UNIVERSITY OF SOUTHERN QUEENSLAND

FACULTY OF ENGINEERING

DEVELOPMENT OF TECHNOLOGY FOR YIELD MAPPING IN SUGAR CANE

A Thesis submitted by

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towards the degree of Bachelor of Engineering

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ABSTRACT

Yield maps provide essential information for the spatial analysis and evaluation of crop production management at a within field level. The work reported here is seen as the first step towards a full yield mapping system for sugar cane agriculture. The major objective was to develop the basic technology to enable the measurement of spatial yield variability in sugar cane, during harvesting. The yield variability measurements were based on the continuous recording of material flowrate through the harvesting machine and the machine driving speed. For the flowrate measurement, it was surmised that the power consumption of the harvester’s elevator system and rotary drum chop system maybe possible indicators of this quantity. An experiment was designed to test this assumption. An AUSTOFT 7000 cane harvester was fitted with hydraulic pressure transducers and shaft speed sensors to measure the power use of the necessary hydraulic motors. The electrical output signals were recorded on an analog tape recorder. Field tests were carried out in a variety of crop and weather conditions. Analysis of the test data indicated that both elevator and chopper power consumption are linearly related to material flowrate. Elevator power consumption was selected as the best technique for yield measurements because of its relative immunity to variations in crop properties. Necessary accuracy was obtained to permit the use of this technique in the yield mapping of sugar cane.

Using the recorded elevator and chopper signals and calculated calibration functions, yield maps were produced for a 0.35ha sugar cane plot. The general yield variation trends of these maps agreed with average yields calculated using weigh truck measurements.

Machine location systems were also reviewed and differential GPS was selected as the best option for locating a harvester in the field, for full scale yield mapping operations.

LIMITATIONS OF USE

CERTIFICATION OF REPORT

I certify that the ideas, experimental work, results, analyses, software and conclusions reported in this report are entirely my own effort, except where due acknowledgment has been given. I also certify that the work is original and has not been previously submitted for assessment in any other course.

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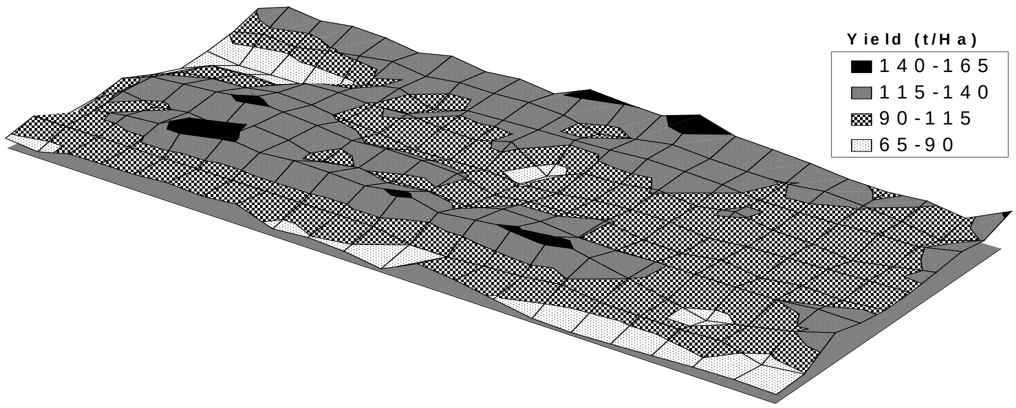


Figure 0.1. A sugar cane yield map. (225m long X 15 rows wide)

> As costs of production rise, each operation in the field and factory comes under close scrutiny to determine if improvements can be made to increase yields or to lower costs in order to improve the margin of profit. Economical reasons are forcing the sugar industry to strive for ever increasing efficiency and output. (Humbert,1968)

Over a quarter of a century later Humbert would be confident that this observation is as real as ever. The pressures on modern agriculture in terms of reducing input costs, maximising output quality as well as minimising adverse environmental impact, have forced farmers to look closely at their production practices. One such practice which produced considerable economical and enviromental pressure is the extensive use of chemicals; but there is room for significant improvements.

Currently most growers uniformly apply chemicals to their crops which are calculated from historical field data. An average yield is predicted for individual fields and 'blanket' application rates of fertilisers and chemicals are tailored to the assumed field output (Massey Ferguson Group Limited, 1993). In practice, crop yields vary not only from year to year, between farms and between fields, but significant yield variations also appear within individual fields (Vansichen & Baerdemaeker, 1993). Experience has shown sugar cane yields also vary significantly within fields (Kirchner & Lee-Lovick,

1991) and this is due to many factors. Variable soil fertility, varieties used, management practices, use of fertilisers, irrigation, control of weeds, pests and diseases, and many other factors explain spatial variation in sugar cane yields (Humbert, 1968, p.4). These variations in field characteristics suggest the proper placement of the inputs such as fertilisers and chemicals according to spatial location would assist in the reduction of production costs. This type of farm management, termed 'site specific' crop management, involves the application of crop management practices which are custom tailored to a specific area in a field (Clark *et al*.,1987).

