoe increased significantly at low feed rates until 80,000 lb/h (36.3 tonnes/h) when it began to decrease rapidly (likely due to insufficient resolution of the cleaning shoe loss sensor).

In all crops, the separator loss was generally underestimated by the direct loss sensor data as well as the monitor data but followed the same general trend as the actual grain loss curve. The cleaning shoe loss sensor data as well as monitor data was observed to be relatively well correlated to actual grain loss in peas and wheat, but overall exhibited a poor correlation in canola.

A possible explanation for the relationship seen on the separator is that at high feed rates, a larger amount of crop material is being forced into the separator area creating a thicker mat of material preventing a proportional amount of grain kernels from impacting the separator sensors. The relationship associated with the cleaning shoe is likely caused by a combination of the cleaning shoe oscillation and insufficient sensor resolution.

Using the relationship equations with inputs of total feed rate and the number of grain impacts, the actual loss can be predicted for both the separator and cleaning shoe through the following equations for each crop shown in **Table 4**. The accompanying analysis used to obtain these equations can be found in **Appendix E**.

Table 4. Grain Loss Relationship Equations

Crop	Separator Loss Relationship	Cleaning Shoe Loss Relationship
Peas	$Grain\ Loss = \frac{A}{893656x^{-0.54}}$	$Grain\ Loss = \frac{B}{3E+06x^{-0.393}}$
Wheat	$Grain\ Loss = \frac{A}{26066e^{-8E-06x}}$	$Grain\ Loss = \frac{B}{-3E-06x^2+0.4166x+42948}$
Canola	$Grain\ Loss = \frac{A}{-3E-06x^2+0.3397x+32869}$	$Grain\ Loss = \frac{B}{-8E-06x^2+1.34x+5986.5}$

where,

A is the average number of impacts registered by the separator loss sensors (impacts/acre)

B is the number of impacts registered by the cleaning shoe loss sensors (impacts/acre)

x is the total crop feed rate in (lb/ac)

However, this method has limitations, as the relationship equation is dependent on combine settings and crop conditions experienced while testing. It is also dependent on the total feed rate, which is currently being monitored by some combine models (for functions such as auto feed rate or adaptive cruise control) that provides feedback on relative changes in feed rate, however the actual feed rate in absolute units is not being measured. Further, the accuracy with which these systems measure relative feed rate is unknown and would require testing to determine if they would be effective in supporting a grain loss rate through the grain loss relationships shown in **Table 4**.

4.4 Existing Technology Optimization

Upon analysing the loss sensor data, it was determined some improvements could be made to the existing loss sensing technology so absolute grain loss feedback could be better supported. Specifically, these improvements were targeted for the cleaning shoe loss sensor, as it was found the sensor output was negatively influenced by the oscillation of the cleaning shoe.

As discussed previously, the oscillation caused grain impacts to occur at the same frequency as the cleaning shoe movement (approximately 5 Hz), resulting in a high

number of grain impacts on the sensor at once. This effectively decreased the resolution of the senor, as it had to sense the amount of grain loss during a very small duration of time. To solve this problem, a few alternatives were determined and are outlined below.

- Mount the loss sensor in the same position (immediately behind the top sieve) but independently of the cleaning shoe. This will prevent the movement of the cleaning shoe from affecting the sensor readout.
- Implement multiple sensors across the rear of the cleaning shoe. This would effectively increase the resolution as there are more sensors to capture the grain kernel impacts over the same area. The number of impacts experienced by each sensor could simply be summed to determine the total number of impacts. This would allow the sensor to better distinguish between amounts of loss experienced during oscillations.

To best solve the issue, both of the alternatives could be implemented by changing the position of the sensor as well as the resolution. Through implementing these improvements, the correlation between the loss sensor signal and grain loss could be enhanced.

5. Review of Loss Sensing Technologies

A number of loss sensing technologies were reviewed to determine if any could be implemented on combines to measure grain loss more accurately. These technologies consist of sensors that measure physical properties including acoustic impedance, acoustic waves, light, vibration, and acceleration.

The specific sensing technologies reviewed included: accelerometers, microphones, ultrasonic, photoelectric, and microwave sensors. Each of these sensing technologies were reviewed in detail including how the technology works, how it could be implemented to monitor grain loss and finally a few specific (off the shelf) sensors that could be implemented and their associated specifications were listed. This detailed information is outlined in the sections following, specifically **Sections 5.1 – 5.5.**

The results of the technology review indicate that there are many types of technology that could be implemented to detect grain loss; however, the practicality and functionality of these technologies need to be further investigated to determine their full potential. Further, these technologies indicate the direction in which real time loss monitoring could go in the future to both increase accuracy of loss detection and feedback to the operator. A summary of the main advantages and disadvantages associated with each of the reviewed sensing technologies is presented in **Table 5** below. The vendor list for all the sensing technologies reviewed can also be found in **Appendix G**.

Table 5. Advantages and disadvantages of loss sensing technologies.

Sensing Technology	Advantages	Disadvantages
Accelerometers	• Functional in dusty conditions • Uses density to distinguish between grain and MOG • Capable of high sample rate	• Requires impact plate • Susceptible to blow over and sluffing on cleaning shoe
Microphones	• Functional in dusty conditions • Proven functionality with detecting grain kernels • Uses density to distinguish between grain and MOG	• Potentially high noise levels; requires lots of filtering • Requires impact plate • Susceptible to blow over and sluffing on cleaning shoe
Ultrasonic	• Functional in dusty conditions • Detects loss over whole area • Good signal range • Potential method for differentiating between grain and MOG	• Significant testing required to correlate signal to grain loss • Might be difficult to distinguish between grain and MOG

Photoelectric	• Combine vibration/motion does not affect sensor • Detects loss over whole area • Good signal range • Capable of indicating location where most loss is occurring	• Dust and fine particles could interfere with sensor • Limited detection • Very difficult to distinguish between grain and MOG
Microwave	• Functional in dusty conditions • Detects loss over whole area • Proven functionality in detecting solid particles in motion	• Might be difficult to distinguish between grain and MOG • Significant testing required

5.1 Accelerometers

An accelerometer is an electromechanical device that measures forces created from accelerating a mass. There are numerous types of technologies implemented in accelerometers. A few of the main types include capacitive micro-electrical-mechanical system (MEMS), piezoelectric, and piezoresistive, all of which exhibit slightly different properties.

All three types of accelerometers can be used to detect vibrational frequencies in a material and if the natural frequency of the material is known, the sensor can be used to determine when the material is subjected to an impact. Theoretically, this could be implemented to detect grain loss by mounting the sensor to a plate with a known natural frequency. When grain kernels contact the plate, the sensor detects this impact by measuring the amplitude of the natural frequency produced. The amplitude of the output signal is also proportional to the magnitude of impact experienced; so like existing piezoelectric sensors, filtering can be implemented to distinguish between a grain kernel and MOG.

The best type of accelerometer to use for a grain loss detection application would depend on variables such as targeted sampling rate, targeted signal frequency, and resolution required. From the three types reviewed from MIDE manufacturing (See **Sections 5.1.1 and 5.1.2**), the piezoresistive accelerometer has the most promising specifications, with the largest frequency range, highest resolution (X and Y axes), and high sampling rate capability.

5.1.1 Piezoelectric and Piezoresistive Accelerometers

Piezoelectric and piezoresistive accelerometers are based on the piezo effect, where material properties change as the material is subjected to a force. In piezoelectric materials, a voltage potential is produced across the material proportional to the force applied, while a piezoresistive material changes in electrical resistance proportional to

the force applied. Both types of sensors typically require an amplifier to increase signal strength and are filtered to increase signal-to-noise ratio. **Figure 16** shows the internal parts on a piezoelectric sensor.

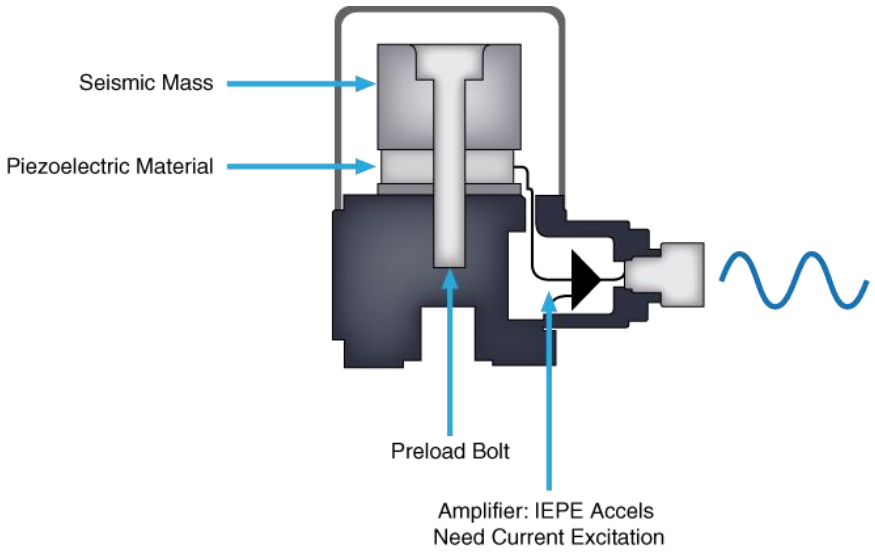

Figure 16. Integrated electronic piezoelectric (IEPE) sensor diagram (National Instruments, 2017).

A few specific sensors of each type were analysed to determine their respective specifications and can be seen in **Table 6**.

Table 6. Peizoelectric and piezoresistive sensor specifications**.**

Vendor	Type	Model	Frequency Range (± 5%) (Hz)	Resolution (X, Y & Z Axes) (g)		Sampling Rate Range
MIDE	Piezoelectric (Tri-axes)	Slam Stick - X	5 - 1,000	0.015	0.06	100 (Hz) to 20 (kHz)
MIDE	Piezoresistive (Tri-axes)	Slam Stick - S	0 - 2,000	0.003	0.015	100 (Hz) to 20 (kHz)

5.1.2 Capacitance Accelerometer

The capacitance accelerometer detects acceleration by sensing a change in electrical capacitance between two parallel plates. This type of accelerometer has properties that make them suitable for low-frequency vibration detection. The specifications associated with one capacitance accelerometer are as follows:

- **Vendor**: MIDE
- **Model**: Slam Stick - C
- **Frequency Range (±5%)**: 0 to 1,000 Hz
- **Resolution**: 0.05 g
- **Sampling Rate Range**: 0 to 1,000 Hz

5.2 Microphones

Microphones are a type of transducer that is used to detect acoustic waves and convert them into electrical signals. There are three main types of microphone transducers including externally polarized condenser microphones, prepolarized electret condenser microphones, and piezoelectric microphones (See **Section 5.2.1** and **5.2.2** for more details).

Microphones as a type of sensing technology have recently been introduced in seeding equipment to detect blocked or plugged hoses by companies such as Seed Hawk and Intelligent Agriculture Solutions. This was done by analysing the sound wave produced from a grain seed striking a stainless-steel membrane with known physical properties. The material emits an acoustic wave that the microphone detects and therefore knows how many seeds are passing through the hose at a given time.

The same theory could be implemented to detect grain loss on a combine by measuring the sound waves produced by grain impacting a material as it leaves either the separator or cleaning shoe. The amplitude of the acoustic sound wave produced is dependent on mass; therefore, impacts from grain could be differentiated from impacts form straw and/or chaff. This sensor would need a relatively high sensitivity to capture the sound of small grains such as canola; therefore, a pressure field condenser-type microphone with high sensitivity would likely be the best suited.

Due to large amounts of acoustic noise and vibration on the combine during operation, filtering methods would likely need to be implemented to get a clean output signal.

5.2.1 Condenser Microphones

The most common type of microphone is the condenser type, which operates by changes in capacitance. This design uses a metal diaphragm that acts as one of two plates in a capacitor. When the diaphragm is subjected to a sound wave, the capacitance between the two plates varies proportionally to the sound pressure. This change in capacitance then creates an output voltage that can be analysed. **Figure 17** shows the internal parts of the condenser type microphone.

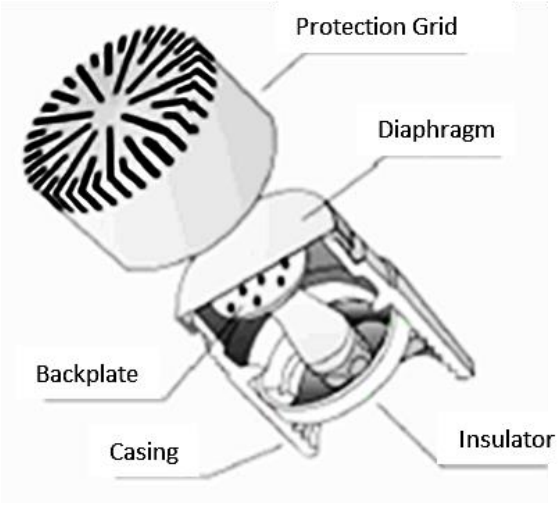

Figure 17. Capacitive microphone (National Instruments, 2016).

The externally polarized condenser microphone requires an external source to charge the capacitor while the prepolarized condenser microphone has a built-in amplifier. The specifications associated with a few condenser type microphones can be seen in **Table 7**.

Table 7. Condenser microphone specifications**.**

Vendor	Model	Diameter in (mm)	Type	Frequency Response (±1 dB) (Hz)	Nominal Sensitivity at 250 Hz (mV/Pa)
G.R.A.S	46AD	0.5 (12.7)	Pressure field	4 – 70,000	50
Bruel & Kjaer	4953	0.5 (12.7)	Pressure field	3 – 10,000	50

5.2.2 Piezoelectric Microphones

Piezoelectric microphones operate on the piezo effect, where a crystal structure is used to produce the back-plate voltage; generally an integrated amplifier is used to increase the output voltage. These microphones are typically used for high-amplitude sound wave detection. Specifications associated with a piezoelectric sensor are shown below:

- **Vendor**: Vesper
- **Model**: PMM-3738-VM1000-R
- **Frequency Response (±1 dB)**: 20 Hz to 8 kHz
- **Nominal Sensitivity (at 250 Hz)**: 12.6 mV/Pa

5.3 Ultrasonic

Ultrasonic sensors work on the principle of emitting a short, high-frequency sound pulse at regular intervals. When an object or material boundary is struck, the sound pulse is reflected back to the receiver at a specific amplitude and frequency. There are two main types of ultrasonic sensor modes including pulse-echo mode, where the sensor acts as both an emitter and receiver, as well as through-transmission mode where two ultrasonic transducers are used, one to generate the pulse wave and one to receive it. A diagram showing how a pulse echo-mode sensor detects an object is shown in **Figure 18**.

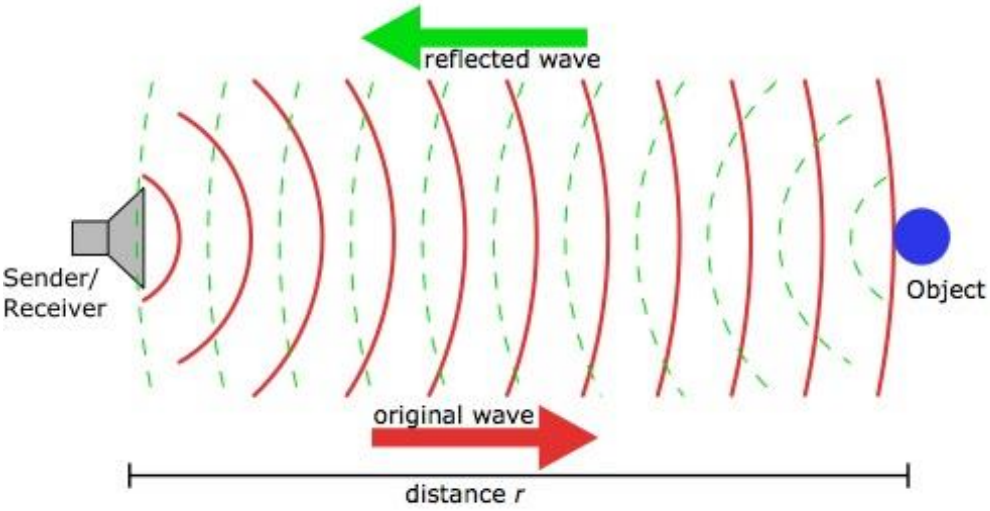

Figure 18. Working principle of a pulse-echo mode ultrasonic sensor (Sensor Wiki. 2016).

Ultrasonic sensors are generally used to detect the distance to an object or material boundary; however, they can also be used to detect the acoustic impedance of a material. Acoustic impedance is the measure of the resistance to sound wave propagation, which is directly proportional to the density of the material. The acoustic impedance of a material is also dependent on the frequency of the sound wave produced.

Using a pulse-echo mode ultrasonic sensor, grain loss on a combine could be monitored by measuring the acoustic impedance of the material (straw, chaff, and grain) passing between the sensor and a highly reflective back surface. The amplitude of the reflected pulse wave would indicate the amount of sound waves absorbed, deflected, and scattered by the material. Therefore, the higher the amplitude of reflected waves the less impedance (lower density) of the material and vice versa. By comparing this amplitude to a baseline value when no material is present (highest reflected amplitude), the amount of material leaving the combine could be monitored. As acoustic impedance of a material is dependent on the sound wave frequency, grain kernels could theoretically be targeted within a straw and chaff mix by using the proper sound pulse frequency. The change in moisture content of the harvest material however could make calibrating the sensor difficult as the material densities would change.

The specifications of a pulse-echo type ultrasonic sensor that could potentially be used in such an application is listed below.

- **Vendor**: MIDAS
- **Model**: 500ES430
- **Type**: Pulse-Echo
- **Frequency Response**: 20 to 100 kHz
- **Min Transmitting Sensitivity (at 50 kHz)**: 119 dB
- **Min Receiving Sensitivity (at 50 kHz)**: -42 dB

5.4 Photoelectric

Photoelectric sensors use light beams (either visible or infrared) to detect the distance or absence/presence of an object. These sensors consist of an emitter and receiver. Similar to ultrasonic sensors, the emitter and receiver can be separate (through-beam sensor) or be placed together in a single sensor (retro and diffuse reflective sensors). The emitter supplies a constant beam of light that is sensed by the receiver. When an object disrupts this light, the receiver detects this change and converts it to an electrical output.

The three main types of photoelectric sensors, through-beam, retro-reflective, and diffuse reflective, can be seen in **Figure 19**.

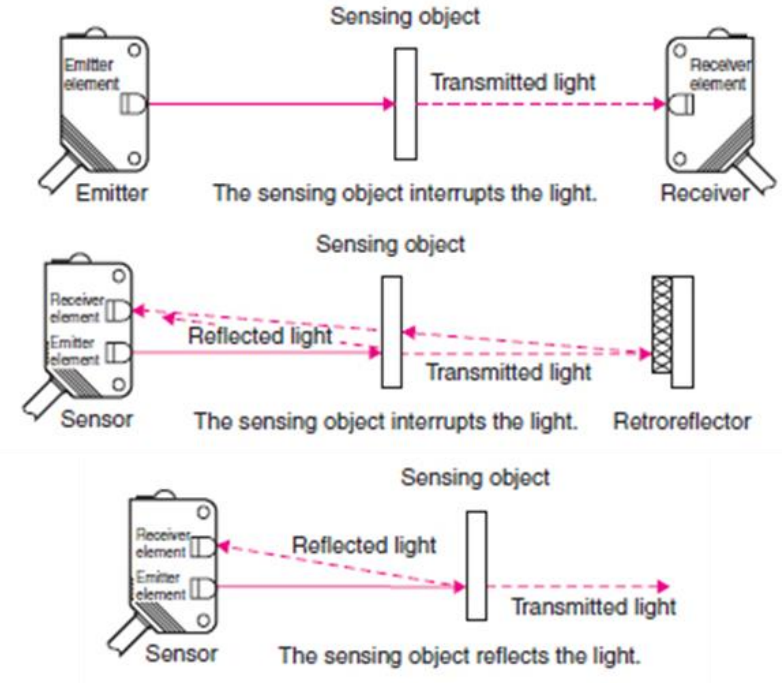

Figure 19. Three main types of photoelectric sensors - through-Beam (top), retro-reflective (middle), and diffuse reflective (bottom) (OMRON, 2017).