Site specific farming has only recently become practical through the rapid advances in technology and it appears to be an obvious technique for increasing the sustainability of agriculture. Modern information technologies will be used to improve the efficiency and cost effectiveness of today's resources (Clark *et al*.,1987). This comes in the form of powerful computers, sensors to control and monitor farming processes and location systems such as the Global Positioning System (GPS). Some examples of the early application of this technology include site specific application of herbicides to weeds which are identified by machine vision (Clark *et al*, 1987) and the spatially variable application of fertilisers to row crops (Schumacher & Froehlich, 1989). Another example of the application of this technology is in the act of yield mapping.

A yield map shows the variation in crop performance between fields, or within individual fields. Figure 0.1 is a yield map constructed using data collected from a sugar cane crop. The variation in crop yield is obvious with definite trends. The figure also shows how evenly spread inputs do not produce even outputs. Yield maps provide essential information for spatial analysis and evaluation of crop production management at a within field level. This information can be an input to decision making for field operations during the next growing season (Vansichen & Baerdemaeker, 1993). The crop yield is a function of many variables as previously stated, but these effects are integrated in the final result at harvest. This culminating variable is the best and most practical method of assessing management techniques for site specific farming practices. By studying several years of yield maps, areas of different yield potential can be identified. Seed, fertiliser and chemical application plans can then be designed around the yield potential of individual parts of each field (Massey Ferguson Group Limited, 1993). This site specific management would result in a highly efficient crop production system. Russnogle (1991) believes yield maps, combined with soil maps to determine the site specific application rates, can result in an estimated 5% reduction in fertilizer application rates over rates determined by soil maps alone.

Yield maps can also greatly improve information available for making management decisions. As well as use in site specific farming purposes, a yield map can also highlight problems with drainage, disease or weed infestation (Clark *et al*., 1987). With accurate yield maps, a farm manager can investigate the many possible reasons for yield variations, as he/she has a clear indication of good and poor areas of the field. Some reasons for yield variations are relatively easy to rectify, for example, subsoiling compacted areas. Other reasons can be established by soil analysis, where the yield map allows this task to be performed more selectively than traditional 'random sample' methods (Massey Ferguson Group Limited, 1993).

A great deal of work has been done on yield mapping in cereal crops. Grain combines have been equipped to measure and record crop yield on-the-go for the development of yield maps. Even though this technique is new technology and is constantly developing, the Massey Ferguson company already offers a yield mapping system for their grain combines. Yield maps would also be of a great benefit to sugar cane farmers.

'The sugar cane plant, *Saccharum officinarum* L., has been described as the most efficient of all storers of the suns energy' (Humbert, 1968, p.16). If the maximum potential of this plant is to be approached, the soil-plant relationship must be at an optimum. The many factors controlling growth must be integrated into an optimum environment. The fact that sugar production in Australia ranges from 160 to 60 tons per hectare, stresses the range in productivity that can occur due to different management. That is why yield maps could make a great input in the form of information to the management of sugar cane agriculture. For example, look at the impact it could have on fertiliser use. The crop, by virtue of the biomass produced per hectare, causes a heavy drain on soil nutrients. If the amount of plant matter removed from the field is known, then the nutrient drain could be inferred. The soil nutrients could then be replaced only to the optimum level, which would reduce the amount of excess nutrients available to do environmental damage and reduce the economic loss due to wasted nutrients.

This information provides support for the application of yield mapping technology to sugar cane agriculture. Concerns from the community call for the economic and environmental sustainability of the sugar industry to be maximised. This will only be reached when management has the most up to date and comprehensive information. Yield mapping provides this vital information for improving the sustainability of sugar cane production.

1.1 Objectives

This project is the first step in the development of a full yield mapping system for sugar cane agriculture. The major objective is to develop the basic technology to enable the measurement of spatial yield variability in sugar cane. Initially, the option of remotely sensing yield was examined, but following a brief literature review (shown in Appendix B), this option proved ineffectual. The next alternative was to map yield during harvesting. This system involves the calculation of point yield, using a measurement of crop mass flowrate through the harvester, and the use of a location system, such as the Global Position System (GPS), to pin point the position in the field. No research has been conducted in this area for application to sugar cane. Therefore the objectives of this project were:

(a) To analyse, assess, and document the options for harvester location, to include dead reckoning, local triangulation and GPS.

(b) Most importantly to design, construct, test and evaluate instrumentation to measure the sugar cane flowrate in a billet cane harvester.

The research conducted to achieve these objectives is explained in this thesis. The first objective is covered in chapter one, where different location systems are examined. The next five chapters focus on the second objective of the design, construction, testing and evaluation of a mass flowrate monitor, which will enable the yield mapping of sugar cane. The objectives were completely fulfilled and as a result Figure 0.1 is the culminating result of this thesis. It is the first sugar cane yield map of it's kind, constructed using data collected from a billet cane harvester

Chapter 2 : LOCATION SYSTEMS REVIEW

As stated in the introduction, harvester location is an integral requirement of the yield mapping process. Figure 2.1 displays the basic steps necessary for yield map construction using data collected at harvest. The location system is as important as the yield monitor, in terms of producing useful and accurate maps. So, naturally a project developing technology for yield mapping sugar cane should examine the options for locating a harvester in the field. This chapter describes three possible techniques of locating a machine in the field, known as the Global Position System, Local Triangulation and Dead Reckoning. This location systems review is not exhaustive, but a brief study required to make an educated decision as to the best system for incorporation into yield mapping of sugar cane.

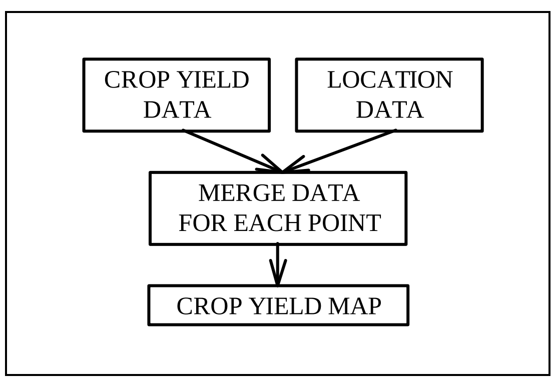


Figure 2.1 Flow chart for the construction of a yield map.

2.1 Global Positioning System

The Navstar Global Positioning System (GPS) is a satellite based radionavigation system developed and operated by the U.S. Department of Defence. GPS enables land, sea, and airborne users to determine their three dimensional position, velocity and time anywhere in the world with unprecedented accuracy. Users longitude, latitude and altitude are calculated by measuring the time it takes a radio signal to be transmitted from GPS satellites and then received by a receiver.

The accuracy of GPS depends on the mode of operation. There are two modes of operation, Differential GPS (DGPS) and Absolute GPS (AGPS). AGPS requires the use of only one receiver and is known a "stand-alone" GPS. The accuracy of AGPS vary from several meters to over 100 metres (Harrison *et al*, 1992). The errors depend on "dilution" of precision by the US military, position of satellites and the number of satellites in view. AGPS is sufficiently accurate for many navigation tasks for marine, aviation or ground vehicle purposes, but it is not good enough for measurements such as surveying or agricultural applications such as yield mapping.

DGPS is designed to improve the accuracy of GPS-derived positioning information. A stationary receiver at a known location (the "base station") receives signals from the satellites, and calculates its own position. Since the actual position of the base station is known, the errors in the satellite signals are accurately calculated. This error information can be recorded in a computer data file for later use (post processing) and/or transmitted to a mobile receiver (the "rover") over a radio link (real time) (Shropshire *et al*, 1993). For yield mapping purposes, post processing would be acceptable because the real time location of the harvester is not required.

The typical accuracy of DGPS is 5m, 95% of the time, but depends on the distance between base station and rover (Shropshire *et al*, 1993). For agricultural purposes, a base station within 700 hundred kilometres provides sufficient accuracy of 5 to 7 metres (Higgins *et al*, 1992). For yield mapping sugar cane this resolution would be acceptable, however it would be preferred if it was less than the standard sugar cane row width of 1.5 metres.

Larson *et al* (1991) claims that the resolution of 1 cm will some day be available with GPS and Hall (1995, pers. comm.) presently believes that with software, the real time accuracy can be improved to less than 50 mm. These levels of accuracy are not necessary for yield mapping purposes, but it could provide opportunities for other on farm applications of this technology.

The costs of GPS hardware can range considerably. A simple handheld unit can cost as little as $2000, while a complete real time DGPS system with radio broadcasting base station and receiving mobile station costs approximately $20,000 (Leica Inc., 1995). For yield mapping purposes however, a single mobile receiver using post processing would be suitable at approximately $5000. The base station correction data could be obtained from any of the stations which are presently appearing all over Australia. In less than three years this data will be available anywhere for little cost. It is also expected that the cost of GPS hardware will reduce as this technology becomes more commonplace.

GPS location hardware could easily be incorporated into the process of yield mapping. Installation would be a matter of mounting an antenna on the cabin of the harvester and securing the receiver in the cabin. The location data would be interfaced with the necessary data logging equipment, which would simultaneously log yield measurements. Post processing of the location data would simply involve software application on a PC.

GPS technology has been used for agricultural location and positioning applications in the United Sates by Borgelt and Sudduth(1992), Colvin *et al*. (1991), Larsen *et al*. (1991) and others.