A single photoelectric sensor as used in most applications would be limited in its usefulness to detect grain loss as it can only detect objects along a single linear path. However, if an array of photoelectric sensors was used, a curtain or plane of detection could be produced where any material passing through could be detected. Curtain detection technology exists and is being used in industry today (e.g., the Banner EZ-Array shown in **Figure 20**).

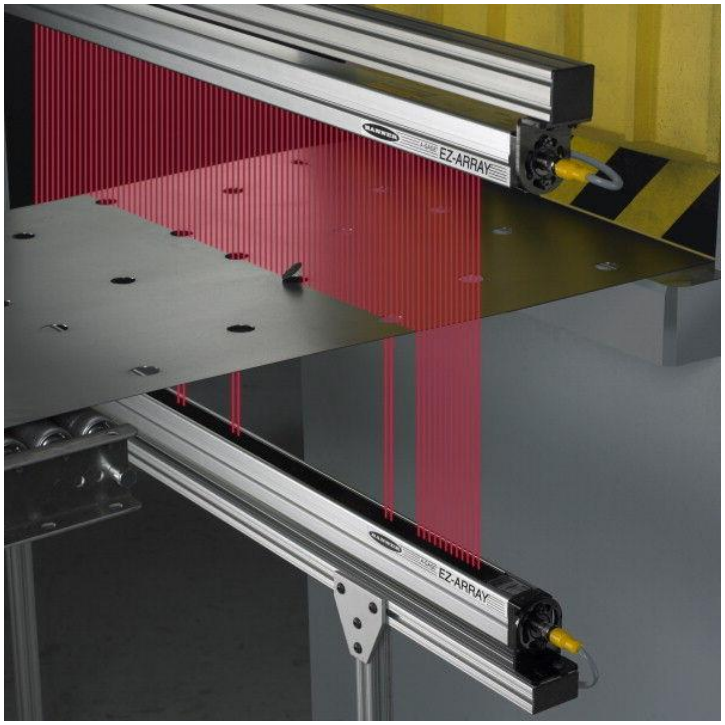

Figure 20. Banner EZ – Array (Banner, 2017).

The Banner EZ-Array is a type of through-beam sensor with a separate emitter and receiver. Some specifications associated with the Banner EZ-Array can be found below.

- **Available Lengths**: 5.9 to 94.5 in (150 to 2,400 mm)
- **Beam Spacing**: 0.2 in (5 mm)
- **Range**: 13.1 ft (4 m)
- **Light Source**: Infrared

The specifications show the sensor could, in theory, cover the entire opening at the rear of the cleaning shoe to detect material including grain loss exiting the rear of the combine. Depending which light beams are being triggered, the sensor could also be used to determine where in relation to the cleaning shoe the material is being lost, being blown over the cleaning shoe, or sluffing along the bottom. However, using this method would make distinguishing grain from MOG difficult as the light beams would detect both materials. This would limit the usefulness of this type of technology unless some type of selective conditioning could be imposed. Also, the accuracy of photoelectric sensors can

be negatively affected by dust and suspended particles in the air, further limiting its ability to be used in a grain loss application.

5.5 Microwave

Microwave sensors base their measurements on the Doppler principle to detect motion. High-frequency microwaves (24 or 125 GHz) are produced by the sensor to create a uniform field. The corresponding frequency and amplitude changes created by moving particles throughout this field can then be detected. Some common types of microwave sensor applications include such things as industrial- and security-type motion detection, medical screening, proximity detection, and non-obstructive mass flowrate of material. They have been found to be very accurate and reliable in detecting flow of powders and granular material in chutes or pneumatic conveying lines, which has been difficult to measure in the past.

The same principles used in monitoring mass flowrates could be applied to detecting grain loss. **Figure 21** shows an example of a microwave sensor being used to detect mass flow rate in an industrial application.

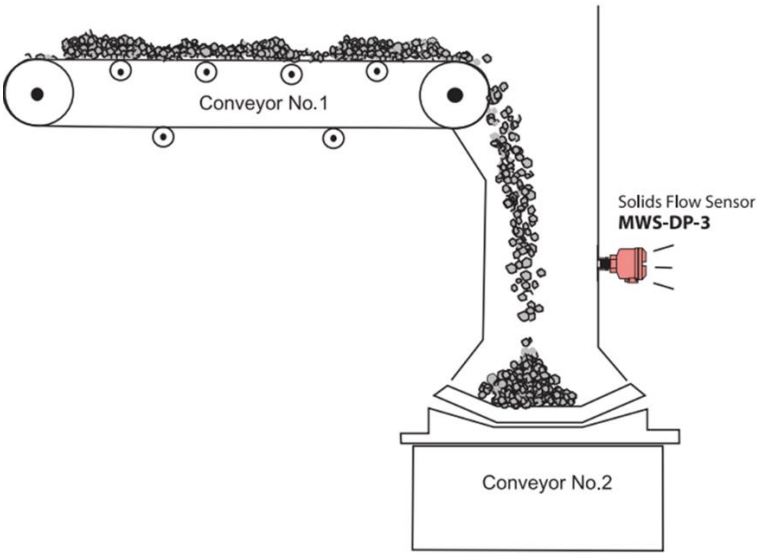

Figure 21. Microwave sensor used to determine mass flowrate (WADECO, 2017).

Similarly, the rate of lost grain kernels leaving the rear of the cleaning shoe could potentially be monitored by measuring the disturbance the grain kernels make while moving through a uniform frequency field. The specifications associated with one microwave based mass flowrate sensor can be found below. As seen, this specific sensor has a relatively large operating distance of 3.3 ft (1.5 m); however, this depends on the material being measured.

- **Vendor**: WADECO
- **Model**: MWS-SP-3

- **Detecting Method**: Doppler Principle
- **Frequency**: 24 GHz
- **Operating Distance**: up to 3.3 ft (1.5 m)

Again, the ability of the sensor to distinguish between grain and MOG is unknown.

6. Conclusions and Recommendations

This project investigated the ability to convert a combine loss sensor signal into an actual grain loss rate, so grain loss during harvest could be better managed. More specifically, the combine loss sensor signal was compared to actual grain loss to determine if a correlation exists with current technology or could exist with modified or alternative technology. Through the results obtained during lab and field testing, the strength of this correlation can now be realized and conclusions can be made about the practicality of using existing loss sensing technology to support an actual grain loss rate.

The combine loss sensor signal and actual grain loss generally showed a positive correlation when testing in peas and wheat, as the two sets of data followed the same general trend but showed a relatively poor correlation when testing in canola. The loss sensor signal correlation to actual grain loss was dependent on feed rate, and underestimated grain loss as feed rate increased in most cases. This was generally found to be true on the separator area in all crops and the cleaning shoe while field testing in peas and wheat. The correlation between the cleaning shoe loss sensor and actual grain loss was found to worsen as grain kernel size was reduced, with the best correlation in peas and the worst in canola.

To convert the loss sensor signal into a loss rate, relationship equations were produced for each crop and applied to the loss sensor signal. However, these relationship equations are dependent on total feed rate (actual not relative), which current combine technology has no means of measuring. Also, the dependency of the grain loss relationship (impacts per bushel of loss vs feed rate) on crop condition and combine settings as well as its change between combine makes and models requires more research to fully understand. Therefore, it can be concluded that the ability for existing loss sensing technology to provide an actual grain loss rate is limited; though the correlation to actual loss wasn’t consistent, for most conditions, the grain loss monitor system tested did provide a reliable indication of when actual loss was increasing or decreasing. In large grain crops, a grain loss rate could likely be determined through the use of relationship equations and correction factors. However, in small grain crops, sensor resolution proved to be insufficient to accurately support an actual grain loss rate, especially on the cleaning shoe. Some improvements to solve this issue included mounting the cleaning shoe loss sensor independent of the cleaning shoe, or implementing multiple sensors across the rear of the cleaning shoe to effectively increase sensor resolution.

Upon a review of other potential sensing technologies, several types showed promise in their ability to detect grain loss. Accelerometers and microphones could be implemented to detect grain kernel impacts through vibrational and acoustic pressure waves.

Ultrasonic and microwave-based technology could be used to detect grain loss through changes in acoustic impedance and field frequencies. Light-based technology was also reviewed in the photoelectric sensor where an array of sensors could be implemented to detect material discharged from the combine; however, this technology showed limitations in its practicality. Further research and development is required to determine the full capabilities of these technologies for this application.

7. Knowledge Transfer Activities

To date, the project has had exposure in the Humboldt Journal in the form of a news article that described the project purpose and plan as well as acted to garner attention and spread the importance of managing grain loss during harvest.

Future technology transfer activities will include the presentation of project results to the agriculture community including the media, producers, and manufacturers. This will include a media release (300-word article) on the project results once the project is completed as well as posting the report on PAMI's website. To further promote the importance of managing grain loss during harvest as well as help share the project results, posts via social media will be used including Twitter, Facebook and LinkedIn. Using these social media tools will provide an effective way to reach a broader selection of the public, producers and manufacturers throughout western Canada.

In addition, PAMI will be issuing a media release to major Saskatchewan and Western Canadian agricultural publications as well as PAMI producer networks and partners on the project results and findings.

8. Follow-up Research

To build on the knowledge gained from this initial project, further research and testing on alternative sensing technologies could be performed to better understand their full capabilities to detect grain loss on a combine harvester. This would involve selecting a few of the most promising technologies and through field testing determine the performance of each technology including if and how well the sensor technology can distinguish between grain and MOG. Also, the improvements suggested to existing sensing technology could be tested to determine how it effects the correlation between the loss signal and grain loss.

The ability of existing technology to measure grain loss could be explored across different makes and models of combines. The design of most grain loss sensors is similar across makes and models; however, there are slight differences such as sensor position, sensor type, and flow characteristics (how the material flows through the combine) that might make one design more effective than another. How these differences affect the grain loss signal correlation can be used to support the development of a prototype grain loss rate system. In addition, the grain loss signal correlation requires more testing to verify the results found in this report. Specifically, the consistency of the grain loss relationship (impacts per bushel of loss over a range of feed rates) needs to be verified in different crop conditions and perhaps more crop types to determine how these factors affect the relationship.

Another important area to investigate is the ability of current combine technology to accurately measure MOG feed rate. Some combine models are currently measuring relative feed rate for functions such as auto feed rate or adaptive cruise control but are not measuring actual feed rate. Testing the ability of these technologies to accurately measure MOG feed rate would provide valuable information on the ability of current technology to support a grain loss rate. Also, as the loss sensors tested provided a relatively reliable indication of grain loss in many cases, further work could be done to develop a functional app for a tablet using the current loss sensing technology. This could be used as an initial proof-of-concept build and help promote further research into actual grain loss detection.

Finally, to better manage grain loss, additional research should be conducted on real time feedback of separator and cleaning shoe performance. This could be done by placing sensors (similar to grain loss sensors) to detect the flow of grain throughout the separator and cleaning shoe systems. This might be done on the cleaning shoe by placing sensors underneath the chaffer and bottom sieve (along the total length) to determine where in relation along the cleaning shoe and in what percentage the grain is falling through. Similarly, sensors could be placed along the length of the separator area

to determine where in relation to the length of the separator the grain is being separated from the MOG. This would be very useful information in both managing grain loss and properly setting the combine, and like the grain loss sensors could be configured into a tablet app to be monitored in real time during harvest.

9. References

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Appendix A

Raw Loss Sensor Data from Lab Tests

Lab tests were performed on the combine loss sensors (both separator and cleaning shoe sensors) prior to field testing to determine the signal characteristics across grain types. From these signal characteristics, the data acquisition equipment settings could be optimized, such as sample frequency, gain setting, and filter frequency. Multiple tests were performed at a seed drop height of approximately 4 in (10 cm), the following figures show a summary of representative signals from both the separator and cleaning shoe across the three grain types.

Figures A-1 to **A-3** show the raw data collected from dropping approximately 10 grain kernels one second apart of each of the grain type (peas, wheat, and canola, respectively) on the cleaning shoe sensor.

Figures A-4 to **A-6** show the raw data collected from dropping multiple seeds on the separator sensor, simulating a high loss scenario in peas, wheat, and canola respectively.

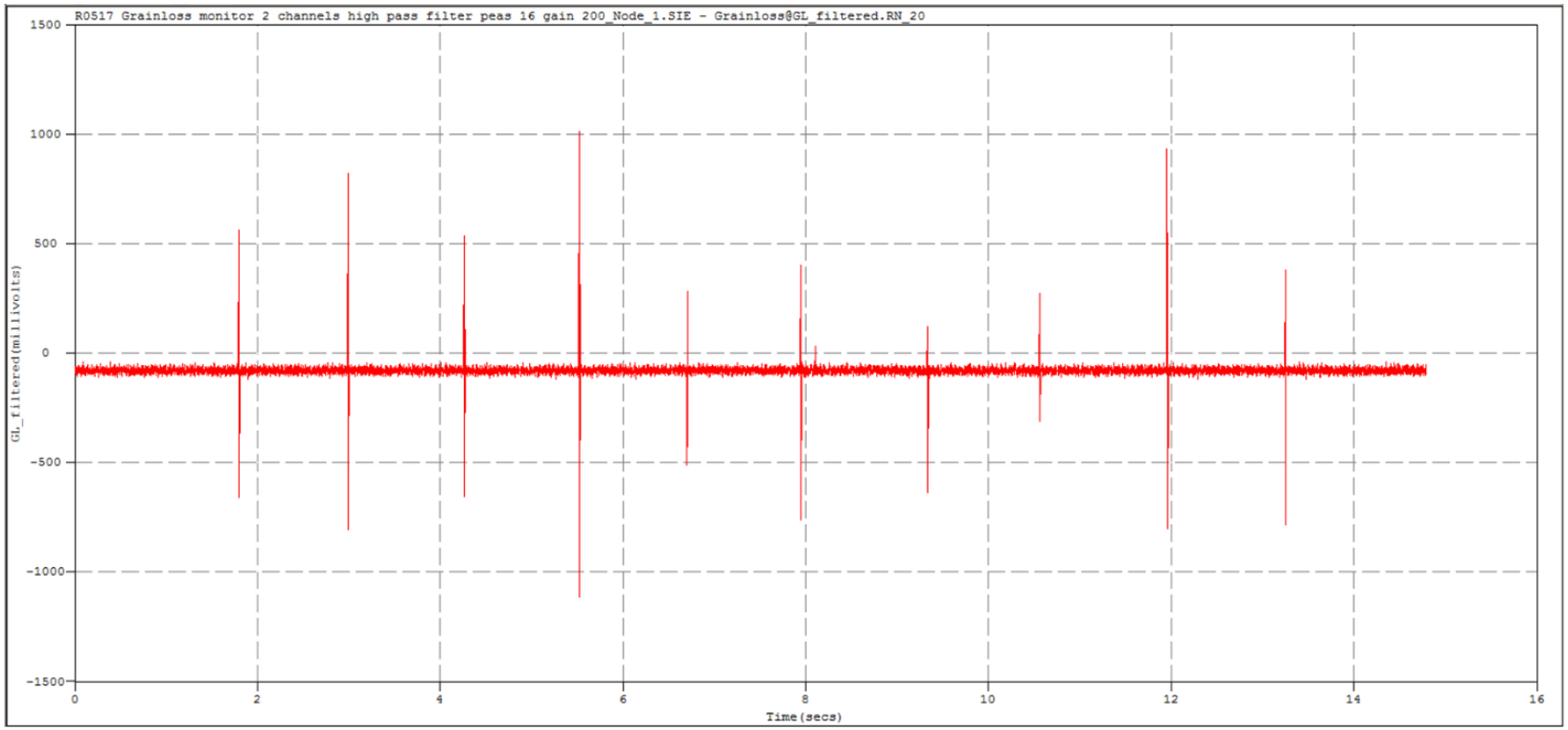

Figure A-1. Cleaning shoe sensor output for peas (individual kernels dropped).

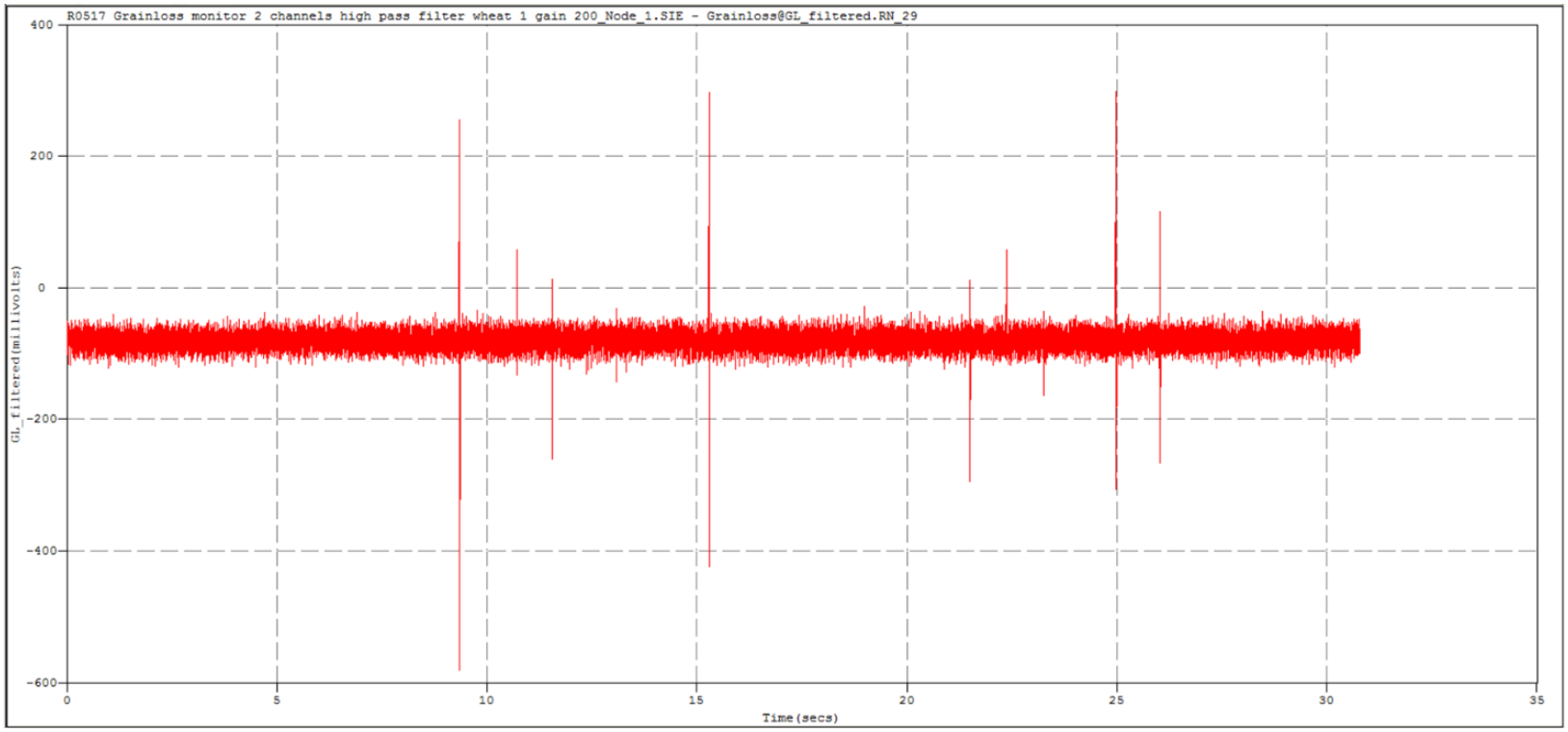

Figure A-2. Cleaning shoe sensor output for wheat (individual kernels dropped).