2.2 Local Triangulation

Various techniques have been devised to determine the position of an unknown point by triangulation from two fixed points of known location. The system usually works utilising transmitters placed at known locations and a receiver on the moving machine (Figure 2.2). The angle α is measured by the receiver, using the two signals which travel directly to the machine from the fixed stations. This measured angle along with the length between the fixed stations, L, defines the two dimensional position of the machine.

These two results enable the opposite sides of the triangle to be calculated and then the square coordinates of the moving machine deduced.

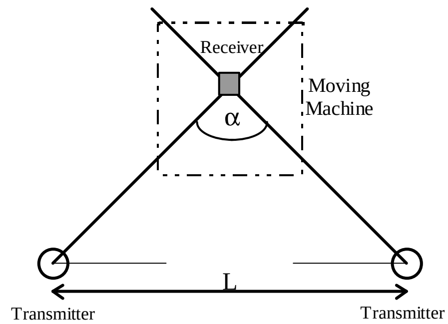


Figure 2.2. Concept of Local Triangulation

Several systems have been developed incorporating either laser or microwaves as the transmission signals. These individual systems will not be examined here, but literature is available on laser systems by Gordon and Holmes (1988) and Schulevich *et al*. (1987); and on microwave systems by Monod and Mechinau (1988) and Palmer (1991).

The reported accuracy of local triangulation varies somewhat. Gordon and Holmes (1988) tested a laser system and found maximum errors of 1.2m, while Stafford and Ambler (1991) reported accuracy of better than 10 mm. Searcy *et al* (1989) reported errors of microwave system, during a yield mapping exercise, of between 1 and 2 metres. In any case all of these systems would provide more than suitable positioning for yield mapping purposes.

There are concerns for the range of these systems. The radiated power of the lasers must be limited because of safety aspects and this restricts the range of operation. To increase the range of the microwave system, transmitter stations can be set up at regular intervals arround the field. The laser systems also have the disadvantage that they require line of sight and are subject to signal degradation from dust and precipitation. The direct line of sight maybe a problem during yield mapping of sugar cane, particularly when harvesting a tall crop.

The capital cost of these systems are unknown by the author, but they are assumed to be comparable to the cost of GPS hardware. Monod and Mechinau (1988) believes the microwave system can be viable if used extensively by a cooperative of farmers who set up permanent transmitter stations throughout the desired area.

Overall, these systems incorporating local triangulation, do not offer any major advantages over GPS, except possible present accuracy. It is expected that GPS will become at least as accurate as this and therefore, for yield mapping purposes, GPS is the better option.

2.3 Dead Reckoning

Another location system which has been used for agricultural position is dead reckoning. For this system, position is determined relative to a known starting location by identifying the direction of travel and measuring the distance travelled. For row crops, such as sugar cane, the direction of travel is always parallel to the previous row and therefore can be satisfactorily defined by the row number which is being traversed. Distance travelled may be determined by direct measurement or by integrating a velocity signal over time. These measurements are normally calculated from wheel sensors. A major problem with this system is the errors produced by wheel slip. These errors are cumulative, and if not corrected by using a position check, can greatly decrease the reliability of the location system. During yield mapping operations in sugar cane, the system would be corrected at the start of each new row, hence the largest errors would occur at the ends of the rows. Schumacher and Froehlich (1989) measured errors of 0.82%, equating to 8.2 metres per kilometre and the author of this thesis also discovered errors of this magnitude during the coarse of this project. This proportion of error would be acceptable for yield mapping purposes in sugar cane agriculture, where most of the row lengths are far less than one kilometre.

Obviously the capital cost of this system would be very low in comparison to the previously discussed techniques, however the additional burden of recording row numbers while harvesting would greatly reduce the adoption of this technique in the sugar industry.

Schumacher and Froehlich (1989) successfully used this system for spatially variable chemical application and Lemmne (1992) carried out cereal yield mapping. The sugar cane yield maps shown later in this thesis were also produced using dead reckoning location data.

2.4 Location Systems Conclusion

From the review of existing literature and the comparison of these techniques for use in yield mapping sugar cane, it appears that GPS, using differential correction, is the best option available for harvester location requirements. Although there is a high initial outlay, the system could easily be incorporated into the yield mapping process. In the future, the accuracy of this system will increase, enabling it's use in other agricultural practices also.

Chapter 3 : YIELD MONITOR DESIGN

Most researchers agree that a yield monitor, location device and a data acquisition system are the major portions of a successful yield mapping system (Stott *et al*., 1993). Location devices for yield mapping sugar cane were discussed in the previous chapter and suitable data acquisition systems are extensively available. This leaves the heart of the yield mapping system, the yield monitor, as the only portion impeding the successful production of a yield mapping system for sugar cane agriculture. This chapter is devoted to the design of such a yield monitor. The monitor will firstly be defined in terms of its function in the yield mapping operation. Next, the general requirements of the monitor are stated. Then a review will be conducted on existing yield monitor technology and it's possible application to sugar cane agriculture. In this review, a technique will be selected to carry out the job of yield monitor for sugar cane. Finally this technique will be briefly analysed to determine the expected characteristics and performance.

3.1 Yield Monitor Definition

During harvesting the material flow into the machine can be expressed as a function of local yield, travel speed and cutting width:

$$\mathbf{Fr}(t) = \mathbf{Yi}(t) \cdot \mathbf{Sp}(t).\mathbf{Wa} \quad \text{...Equation 1}$$

where **Fr**, is material flowrate (kg/s),

Yi, is crop yield (kg/m2)

Sp, is driving speed of the machine (m/s)

Wa, is actual cutting width (m)

and t, time (s).

For sugar cane, being a row crop, the cutting width can be assumed constant and although it may vary slightly between farms it can easily be measured. Machine driving speed is a function of time, and for reliable yield maps it must be accurately measured. Driving speed can be measured in many ways and methods previously used during yield mapping operations include Radar Doppler measurement (Vansichen and De Baerdemaeker, 1993), direct wheel measurements (Lemne, 1993) and even differentiation of GPS location data (Stott *et al*., 1993). This leaves the material flowrate into the machine as the final variable required to enable the measurement of crop yield. This variable is also the most difficult to measure. Presently, there are no flowrate measurement techniques available for sugar cane harvesters. Therefore the major problem at hand, is to develop a technique for measuring the mass flowrate of sugar cane through a billet harvester.

3.2 Yield Monitor Requirements

The first step in the design process of the sugar cane flow sensor is to define the functional and performance requirements.

3.2.1 Performance Requirements

According to Harvard (1983), accuracy within 5 or 10 % may be all that is required when relating cereal crop yield to site specific field treatments. This figure should be the equivalent for sugar cane agriculture. De Baerdemaeker *et al*. (1985) believes it would be necessary to have an accuracy within 2 % if the grower desires a gross measurement for each field. In the sugar industry however, this accuracy may not be required because this information is available from the sugar mill, which records the mass of the sugar cane received at the mill for payment purposes.

Through consultation with farmers, the author believes that the yield monitor should be able to resolve a significant change in yield occurring over 10 metres. That is, when viewed on a yield map, changes in yield between each successive 10 meters should be determinable.

3.2.2 Functional Requirements

De Beardemaeker *et al.* (1985) formed a set of functional requirements for a grain flow measuring system. These requirements are given with some adjustments for application to sugar cane measurement.

1. The maximum flow of sugar cane at present is approximately 50 kg/s (measured later in the thesis). The flows in the harvester can fluctuate strongly, implying that the proposed accuracy should be maintained over the entire range of flows.

1. Sugar cane conditions (size, variety, moisture content, foreign material, etc) should not influence the obtained results; or in case they do, it should be in a predictable manner.

1. Even when operating on slopes, the accuracy should be maintained.

1. Machine vibrations or shocks should not influence the readings.

1. The sensing device should under no circumstance impede the material flow in such a way that normal harvester operation is slowed down.

1. The fitting, installation and removal of the monitor should be possible without major rebuilding.

1. The cost should not exceed $3000.

1. Calibration checks must be easy and practical.

1. The sensing device and associated electronic circuitry must operate properly in rough, dusty and moist conditions.

3.3 Yield Monitors Review

Although there has been no research into the a mass flow measurement technique for sugar cane, ample research has been conducted on flowrate sensors for cereal crops and is summarised by Borglt and Sudduth (1992). In this paper the basic principles of 13 grain flow devices are briefly described. Although the flow properties of grains are very different to that of billeted sugar cane, there are principles that may be successful for both materials. Some of the these methods reviewed, which may work for sugar cane, are:

a) Gamma ray absorption

This system consists of three units - a gamma ray emitter, a detector, and a display unit. The emitter is mounted under the crop material flow, with the detector mounted directly above the emitter. As the material passes through the measuring gap between the emitter and detector, it reduces the intensity of the gamma radiation registered by the detector. This reduction is proportional to the grain mass flowrate.

a) Impact plate

This sensor uses the change of momentum in moving crop matter, impacting against a curved plate, as an indicator of flow. On a cane harvester the curved plated could be mounted at the outlet of the elevator, so the billets falling from the elevator are forced to change direction. The force exerted on this plate should be proportional to the mass flowrate.

a) Pivoted auger

For the measurement of grain flow, an auger is mounted with one end pivoted and the opposite end supported by a load cell. The application of this principle for sugar cane could involve a load cell or pressure transducer incorporated in the hydraulic rams that support the harvester elevator. Obviously as the elevator becomes loaded with billets these rams must provide extra support and this would be proportional to the mass flowrate. A problem with this system may be the excessive noise generated by the moving harvester.

a) Elevator photodiodes.