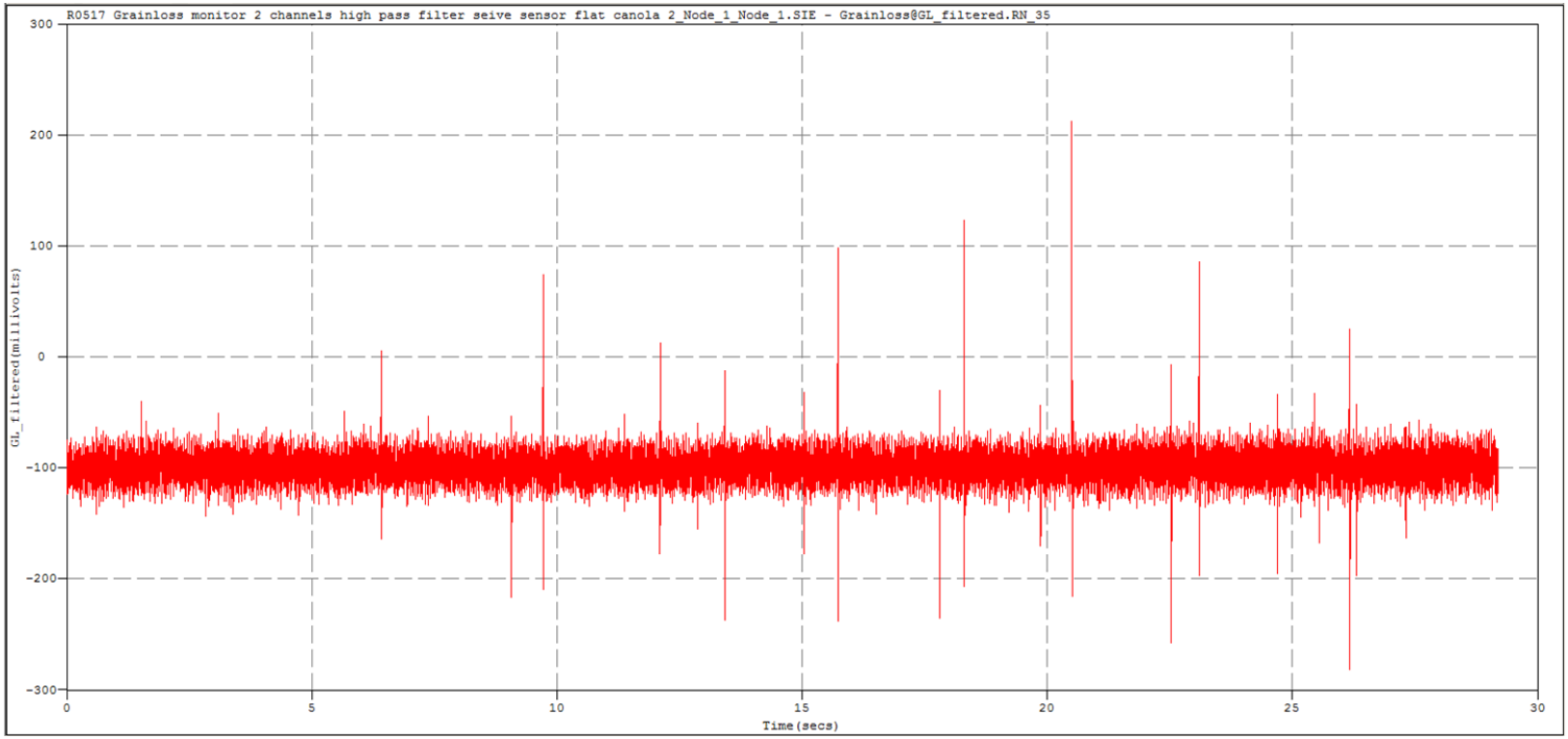

Figure A-3. Cleaning shoe sensor output for canola (individual kernels dropped).

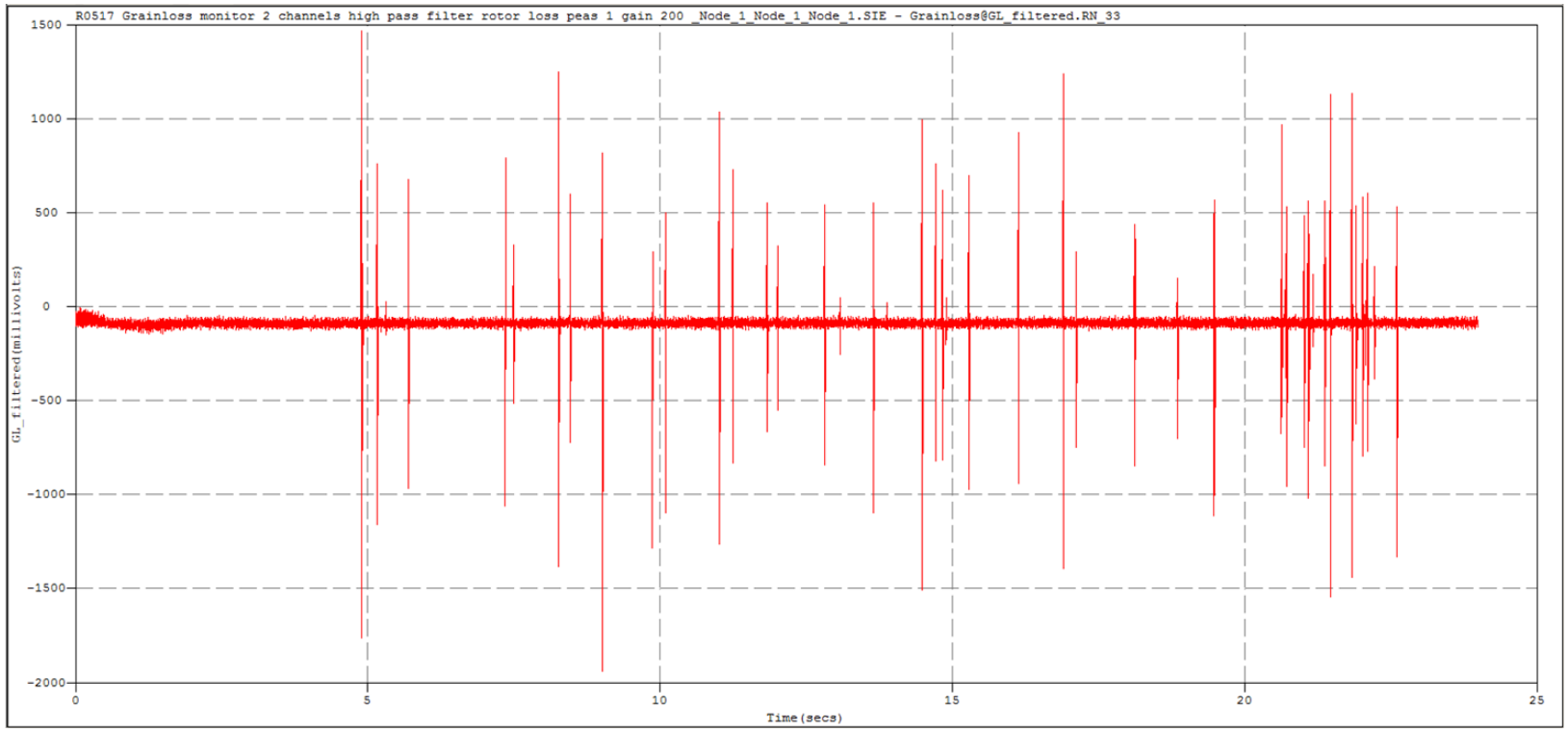

Figure A-4. Separator sensor output for peas (multiple kernels dropped).

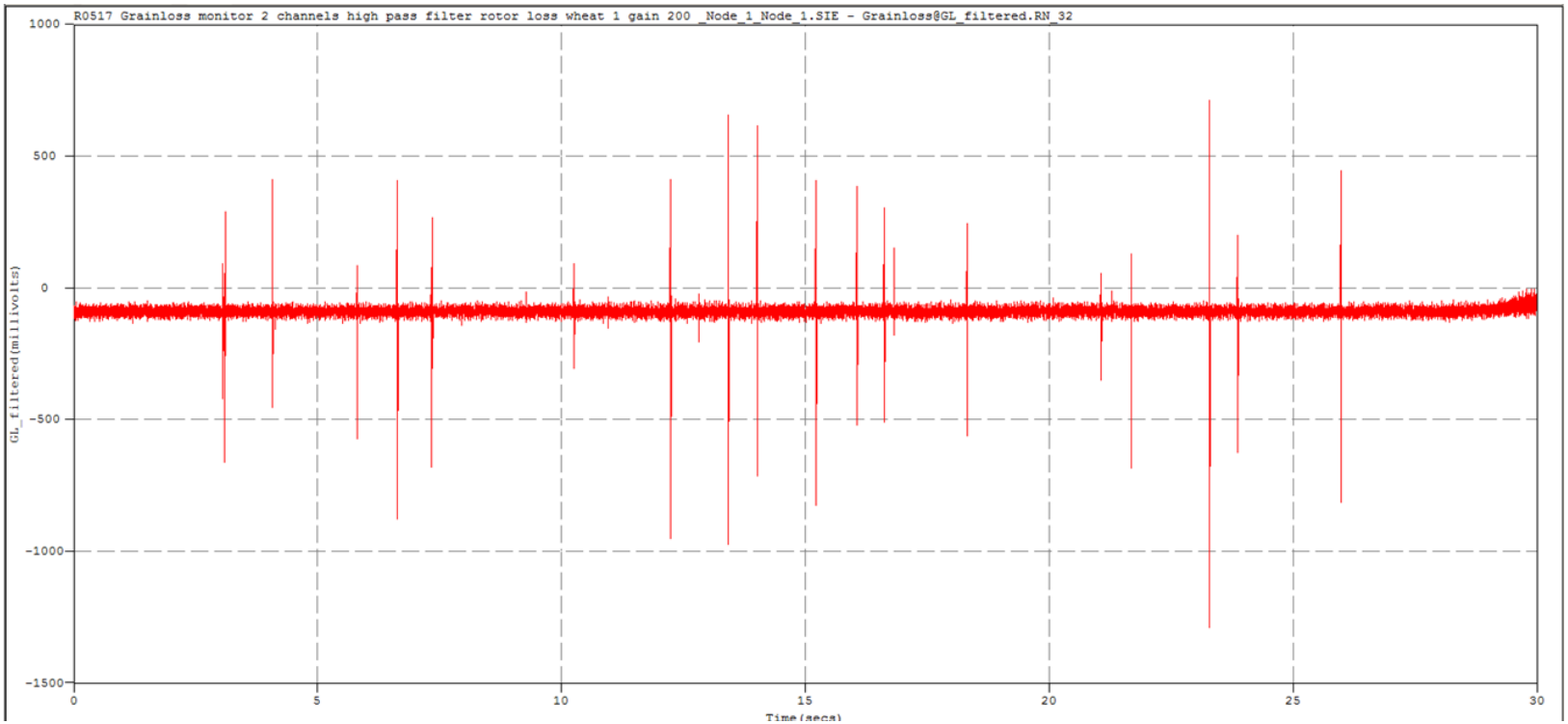

Figure A-5. Separator sensor output for wheat (multiple kernels dropped).

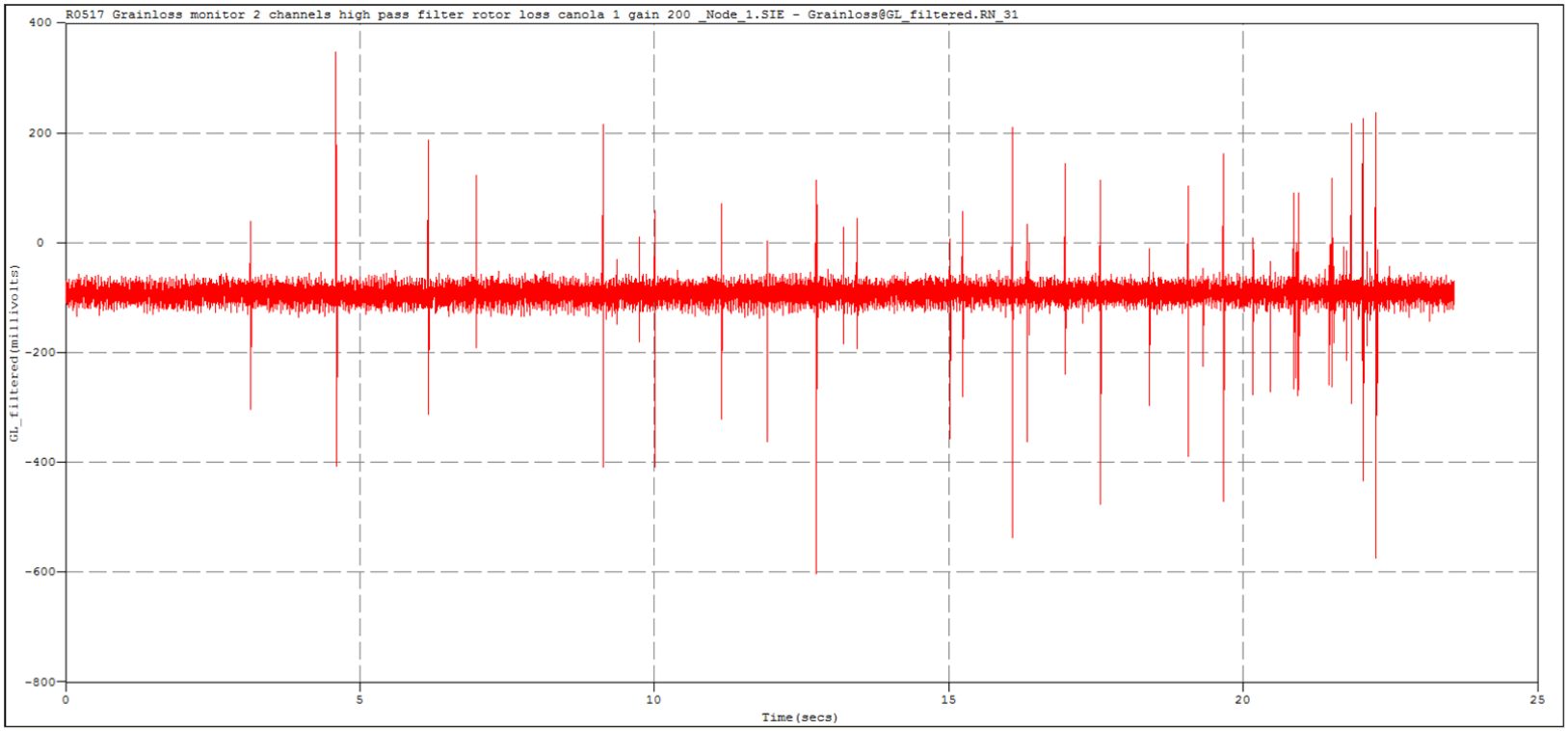

Figure A-6. Separator sensor output for canola (multiple kernels dropped).

Appendix B

Raw Loss Sensor Data from Field Tests

The raw data recorded during a representative field test in peas, wheat, and canola were graphed using Infield so the signal characteristics could be analysed. The entire data for the run was graphed as well as a five second snapshot of the signal during the test period that can be seen in **Figure B-1** through **Figure B-6**. The figures show the right separator, left separator, and cleaning shoe loss sensors signal from top to bottom, respectively. Also, note that a start switch was integrated into the data logging equipment when field testing in wheat and canola, seen at the bottom of the graphs. This ensured the data recorded during the test period could easily be extracted for data analysis.

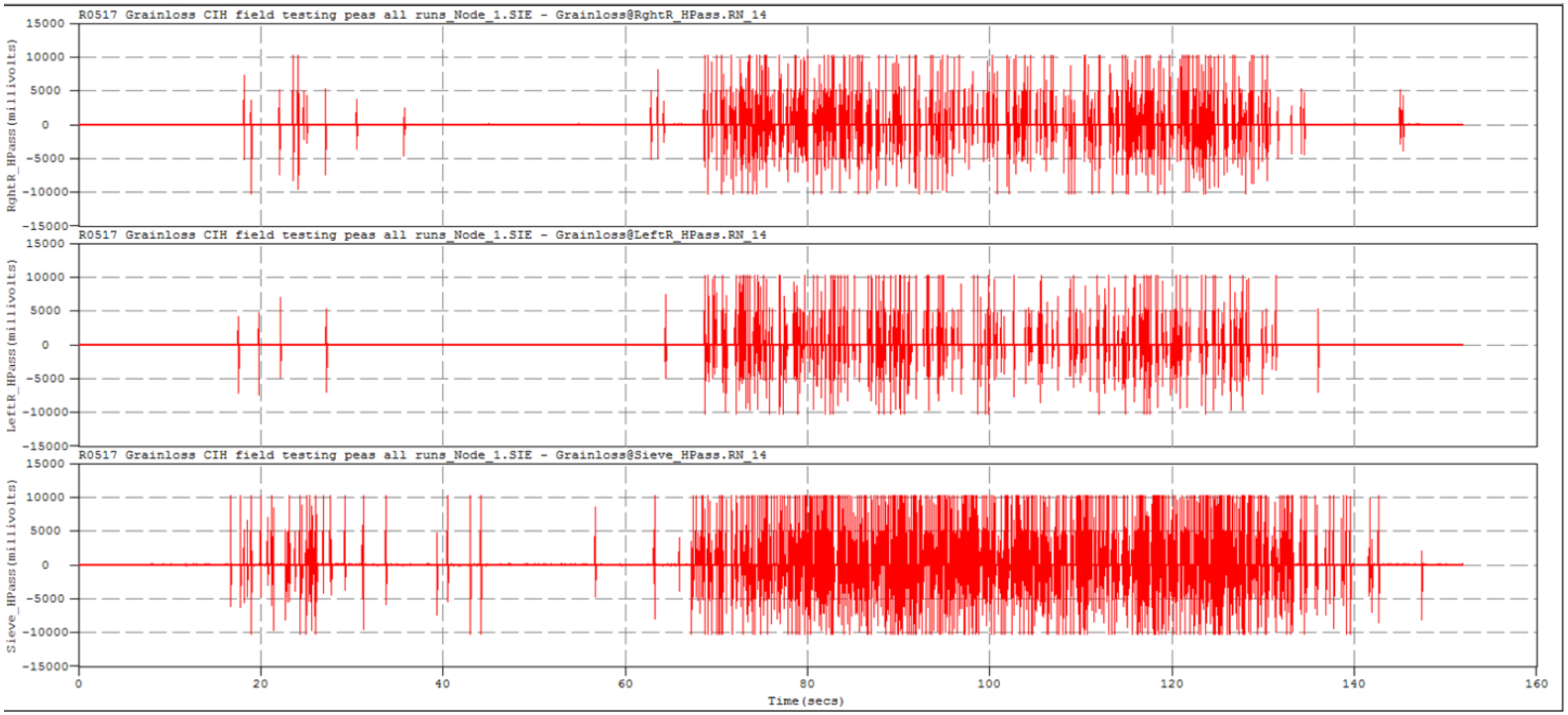

Figure B-1. Pea loss sensor data (full test).