A light source and photodiodes can be mounted on an elevator to measure the depth of crop material on individual flights. The light that is received at the photo diodes gives an indication of the quantity of material on each flight.

These techniques may be successful for sugar cane, however a far simpler method was investigated by Vansichen and De Baerdemaeker (1993).

A measurement technique for yield mapping of corn silage was devised by Vansichen and De Baerdemaeker (1993). Although the harvesting technique of silage is notable different to that of sugar cane, the similarity lies in the fact that both methods involve the removal and billeting of a whole crop. For this method, the mass flowrate measurement involved instrumenting the base unit drive shaft and the blower shaft of the forage harvester with torque and angular speed sensors. The base unit included the cutterhead, feedrolls and the row-crop header. The blower consisted of a paddle wheel that gave the chopped material momentum to flow through a spout into a trailer. Tests were carried out by harvesting the corn silage at different ground speeds. For each test run the average flowrate over a certain time period was determined by weighing the amount of material harvested and dividing this by the period length. The power signals (torque x angular speed) were averaged over the same time period. The results of the experiment indicated that silage flowrate was proportional to the measured power on each shaft. Under the assumption of linearity, regression coefficients were calculated and the coefficients of determination were greater than 0.94.

This concept of relating material flowrates to power consumption could be applied to various components of a sugar cane harvester. The forage harvester's base unit, described above, is analogous to the sugar cane harvester's choppers and feed rollers. In both cases, the system's function is to deliver the whole stalk of the crop to a point where the material is sliced into billets. The rotary drum chop system (chopper system) of a sugar cane harvester, uses seven cuts per second to billet sugar cane at a rate of up to 50 kg/s. Logical thought would imply that as the number of stalks increase, higher cutting forces are required. This thought is supported by Persson (1987), who gives a detailed overview of the ample research that has been done on the cutting forces required for plant material. From this work it can be stated that the cutting power requirement of a given forage harvester in a given crop is linearly related to the material flowrate. This statement lends support to the use of a cane harvester's chopper power as a technique for measuring mass flowrate. This work by Persson (1987) will be further examined later in this chapter.

Another component of a sugar cane harvester, whose power consumption may be related to the material flowrates is the elevator. The elevator's job is to deliver billeted sugar cane from the chopper system up and into the 'haulout' vehicles. This system is driven by two hydraulic motors, coupled at the top of the elevator. Billeted cane is lifted some 2 to 3 vertical metres over the length of the elevator, and obviously energy is required to overcome gravity. There is also the effect of friction on the elevator floor as the sugar cane is dragged up the elevator. From these two effects it would indicate that the mass of cane being elevated would be proportional to the power require to move it. The only concern would be that this increase in power requirement, would be negligible to the total power requirement for the system, and as a result would be masked. This statement is refuted by Dick (1995, pers. comm.), who did some preliminary work looking at the pressure fluctuations in the elevator hydraulic system of a CAMECO cane harvester. He found that there was a significant difference between ‘free running’(no load) hydraulic pressure of the elevator motors to the heavily loaded condition. The pressure readings increased from a 800kPa at ‘free running’ to an operating pressure of 1400kPa. Therefore on this evidence there is also support for the use of elevator power as a measure of sugar cane mass flowrate.

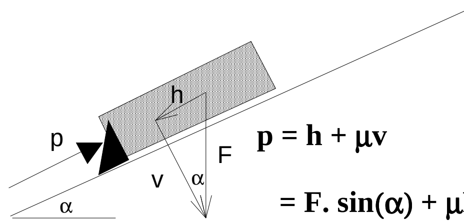
From this preliminary research it appears that the power consumption of the rotary drum chop system and the elevator system of a sugar cane harvester may be a successful in the measurement of sugar cane mass flowrate through the harvester. Due to the similarity in testing both these methods, it was decided to trial both methods simultaneously as possible uses for yield monitoring. The rest of this thesis deals with the design and undertaking of scientific experiments necessary to prove or disprove the hypothesis that sugar cane mass flowrate in a harvester is related to the power consumption of the elevator and rotatory drum chop systems.

3.4 Analysis of Selected Monitors

The elevator and chopper power consumption have been selected as monitors of mass flowrate with little analysis. This sections further analyses these methods to predict the relationship between the variables of mass flowrate and power consumption and also to predict any other variables that may effect the relationship.

3.4.1 Elevator System

The critical variables in the power consumption of the elevator are the mass flowrate of sugar cane, the angle of the elevator and the coefficient of friction. For yield monitoring purposes we would like the variables of elevator angle and coefficient of friction to remain the same to obtain consistent mass flow results, however it is likely these variables will change. For example a harvester operating on slopes will change the relative horizontal angle of the elevator and the coefficient of friction may also vary due to crop properties or available water. Therefore it would be interesting to get a feel for the sensitivity of the power usage to the change in these variables.



$$\mathbf{p = h + \mu v}$$

$$\mathbf{= F.\ sin(\alpha) + \mu F.cos(\alpha)}$$

Figure 3.1. Simple model of the force, p, necessary to raise sugar cane billets up a harvester elevator.