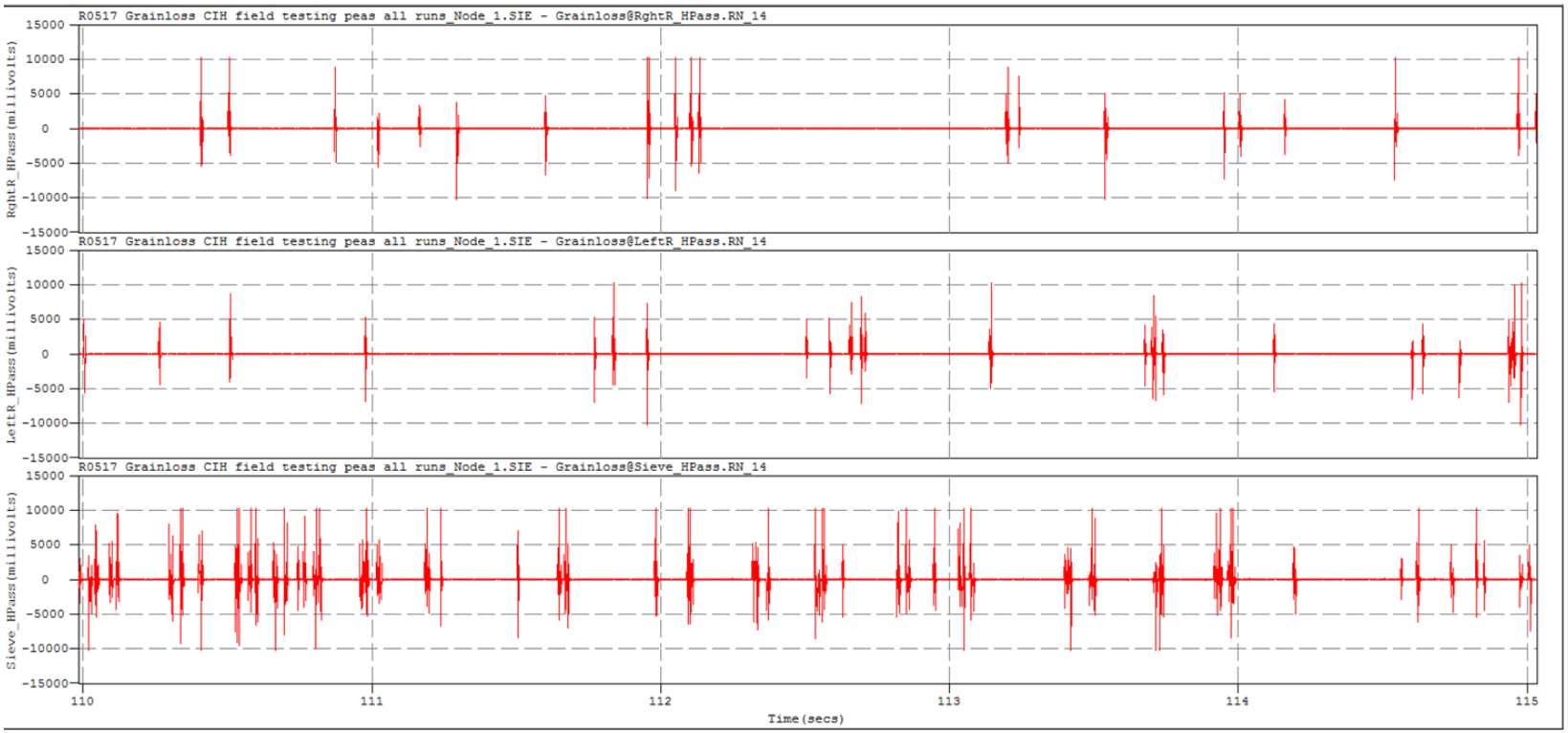

Figure B-2. Pea loss sensor data (five second section during test period).

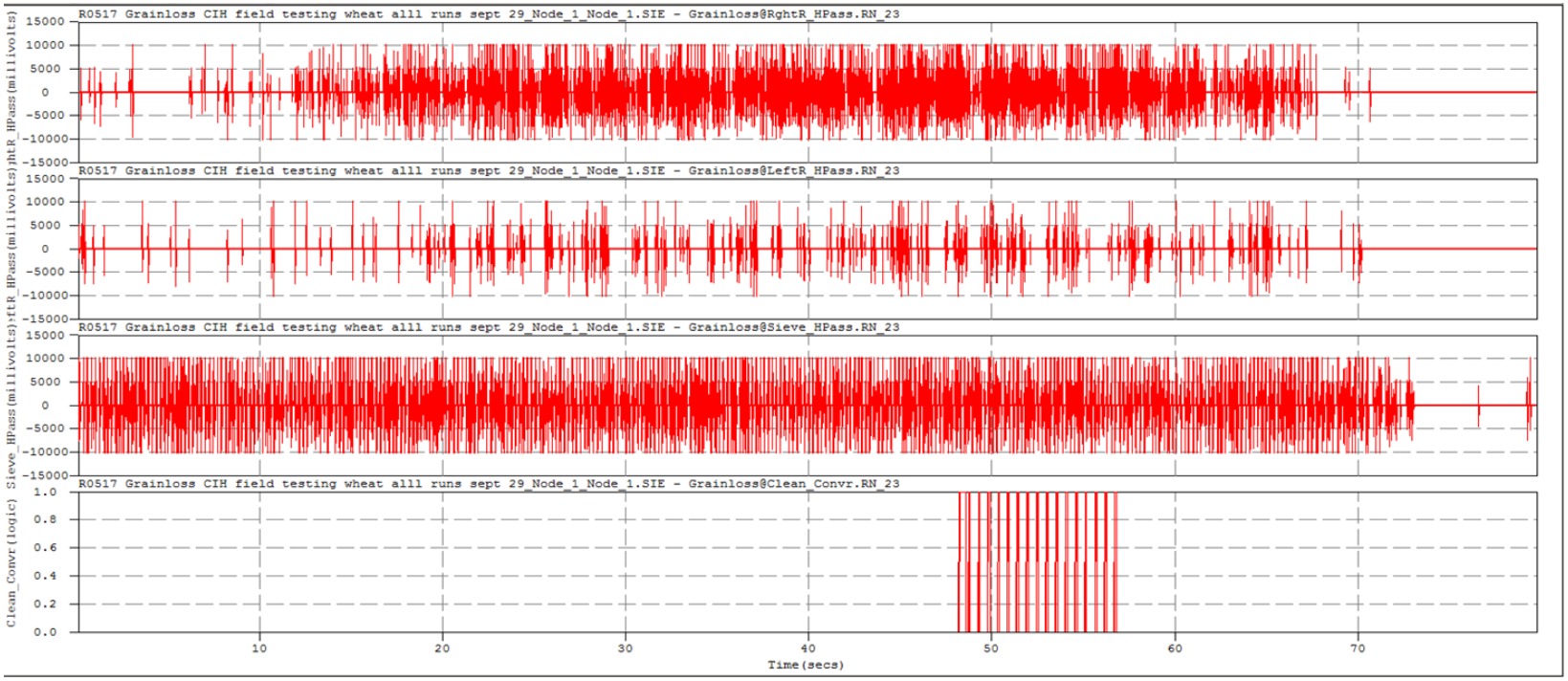

Figure B-3. Wheat loss sensor data (full test).

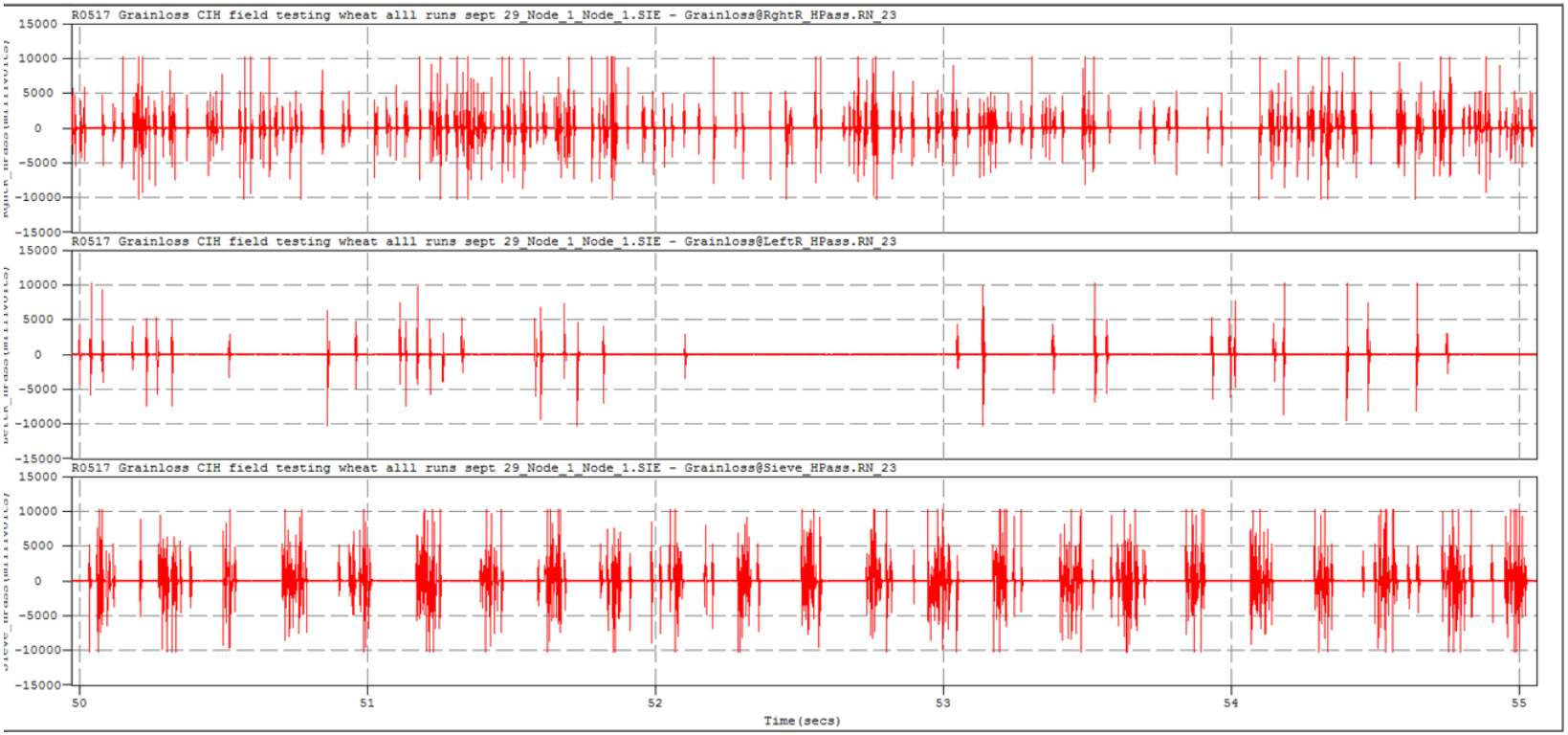

Figure B-4. Wheat loss sensor data (five second section during test period).

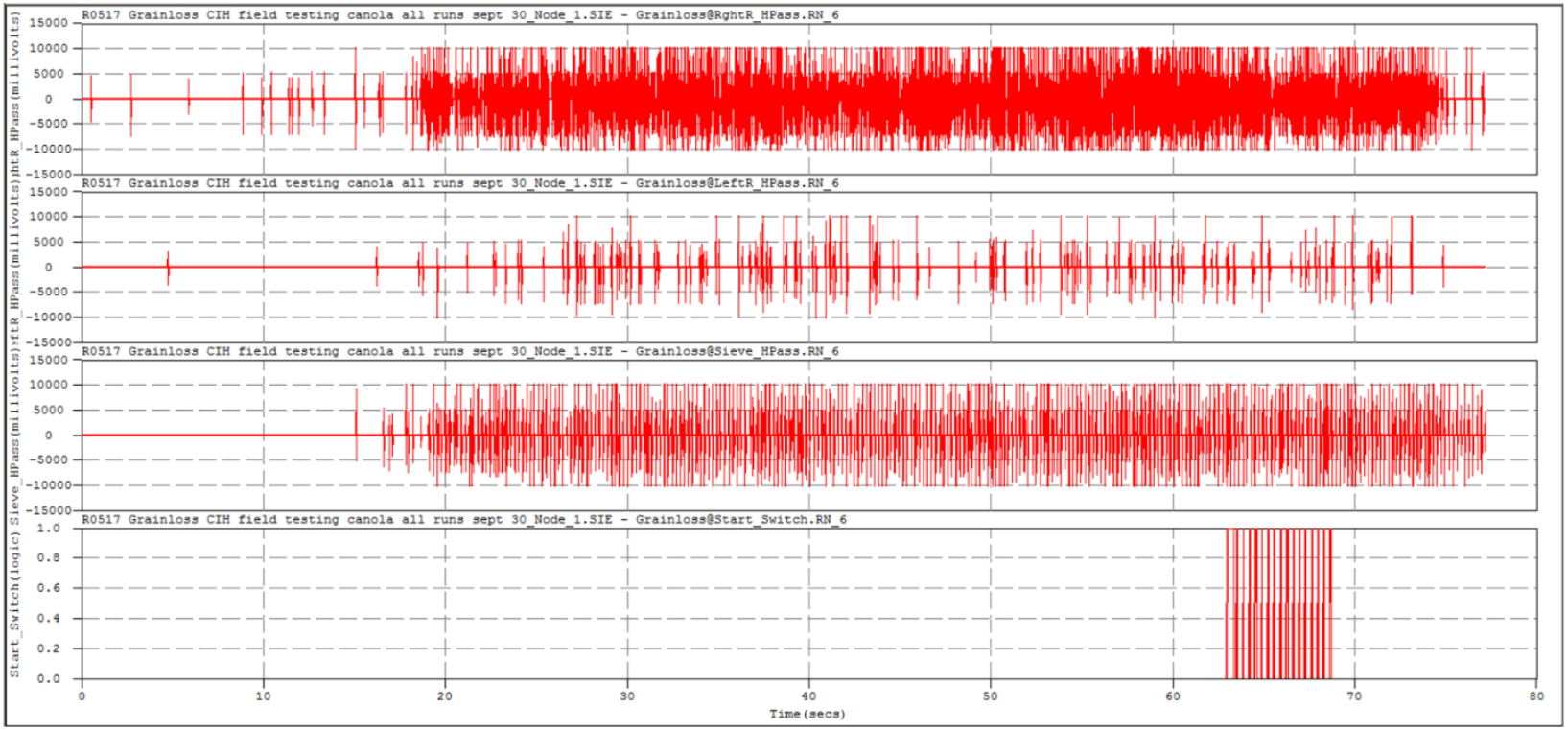

Figure B-5. Canola loss sensor data (full test).

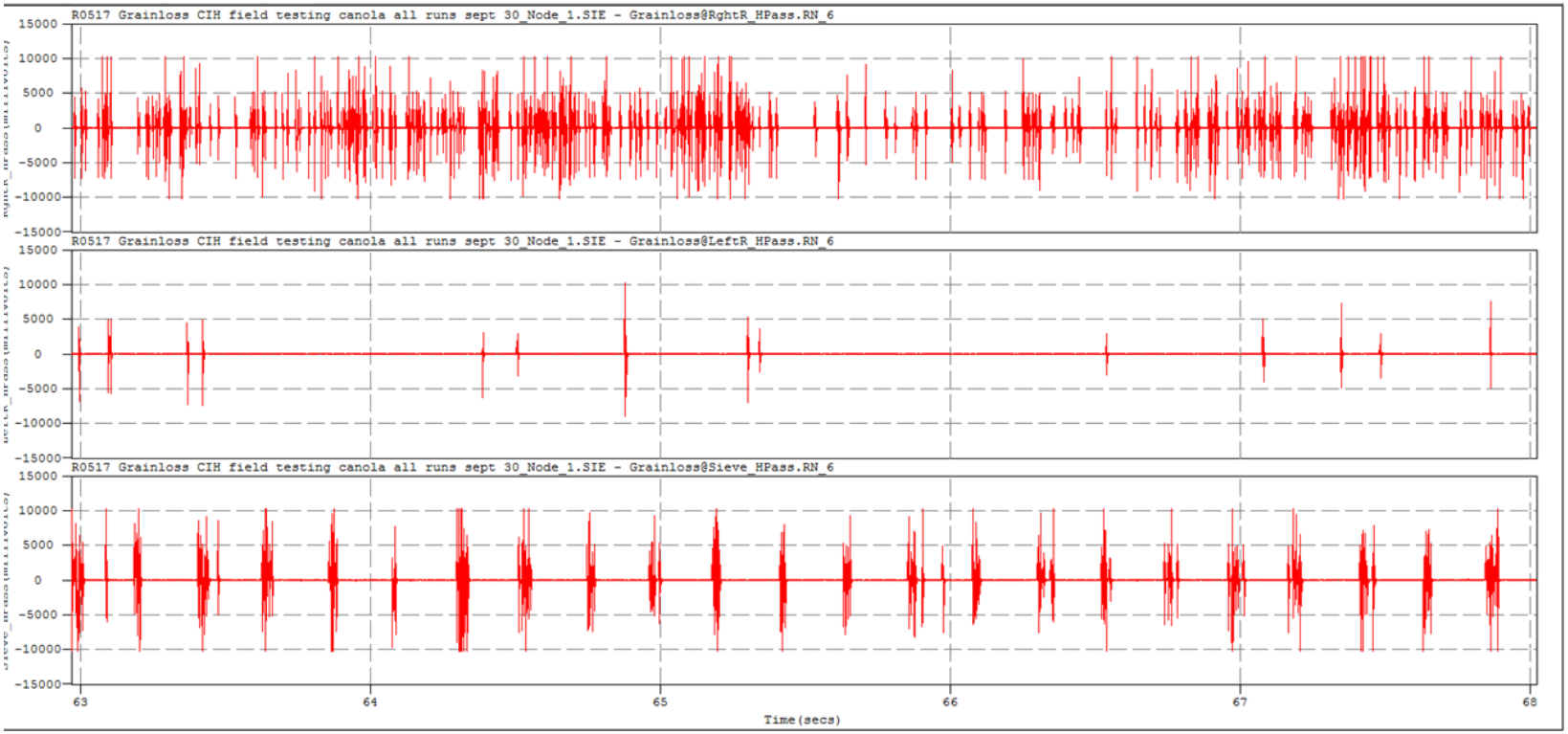

Figure B-6. Canola loss sensor data (five second section of test period).

Appendix C

Grain Loss Curves - Optimum Settings

The following graphs show actual grain loss plotted alongside the sensed grain loss (both monitor data and loss sensor data) for both the separating area and cleaning shoe over a range of feed rates.

The loss sensor sensitivities were set to 84 and 16 for the separator and cleaning shoe loss sensors, respectively. The separator loss curves when testing in peas are shown in **Figure C-1** and **Figure C-2**. Note, **Figure C-1** to **C-4** are for reference and are duplicates of **Figure 10** to **19** from **Section 4.3.3**.

Peas – Separator Loss

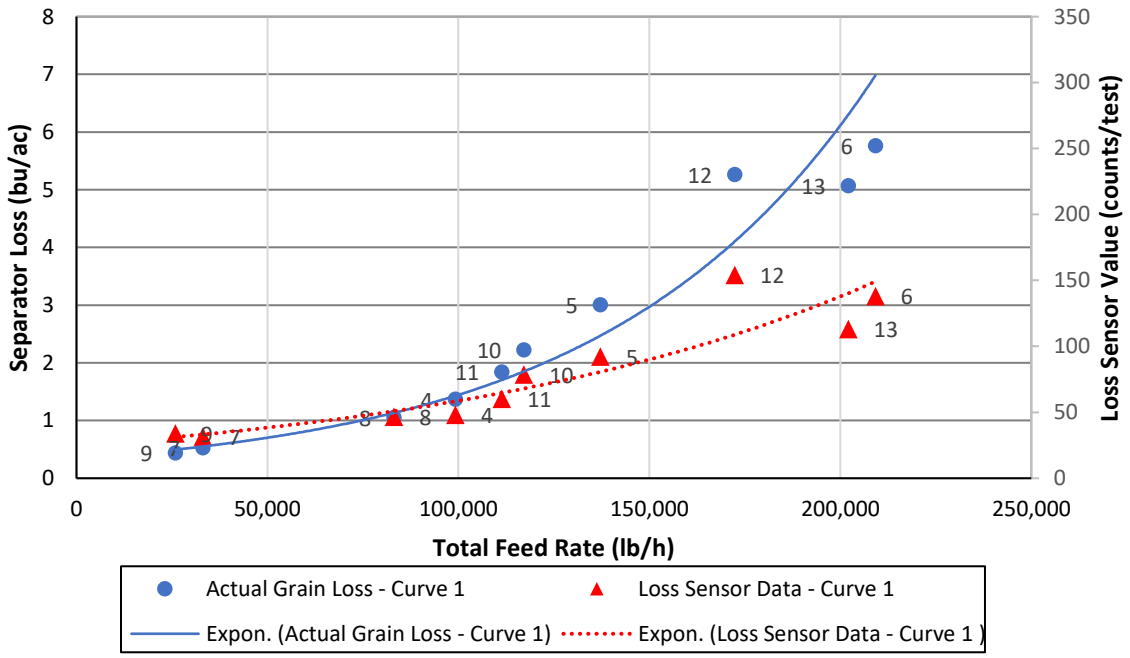

Figure C-1. Actual grain loss and loss sensor curves on separator area in peas.

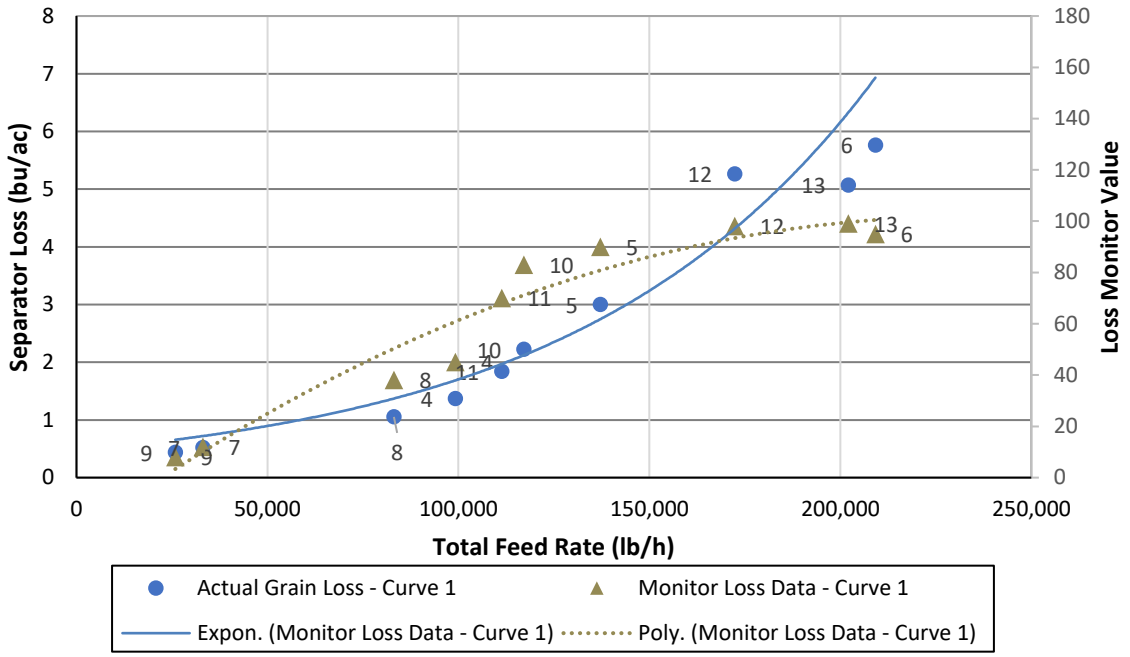

Figure C-2. Actual grain loss and monitor loss curves on separator area in peas.

Peas – Cleaning Shoe Loss

The cleaning shoe loss curves when testing in peas can be seen in **Figure C-3** and **Figure C-4.**

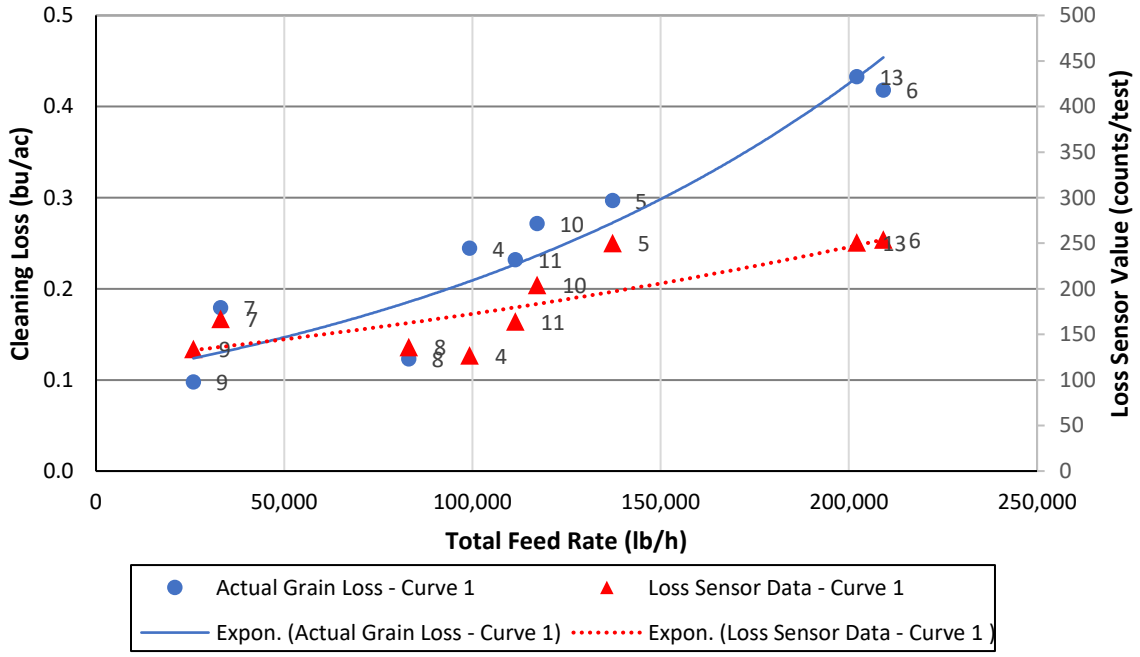

Figure C-3. Actual grain loss and loss sensor curves on cleaning shoe in peas**.**

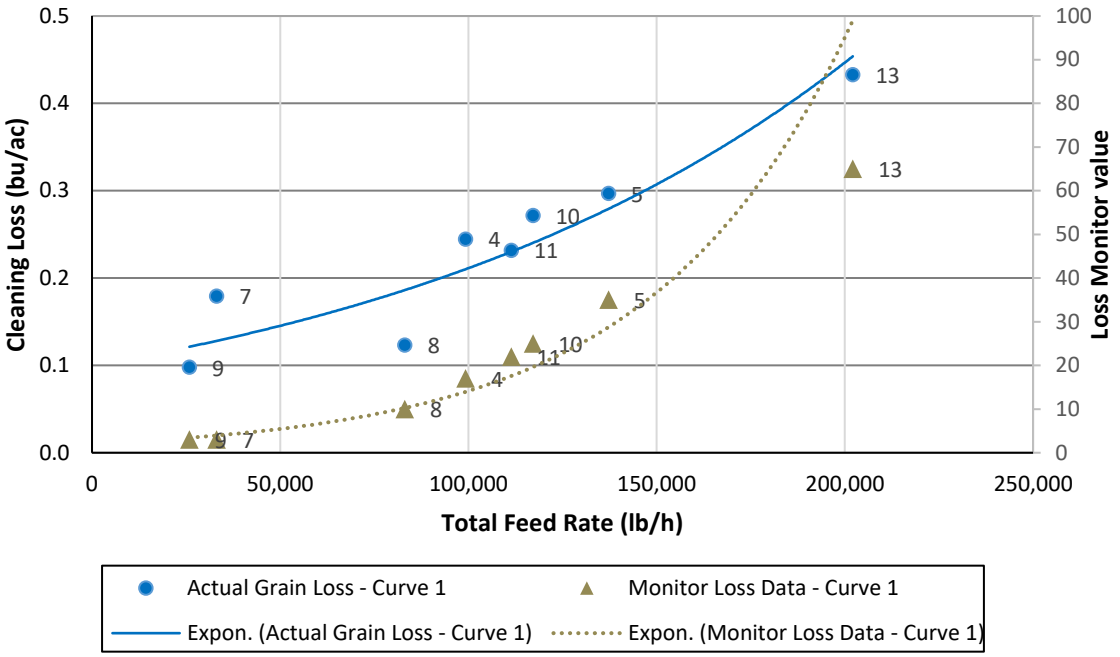

Figure C-4. Actual grain loss and monitor loss curves on cleaning shoe in peas.

The same graphs were produced for wheat, where the separator loss curves are shown in **Figure C-5** and **Figure C-6**. For this loss curve, the separator and cleaning shoe loss sensor sensitivities were set to 70 and 30, respectively.

Wheat – Separator Loss

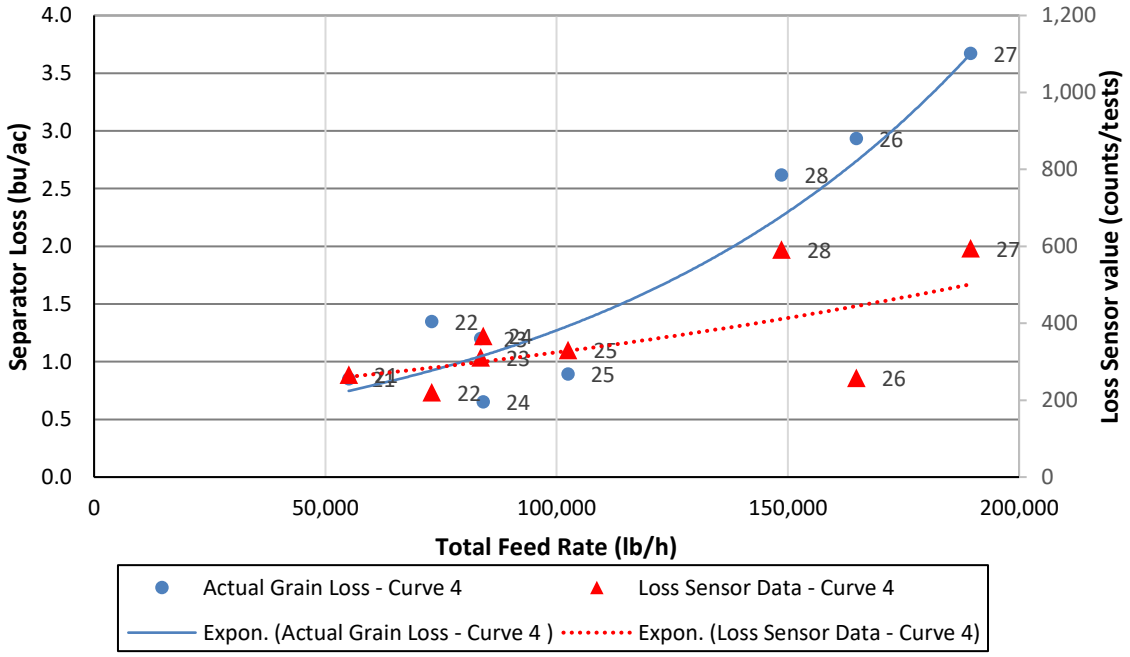

Figure C-5. Actual grain loss and loss sensor curves on separator area in wheat.

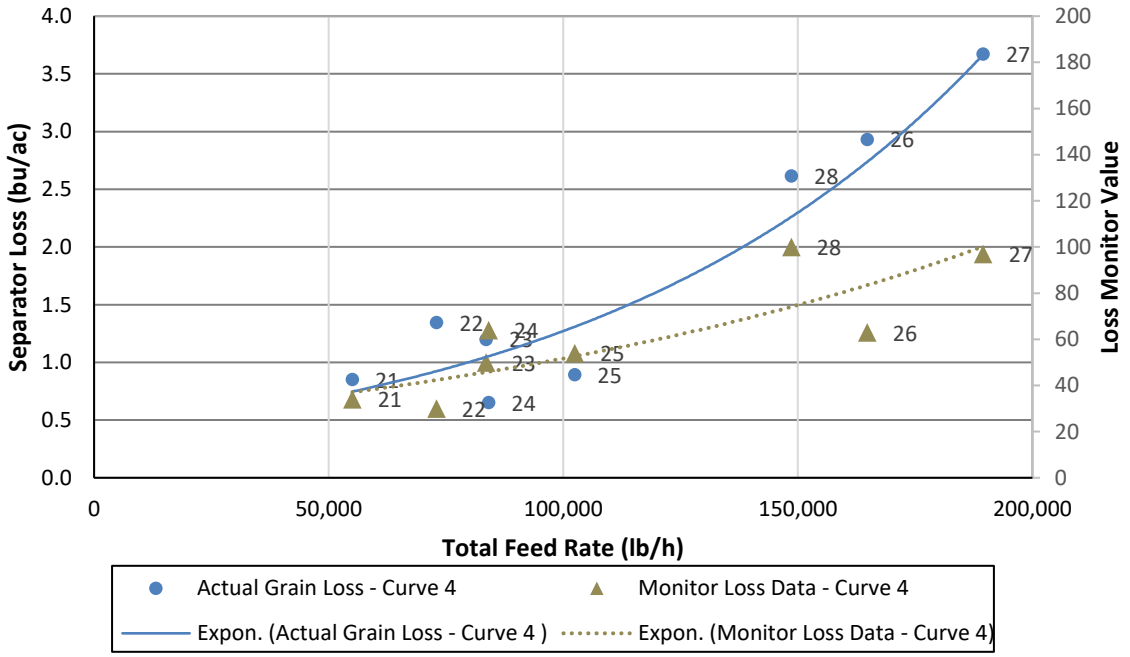

Figure C-6. Actual grain loss and monitor loss curves on separator area in wheat.

Wheat – Cleaning Shoe Loss

The cleaning shoe loss curves when testing in wheat are shown in **Figure C-7** and **Figure C-8**.

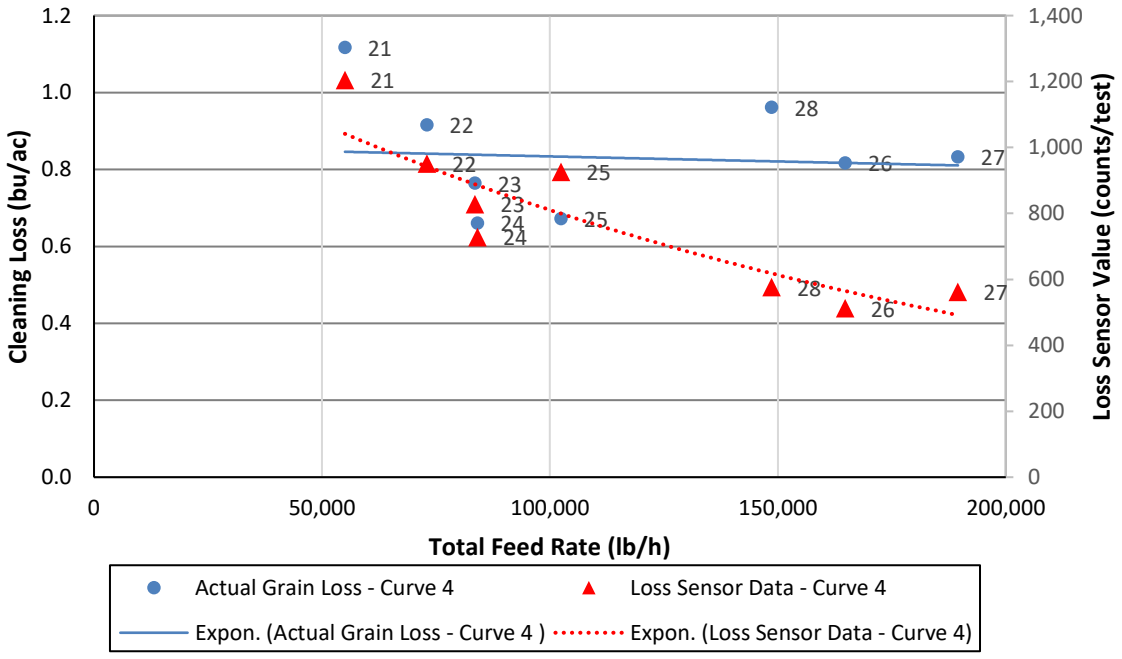

Figure C-7. Actual grain loss and loss sensor curves on the cleaning shoe in wheat.