The relationship between the principal variables is shown in Figure 3.1, where force ‘p’ can be assumed proportional to power, and weight force ‘F’ proportional to mass. Some preliminary analysis was carried out on this model to determine the sensitivity of the power requirements of the elevator to its angle to the horizontal and coefficient of friction. The calculations are given in Appendix C and are graphically represented in Figure 3.2. Although it is unlikely that the coefficient of friction will vary from 0.1 to 0.5 and the elevator angle from 40 degrees to 60 degrees, the graph does give an indication of the errors that may be involved. From the figure it appears that the power requirement is most sensitive to the coefficient of friction, with an approximated 30% increase in power over the given range. The variation in elevator angle also produces significant changes in the power requirement, with an approximated 20% increase in power over the 20 degree change. From this analysis it appears that the two parameters of elevator angle and coefficient of friction, could produce significant errors in the measurement of mass flowrate. Therefore both parameters may need to be taken into account in the integration of a full yield mapping system on a sugar cane harvester.

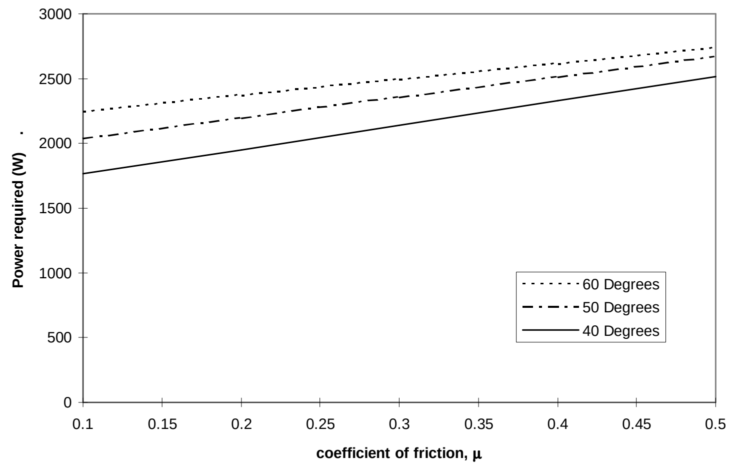


Figure 3.2. Theoretical Elevator power requirement for varying coefficients of friction and elevator angles.

3.4.2 Chopper System

While the elevator system measures mass flow somewhat directly, the chopper system measures the rate more indirectly. A mass flowrate is inferred using the assumption of a specific cutting energy/power (eg Watts/kg). However, the magnitude of this quantity may vary due to a number of factors. Persson (1987) analysed the factors which affect the specific cutting power of plant material. These are:

<u>Major factors:</u>

Feed rate

Length of cut

<u>Crop Factors:</u>

Moisture Content

Plant Maturity

Species

Mode of operation:

Material thickness

Knife velocity

Design Factors:

Width of cut

Edge angle

Sharpness

For the chopper measurement to work, all these variables except the feed rate would have to remain relatively constant. This is unlikely over a full harvesting season, but if these variables remain constant over a harvested field then this technique can be used to measure relative yield differences. These relative results can be used directly for crop management purposes. Actual yield variation could be determined by recalibrating the system, knowing the total yield of the field. So, although there are many variables that could affect the accuracy of the flowrate measurements of the chopper system, it could be successful in measuring relative yield differences, from which actual yield differences can later be determined.

Chapter 4 : HARVESTER INSTALLATION AND INSTRUMENTATION

Instruments were selected and constructed to carry out field tests on a cane harvester. These items were then installed to obtain the required results. This chapter briefly reviews each of the instruments used and then explains how each was installed on the harvester.

4.1 Instruments

Various electrical transducers were used to measure various physical properties. The output signals were conditioned by an 'Electronic Black Box' and then a Tape Recorder was used to record the conditioned signals. The characteristics of each of the transducers, the Electronic Black Box and the Tape Recorder are explained in this section.

4.1.1 Transducers

Transducers were required to sense the necessary physical properties. The most important property was the hydraulic pressure in the elevator and chopper systems. Sensors were also required to determine the angular velocity of various shafts. The properties of these two sets of transducers are explained below.

4.1.1.1 Pressure Transducers

The transducers selected were DRUCK PTX 500 series industrial pressure transmitters. They consisted of a cylindrical stainless steel casing, approximately 100mm long and 40mm in diameter, with the required electronics contained within. Operating pressure ranges for both transducers of 0 to 100 bar gauge, were selected. This was decided after consultation with the harvester manufacturers, who recommended this range as the normal operating pressures of the chopper and elevator hydraulic systems.