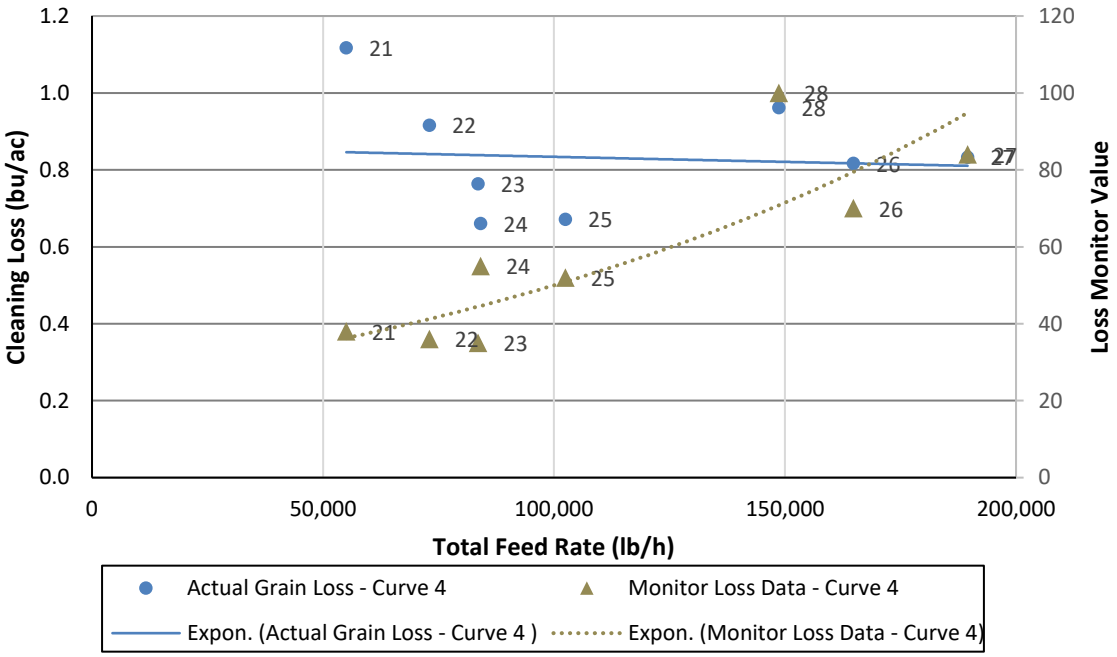

Figure C-8. Actual grain loss and monitor loss curves on the cleaning shoe in wheat.

Similar graphs were also produced for canola, where the separator loss curves are shown in **Figure C-9** and **Figure C-10**. The separator and cleaning shoe loss sensitivities were set to the same values as when testing in wheat at 70 and 30, respectively.

Canola – Separator Loss

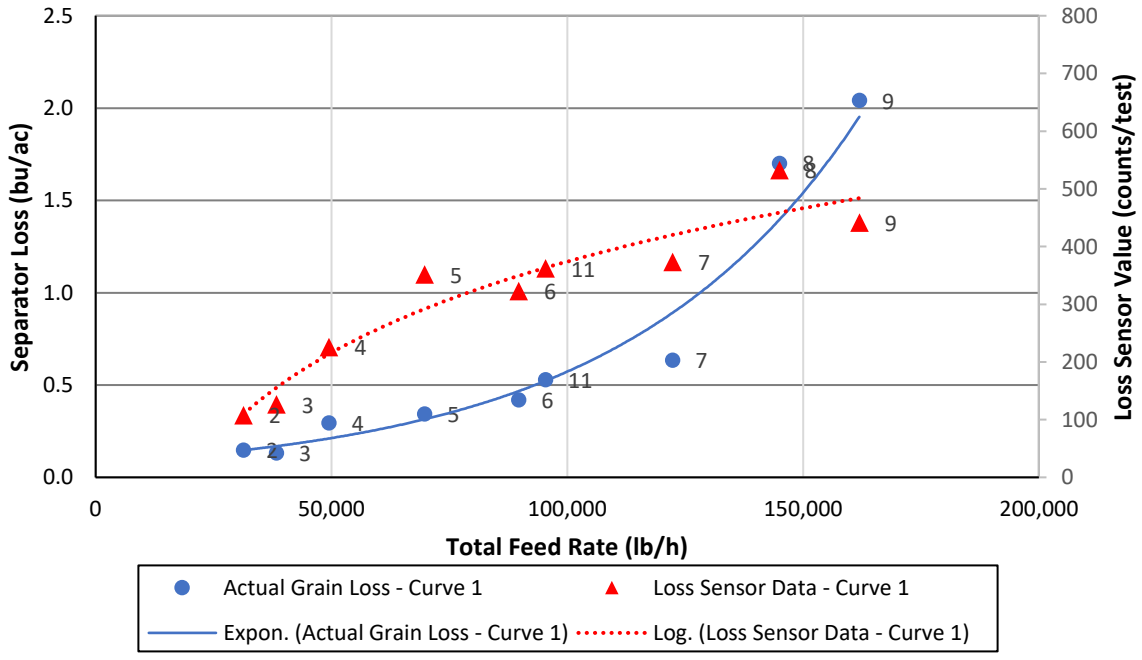

Figure C-9. Actual grain loss and loss sensor curves on separator area in canola.

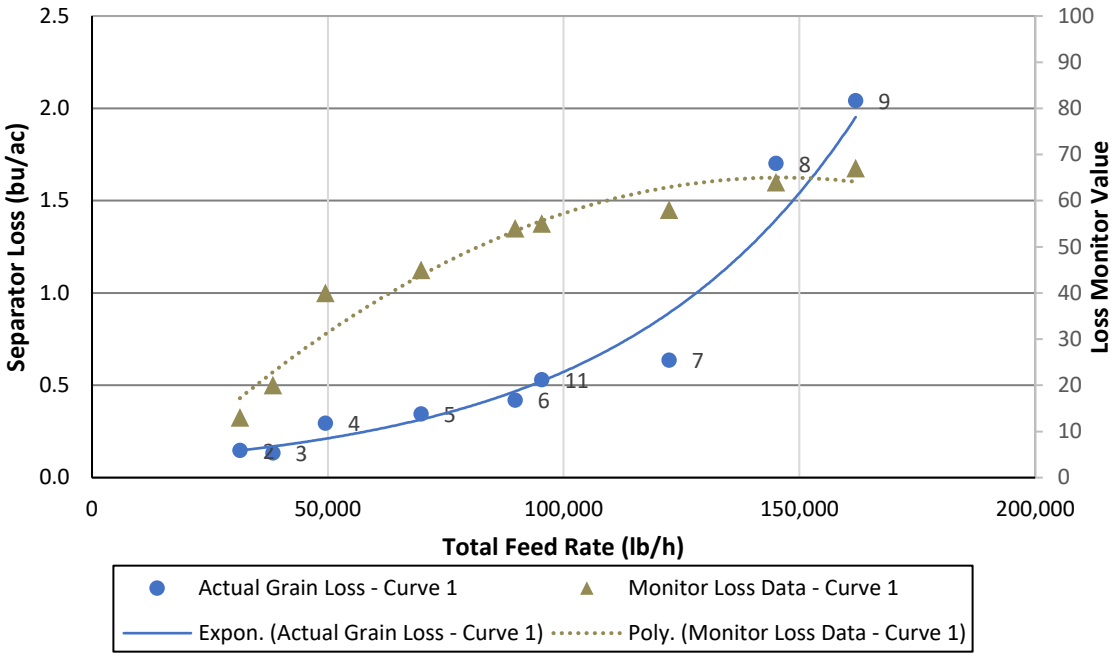

Figure C-10. Actual grain loss and monitor loss curves on separator area in canola.

Canola – Cleaning Shoe Loss

The cleaning shoe loss curves when testing in canola are shown in **Figure C-11** and **Figure C-12**.

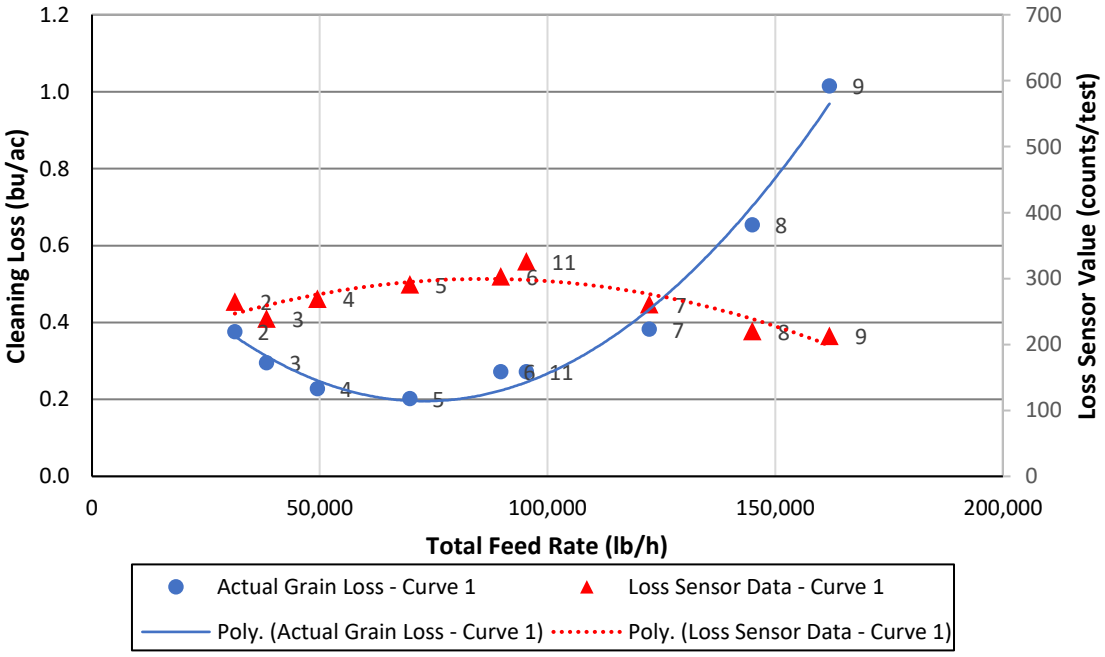

Figure C-11. Actual grain loss and loss sensor curves on the cleaning shoe in canola.

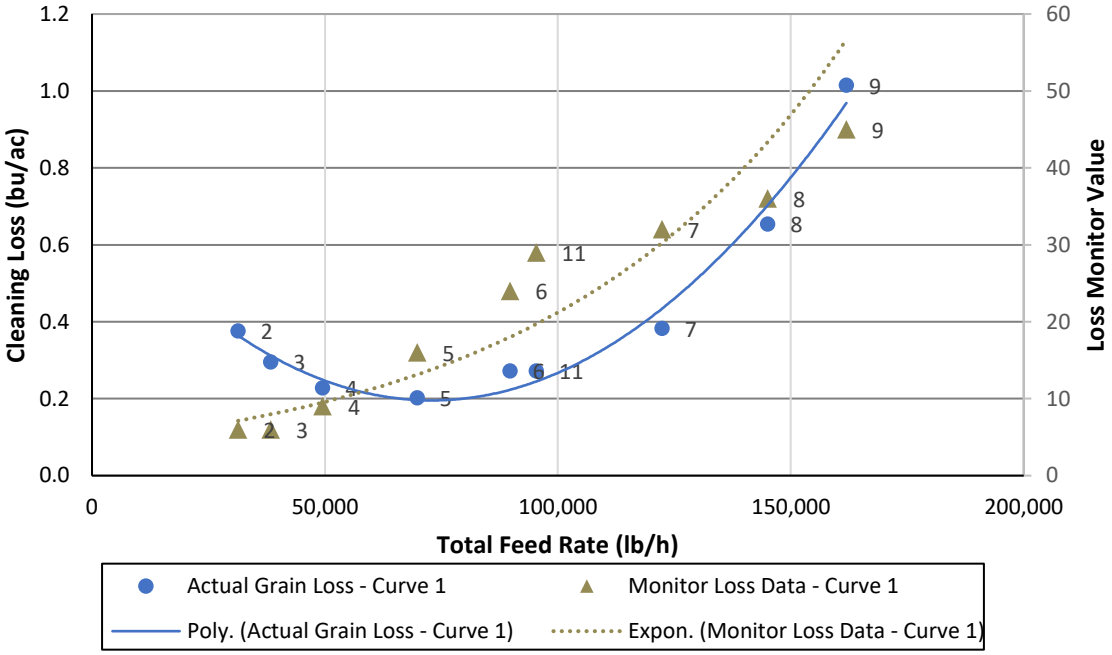

Figure C-12. Actual grain loss and monitor loss curves on the cleaning shoe in canola.

Appendix D

Loss Curves – Varying Combine Settings in Canola

The following grain loss curves show the actual loss plotted alongside the sensed grain loss (monitor loss data and loss sensor data) on the cleaning shoe and separator as combine settings were varied while testing in canola.

Two curves were produced to create high-loss scenarios on the cleaning shoe, including blow over and sluffing. These scenarios involved varying the fan speed to blow the grain kernels over the cleaning shoe sensor as well as varying the sieve gap to produce a mat of material moving across the chaffer.

Figures D-3 and **D-4** show the effect high fan speed had on the cleaning shoe loss sensor accuracy in canola (100 rpm over optimum setting, all other settings remained at optimum), while **Figures D-7** and **D-8** show the effect of decreased upper sieve gap (optimum setting reduced by 0.12 in (3 mm), all other settings remained at optimum setting) on sensor accuracy. The accompanying separator graphs can also be seen in **Figures D-1** and **D-2** for the blow over scenario and **Figures D-5** and **Figure D-6** for the sluffing scenario.

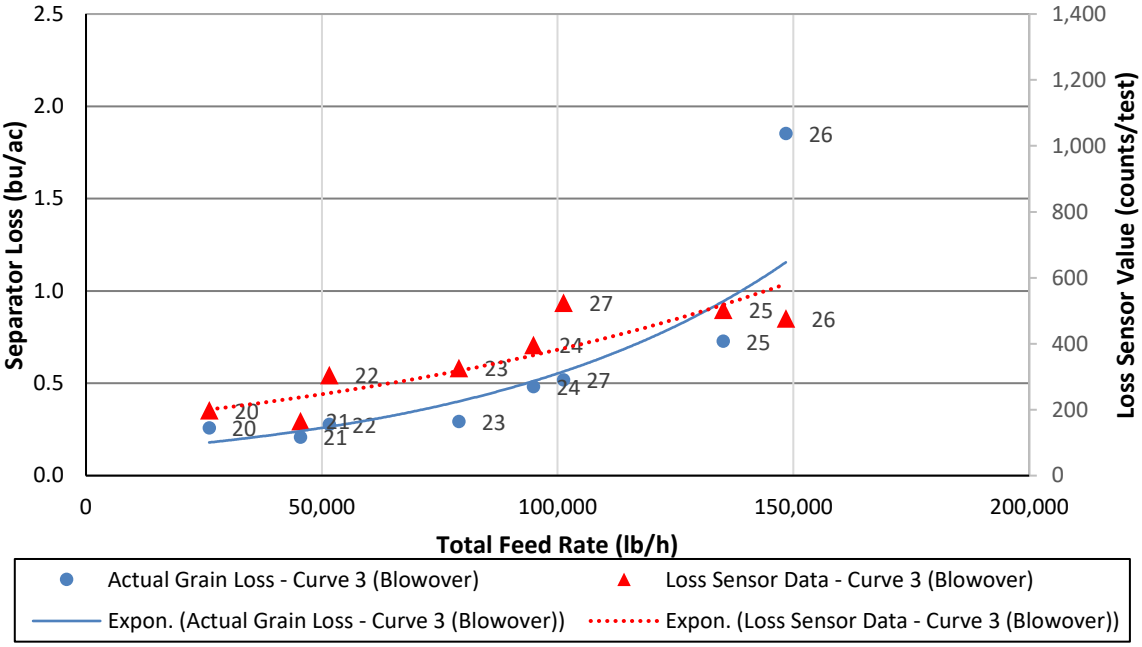

Figure D-1. Actual grain loss and loss sensor curves on the separator in canola – blowover scenario (fan speed: 700 rpm).

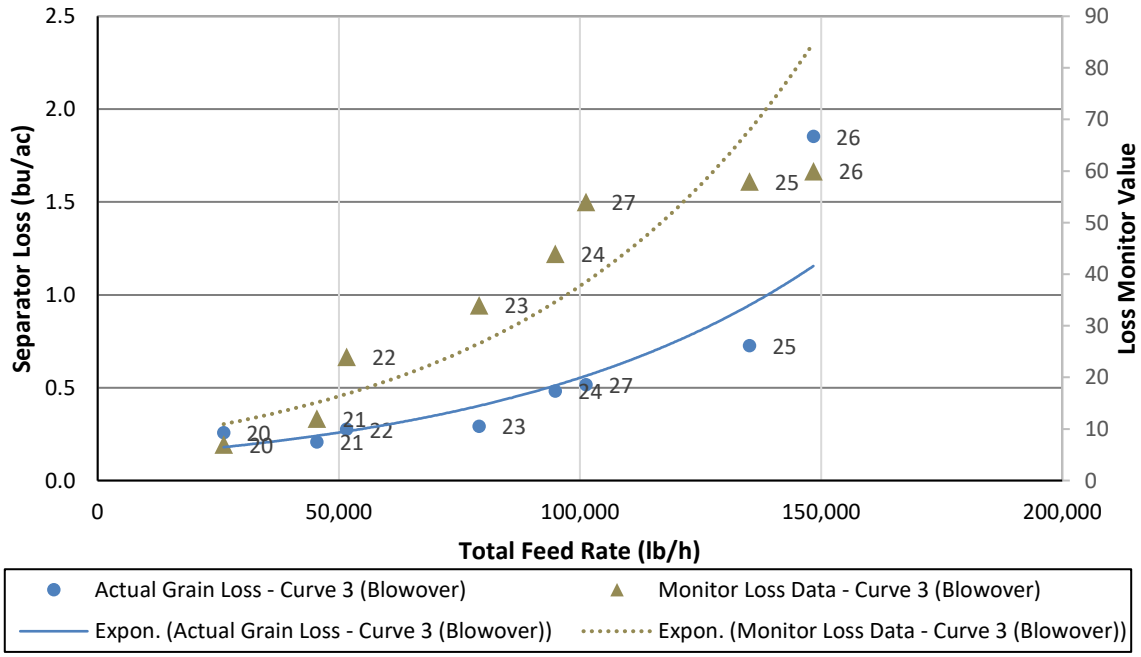

Figure D-2. Actual grain loss and monitor loss curves on the separator in canola – blow-over scenario (fan speed: 700 rpm)

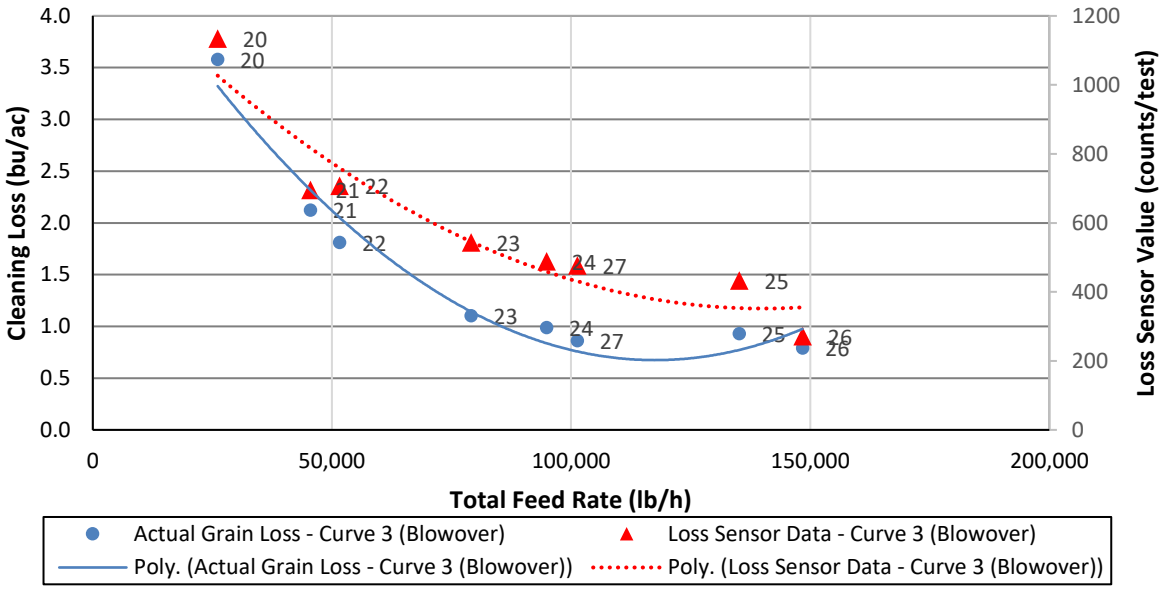

Figure D-3. Actual grain loss and loss sensor curves on the cleaning shoe in canola – blow-over scenario (fan speed: 700 rpm).

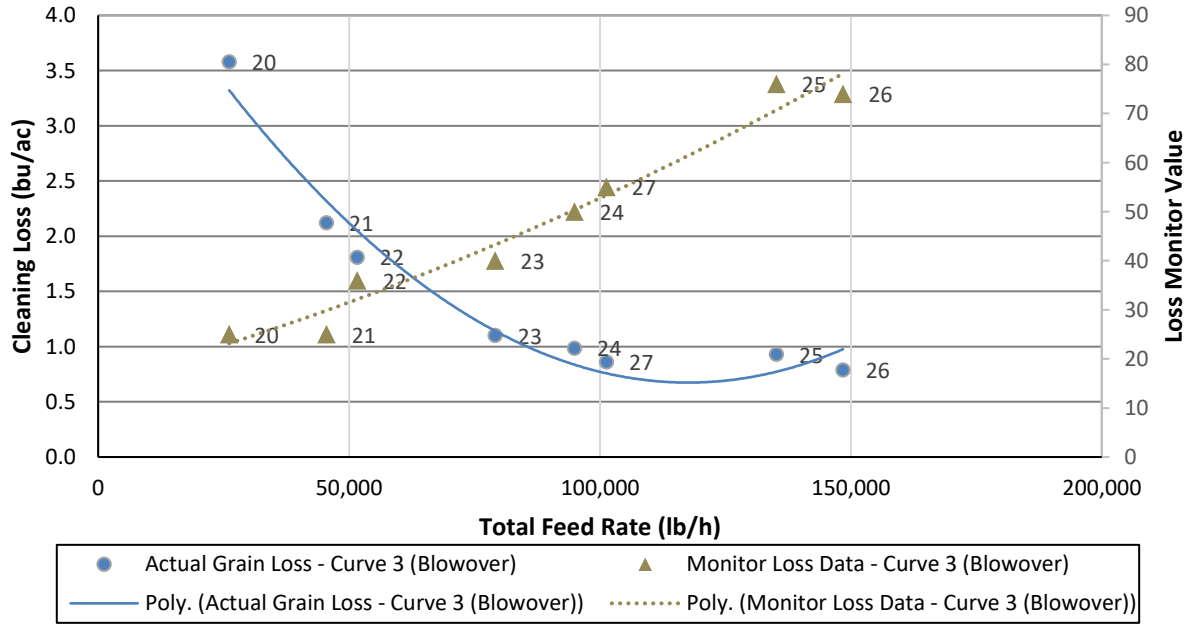

Figure D-4. Actual grain loss and monitor loss curves on the cleaning shoe in canola –blow-over scenario (fan speed: 700 rpm).

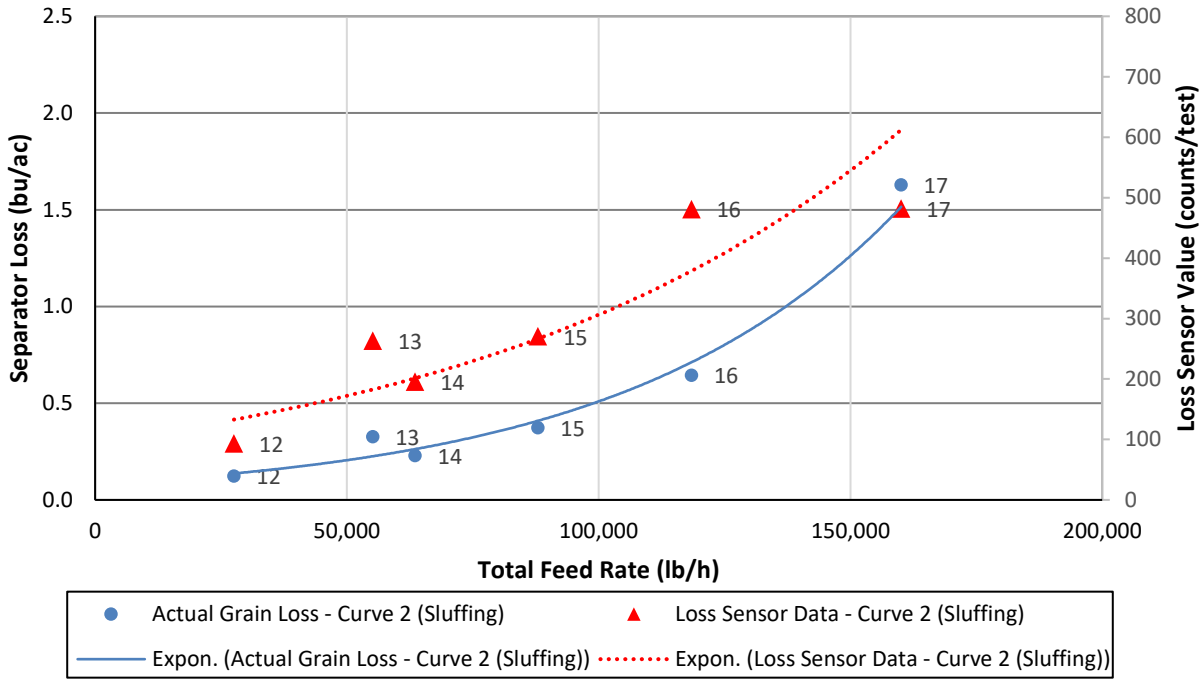

Figure D-5. Actual grain loss and sensor loss curves on the separator in canola – sluffing scenario.

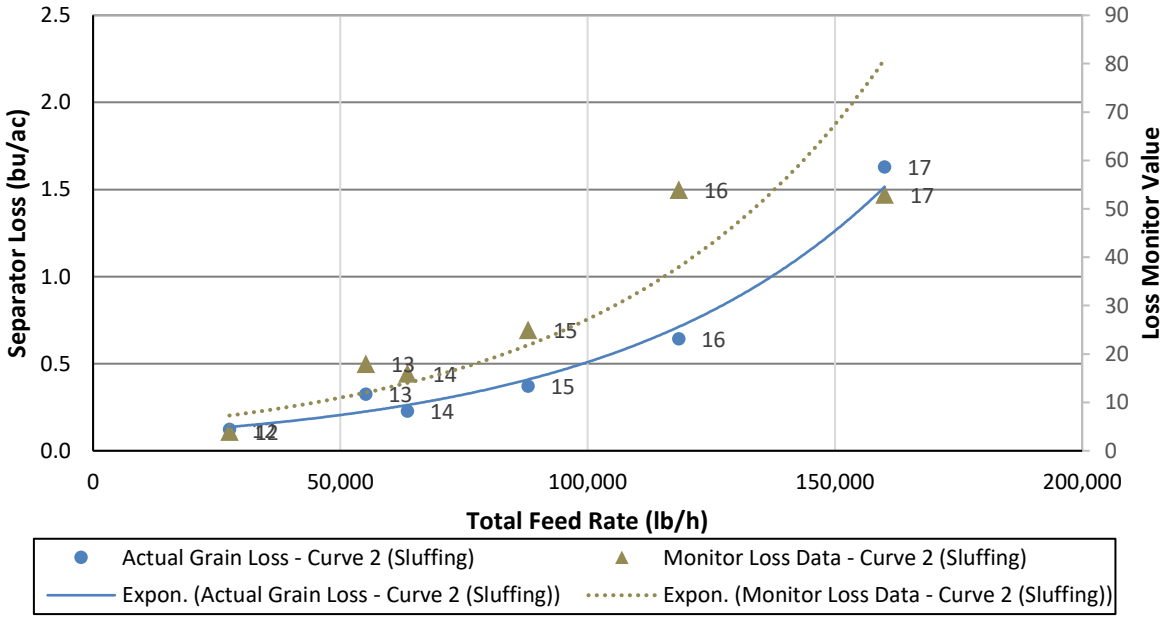

Figure D-6. Actual grain loss and monitor loss curves on the separator in canola – sluffing scenario.

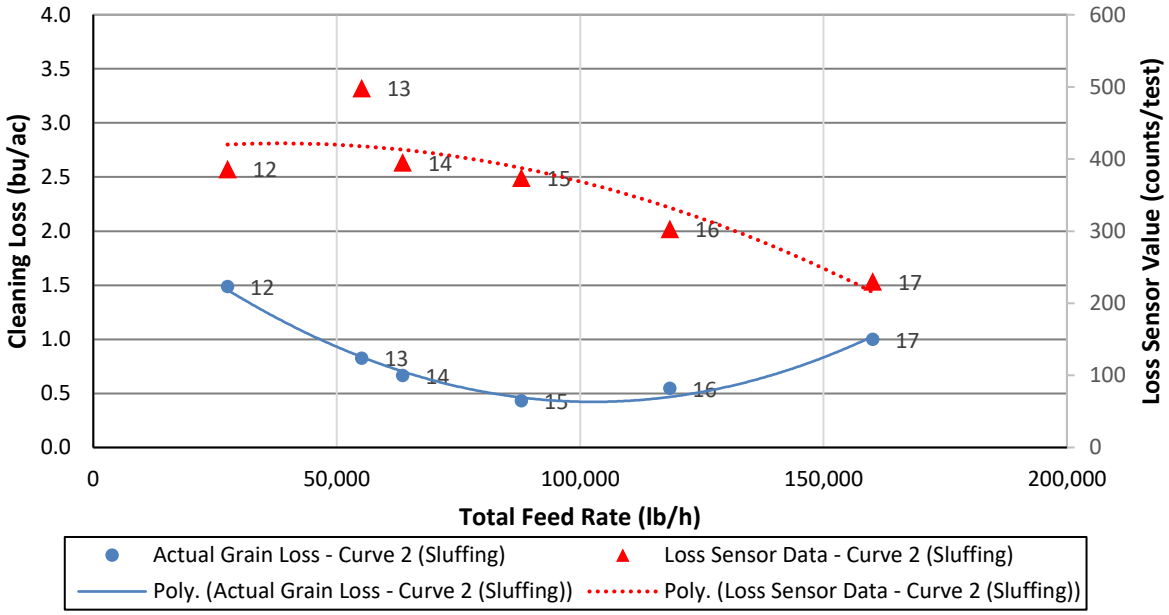

Figure D-7. Actual grain loss and loss sensor curves on the cleaning shoe in canola – sluffing scenario.

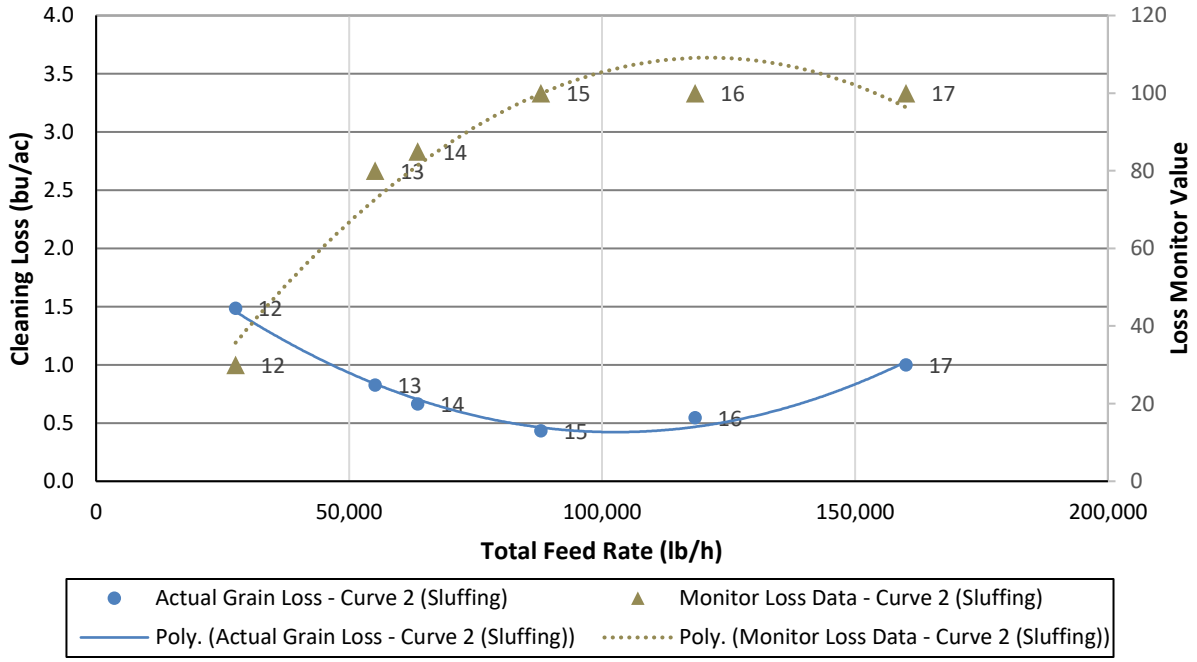

Figure D-8. Actual grain loss and monitor loss curves on the cleaning shoe in canola – sluffing scenario.

Appendix E

Derivation of Grain Loss Relationship

In each of the three crops tested (peas, wheat, and canola) a relationship was observed between the actual grain loss and the loss sensor data collected. This appendix shows the analysis and supporting calculations used to put this relationship into a useable set of equations.

This was done by first calculating the number of seed impacts the sensor received during the test period and converting this value to impacts per acre. This number was then divided by the actual loss in bushels per acre to get the number of impacts per bushel of loss, this data was again graphed over the testing range of total feed rates.

The following graphs and associated equations for testing in peas can be seen below. Note, **Figure E-1** and **Figure E-2** are shown for reference and are duplicates of **Figure 14** and **Figure 15** respectively from **Section 4.3.4**.

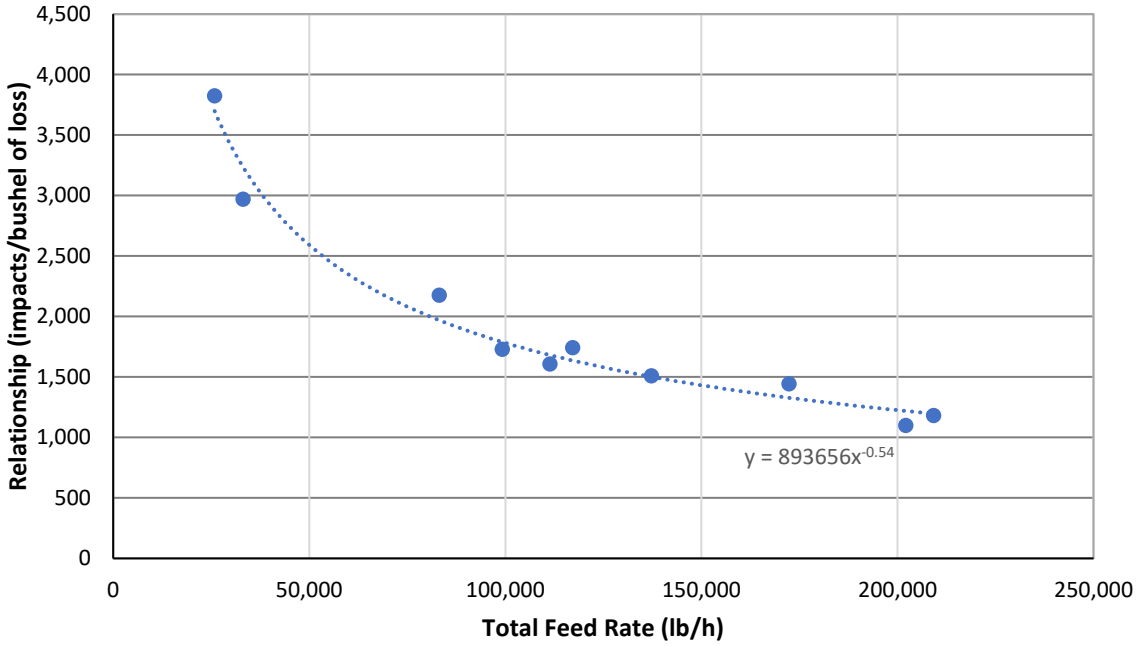

Figure E-1. Separator grain loss relationship – seed impacts per bushel of loss vs feed rate (peas).

As **Figure E-1** suggests the number of seed impacts per bushel of loss, decreases with increased feed rate creating a downward sloping curve.

The curve can be described by the following equation:

$$y = 893656x^{-0.54} \quad (1)$$

Where,

y, is the number of grain kernel impacts that equal one bushel of loss

x, is the total feed rate (lb/h)

The same type of relationship can be seen with the cleaning shoe sensor but with a lower rate of change across feed rates, as seen in **Figure E-2**.

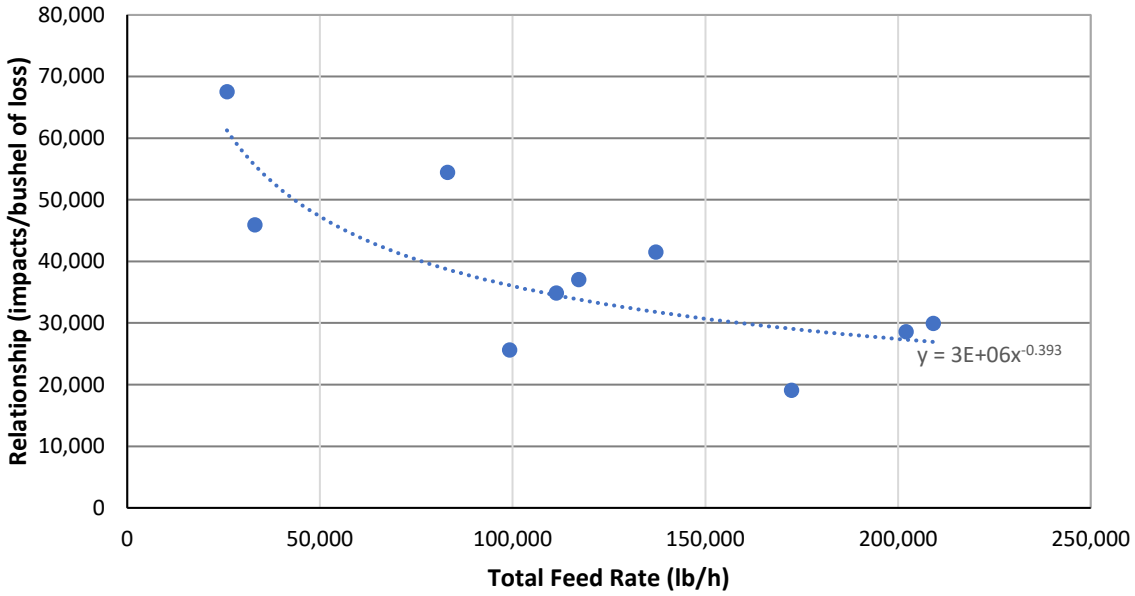

Figure E-2. Cleaning shoe grain loss relationship – seed impacts per bushel of loss vs feed rate (peas).

The cleaning shoe grain loss relationship can be described by the following equation:

$$y = 3E + 06x^{-0.393} \quad (2)$$

Using this relationship equation with inputs of total feed rate and the number of grain impacts, the actual loss can be predicted for both the separator loss and cleaning shoe loss through the following equations:

$$Grain\ Loss = \frac{A}{y=893656x^{-0.54}} \quad (3)$$

where

A is the number of grain impacts on the separator loss sensor (impacts/acre)

$$Grain\ Loss = \frac{B}{y=3E+06x^{-0.393}} \quad (4)$$

where

B is the number of grain impacts on the cleaning shoe loss sensor (impacts/acre)

Similarly, the analysis was done for wheat as shown below.

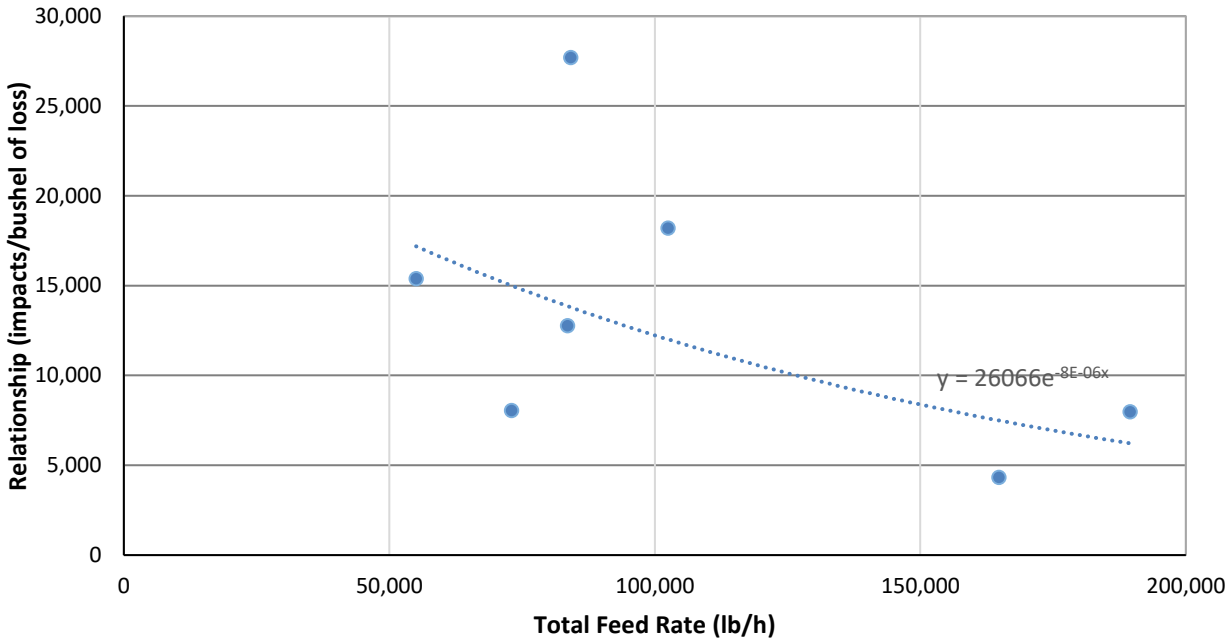

Figure E-3. Separator grain loss relationship – seed impacts per bushel of loss vs feed rate (wheat).

The separator grain loss relationship can be described by the following equation:

$$y = 26066e^{-8E-06x} \quad (5)$$

The curve can be seen to again be downward sloping on the separator, indicating a lower number of impacts per bushel of loss at higher feed rates.

The cleaning shoe grain loss relationship shows an increasing curve until an approximate feed rate of 100,000 lb/h (45.4 tonnes/h) is achieved, and then begins to decrease, as shown in **Figure E-4**.

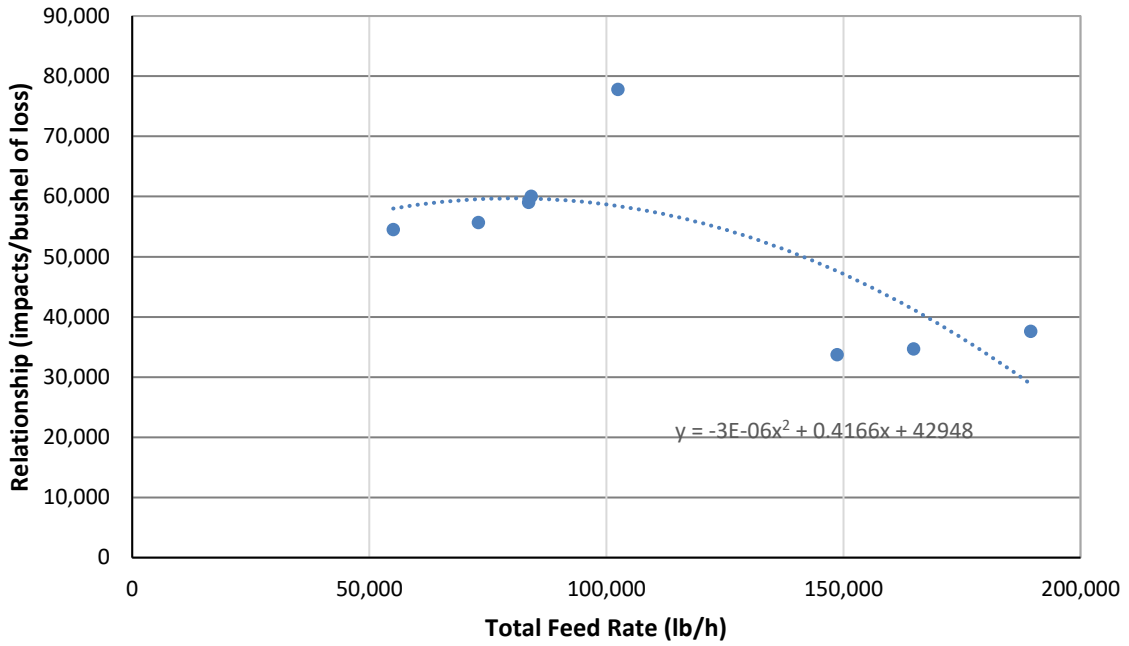

Figure E-4. Cleaning shoe grain loss relationship – seed impacts per bushel of loss vs feedrate (wheat).

The cleaning shoe grain loss relationship can be described by the following equation:

$$y = -3E - 06x^2 + 0.4166x + 42948 \quad (6)$$

Again, using the relationship equation, total feed rate and the number of grain impacts from the loss sensors, the following equations can be used to predict actual loss in wheat.

$$Grain\ Loss = \frac{A}{y=26066e^{-8E-06x}} \quad (7)$$

$$Grain\ Loss = \frac{B}{y=-3E-06x^2+0.4166x+42948} \quad (8)$$

Finally, the figures and analysis associated with canola can be seen below.

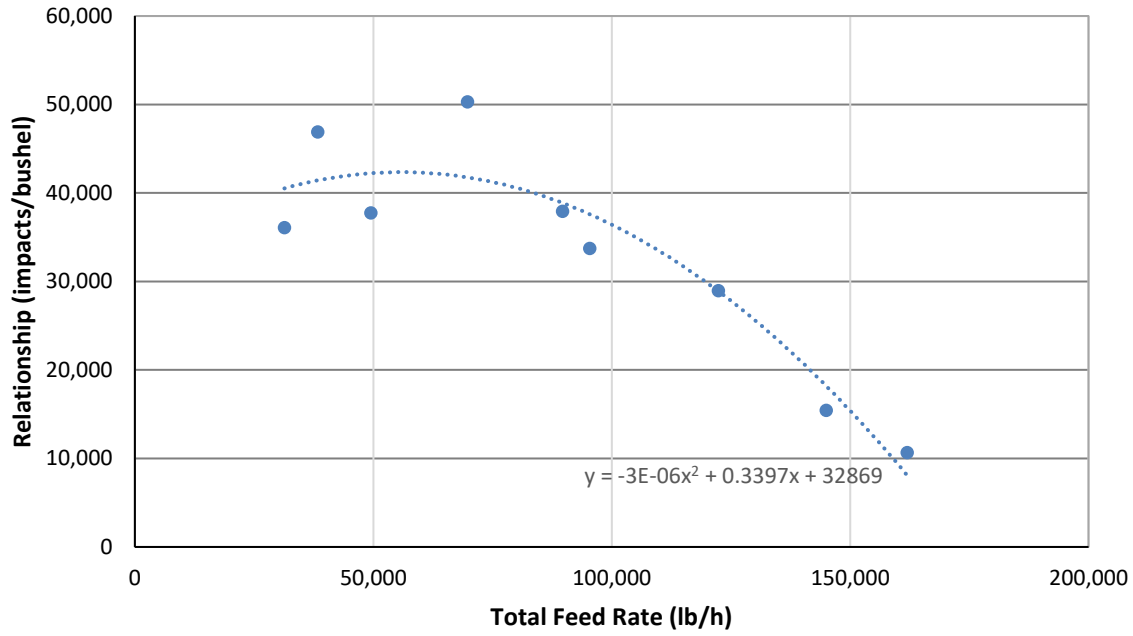

Figure E-5. Separator grain loss relationship – seed impacts per bushel of loss vs feed rate (canola).

The separator grain loss curve shows a slightly increasing curve until a feed rate of approximately 60,000 lb/h (27.2 tonnes/h) is achieved, and then begins a downward sloping curve until the maximum feed rate was achieved.

The separator grain loss relationship can be described by the following equation:

$$y = -3E - 06x^2 + 0.3397x + 32869 \quad (9)$$

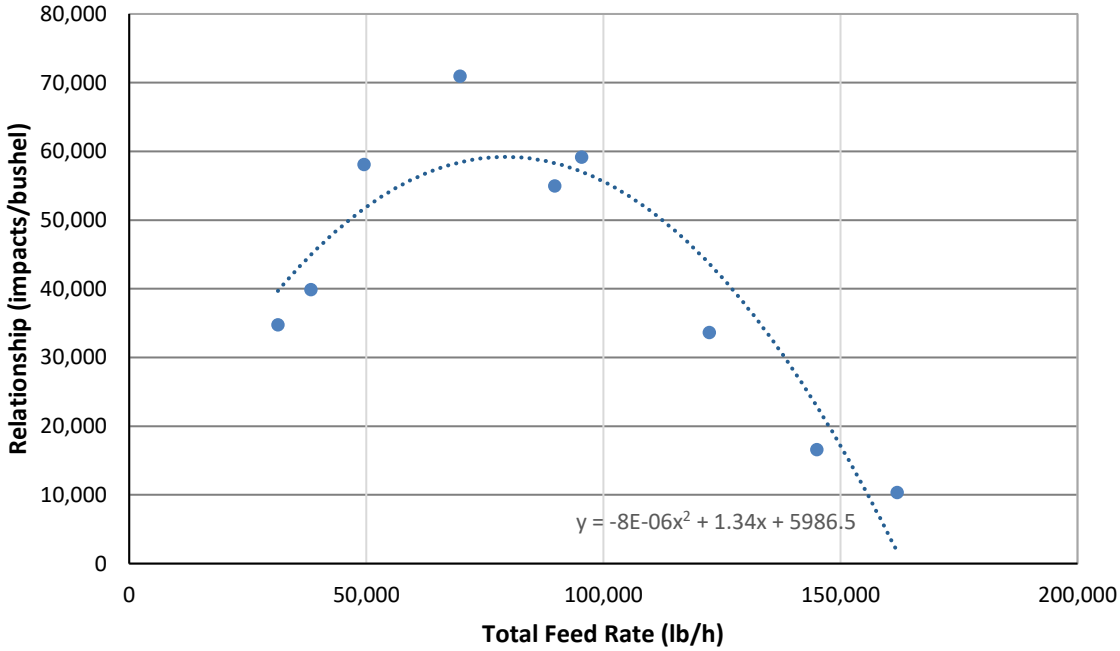

Figure E-6. Cleaning shoe grain loss relationship – seed impacts per bushel of loss vs feed rate (canola).

The cleaning shoe grain loss relationship curve, like the separator, had a positive slope at low feed rates until a feed rate of approximately 80,000 lb/h (36.3 tonnes/h) was achieved, at that point, the slope turned negative until maximum feed rate was achieved.

The cleaning shoe grain loss relationship can be described by the following equation:

$$y = -8E - 06x^2 + 1.34x + 5986.5 \quad (10)$$

Finally, using the relationship equation, total feed rate, and the number of grain impacts from the loss sensors, the following equations can be used to predict actual loss in canola.

$$Grain\ Loss = \frac{A}{y=-3E-06x^2+0.3397x+32869} \quad (11)$$

$$Grain\ Loss = \frac{B}{y=-8E-06x^2+1.34x+5986.5} \quad (12)$$

Appendix F

Loss Curve Test Data

Table F-1. Peas – loss curve test data and associated combine settings.

				Separator			Cleaning Shoe							
Curve Name	Curve	Run	Total Feed Rate (lb/h)	Grain Loss (bu/ac)	Sensor Data (impacts/test)	Monitor Data	Grain Loss (bu/ac)	Sensor Data (impacts/test)	Monitor Data	Rotor Speed (rpm)	Concave Clearance (mm)	Chaffer Clearance (mm)	Bottom Sieve (mm)	Fan Speed (rpm)
Optimum Settings	1	4	99,254	1.4	48	45	0.2	127	17	1140	9	12	8	970
	1	5	137,208	3.0	92	90	0.3	250	35	-	-	-	-	-
	1	6	209,190	5.8	138	95	0.4	254	20	-	-	-	-	-
	1	7	33,135	0.5	32	12	0.2	167	3	-	-	-	-	-
	1	8	83,115	1.1	47	38	0.1	136	10	-	-	-	-	-
	1	9	25,871	0.4	34	8	0.1	134	3	-	-	-	-	-
	1	10	117,156	2.2	79	83	0.3	204	25	-	-	-	-	-
	1	11	111,376	1.8	60	70	0.2	164	22	-	-	-	-	-
	1	12	172,349	5.3	154	98	0.9	354	70	-	-	-	-	-
	1	13	202,119	5.1	113	99	0.4	251	65	-	-	-	-	-

Table F-2. Wheat – loss curve test data and associated combine settings.

Curve Name	Curve	Run	Total Feed Rate (lb/h)	Separator			Cleaning Shoe			Rotor Speed (rpm)	Concave Clearance (mm)	Chaffer Clearance (mm)	Bottom Sieve (mm)	Fan Speed (rpm)
				Grain Loss (bu/ac)	Sensor Data (impacts/test)	Monitor Data	Grain Loss (bu/ac)	Sensor Data (impacts/test)	Monitor Data					
Optimum Settings	4	21	34,942	0.9	266	34	1.1	1204	38	1140	9	12	8	970
	4	22	55,046	1.3	220	30	0.9	951	36	-	-	-	-	-
	4	23	72,995	1.2	311	50	0.8	828	35	-	-	-	-	-
	4	24	83,583	0.7	367	64	0.7	728	55	-	-	-	-	-
	4	25	84,132	0.9	330	54	0.7	926	52	-	-	-	-	-
	4	26	102,463	2.9	258	63	0.8	512	70	-	-	-	-	-
	4	27	164,804	3.7	595	97	0.8	562	84	-	-	-	-	-
	4	28	189,512	2.6	592	100	1.0	576	100	-	-	-	-	-

Table F-3. Canola - combine test data and associated settings.

Curve Name	Curve	Run	Total Feed Rate (lb/h)	Separator			Cleaning Shoe			Rotor Speed (rpm)	Concave Clearance (mm)	Chaffer Clearance (mm)	Bottom Sieve (mm)	Fan Speed (rpm)
				Grain Loss (bu/ac)	Sensor Data (impacts/test)	Monitor Data	Grain Loss (bu/ac)	Sensor Data (impacts/test)	Monitor Data					
Optimum Settings	1	2	49,495	0.1	108	13	0.4	265	6	600	18	14	10	600
	1	3	69,786	0.1	127	20	0.3	239	6	-	-	-	-	-
	1	4	89,725	0.3	226	40	0.2	269	9	-	-	-	-	-
	1	5	122,370	0.3	352	45	0.2	291	16	-	-	-	-	-
	1	6	145,004	0.4	323	54	0.3	303	24	-	-	-	-	-
	1	7	161,941	0.6	374	58	0.4	261	32	-	-	-	-	-
	1	8	95,392	1.7	533	64	0.7	220	36	-	-	-	-	-
	1	9	27,564	2.0	442	67	1.0	213	45	-	-	-	-	-
	1	11	55,132	0.5	363	55	0.3	326	29	-	-	-	-	-
Sluffing	2	12	63,551	0.1	94	4	1.5	386	30	600	18	11	10	600
	2	13	87,946	0.3	263	18	0.8	498	80	-	-	-	-	-
	2	14	118,409	0.2	196	16	0.7	395	85	-	-	-	-	-
	2	15	160,081	0.4	271	25	0.4	374	100	-	-	-	-	-
	2	16	26,115	0.6	481	54	0.5	303	100	-	-	-	-	-
	2	17	45,485	1.6	482	53	1.0	230	100	-	-	-	-	-
Blowover	3	20	51,626	0.3	198	7	3.6	1134	25	600	18	11	10	700
	3	21	79,091	0.2	165	12	2.1	695	25	-	-	-	-	-
	3	22	94,911	0.3	305	24	1.8	707	36	-	-	-	-	-
	3	23	135,156	0.3	326	34	1.1	543	40	-	-	-	-	-
	3	24	148,406	0.5	396	44	1.0	488	50	-	-	-	-	-
	3	25	101,287	0.7	503	58	0.9	433	76	-	-	-	-	-
	3	26	148,406	1.9	477	60	0.8	271	74	-	-	-	-	-
	3	27	101,287	0.5	524	54	0.9	476	55	-	-	-	-	-

Appendix G

Vendor List

Table G-1. Vendor list**.**

Vendor	Vendor Website
MIDE	http://info.mide.com/hubfs/slam-stick-vibration-data-loggers-datasheet.pdf?hsCtaTracking=c32024f3-178f-4f3b-bbf1-6ec4d131432f%7Cbba56a47-81d6-4103-a678-76dc75b24772
G.R.A.S	http://www.gras.us/products/measurement-microphone-sets/product/515-46ad
Bruel & Kjaer	https://www.bksv.com/en/products/transducers/acoustic/microphones/microphone-cartridges/4953
Vesper	https://www.digikey.ca/product-detail/en/pui-audio-inc/PMM-3738-VM1000-R/668-1577-1-ND/7062069
Banner	http://info.bannerengineering.com/cs/groups/public/documents/literature/126701.pdf
MIDAS	http://www.midassensors.com/pdf/500ES430.pdf

For further information regarding this report, please contact:
Joel McDonald – jmcdonald@pami.ca

Saskatchewan Operations
Box 1150
2215 – 8th Avenue
Humboldt, SK S0K 2A0
1-800-567-7264

Manitoba Operations
Box 1060
390 River Road
Portage la Prairie, MB R1N 3C5
1-800-561-8378

Corporate Services
Box 1150
2215 – 8th Avenue
Humboldt, SK S0K 2A0
1-800-567-7264