The combined non-linearity, hysteresis and repeatability of the transducers were extremely good. The product specifications indicate that the output will not deviate from the straight line connecting zero and full scale output by more than 0.3% F.S., and typically 0.15% F.S. The transducers were powered by a supply voltage of 9 to 30V DC. and their output was a current of 4 to 20 mA, proportional to the pressure at the inlet.

Installation into the hydraulic systems involved screwing the transducer onto a hydraulic hose fitting, where the pressure reading was desired. This can be seen on Figure 4.2, where a transducer has been implemented to measure the pressure at the elevator motor.

4.1.1.2 Speed Transducers

Magnetic pickups were used to measure the speed of various rotating shafts. Constructed by AGRI-RIMIK PTY. LTD. in Toowoomba, these sensors return an electronic pulse when a magnet is passed within a critical distance (about 1 cm). The time between these pulses can be measured to calculate the shafts angular speed.

For all applications in this trial a single magnet was attached to the required shaft and the pickup was mounted on a bracket in close range.

4.1.2 Electronic Black Box

Electronics were required to provide electrical power to the transducers and also to condition the transducer outputs for tape recording. This circuitry was contained in the Electronic Black Box. Many hours went into the design and construction if this item, and a thorough description is given in Appendix D.

4.1.3 Tape Recorder

The tape recorder was an AMPEX F.R. 1300, which had capabilities for recording 8 channels of information. The information was recorder on reel to reel tapes, which at the selected speed of 30 inches of tape per second, could run for 15 minutes. At this speed the frequency response of the recorder was exceptional, with a bandwidth from 0 to 10 kHz. This property was important for recording hydraulic pressure signals, which fluctuate rapidly.

The tape recorder's basic operation consisted of recording input voltage signals, supplied through electrical connections. These signals could be played back at any time for analysis.

For this experiment, it was unknown at what rate we should sample to obtain the required information. So, it was very convenient to simply record analog signals containing virtually all possible data (up to 10 kHz range) and then, at a later date, digitised or sample the signals at any desired rate.

4.2 Installation

The instruments discussed above were installed on an AUSTOFT 7000 Cane Harvester, shown in Figure 4.1. In the following section the interaction of the whole system of instruments will be explained and then the placement of the individual transducers will be described.

Figure 4.1. The AUSTOFT 7000 sugar cane harvester used in the field tests.

4.2.1 Full System

Figure 4.2 displays the basic interaction between the various instruments on the harvester. There were basically four sets of measurements. These were the chopper system power, elevator system power, harvester engine speed and harvester ground speed. Details of each of these measurements are discussed in the next sections.

Electrical cables relayed the signals from the transducers, back to the Electronic Black Box. This cable was shielded 4 core type, appropriately grounded to prevent the interference from any electromagnetic fields around the harvester. The Electronic Black Box and Tape Recorder were placed within the harvester cabin, along with an oscilloscope for easy monitoring of the incoming signals. An electricity generator was required to supply the Tape Recorder with 240V AC.

Details of the chopper system, elevator system and speed measurements are given below.

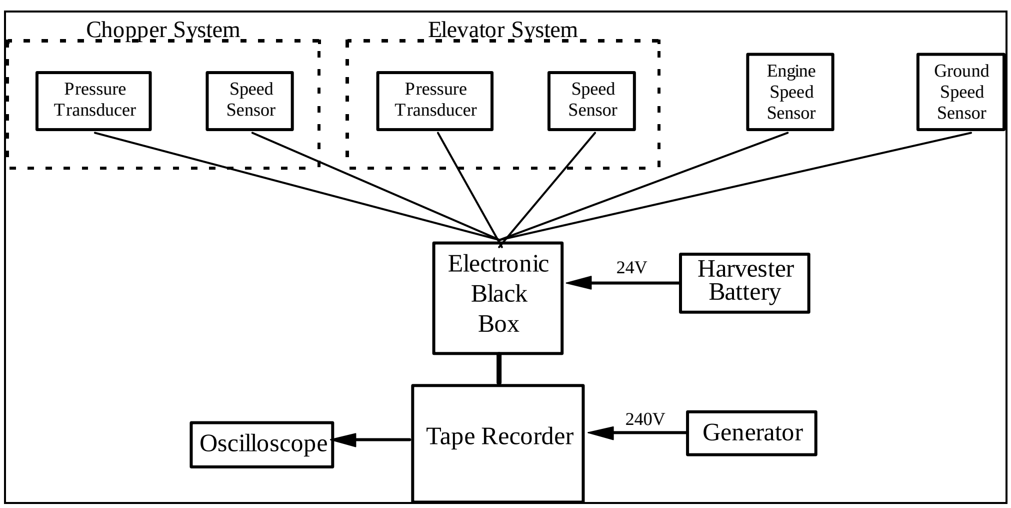


Figure 4.2 Block diagram of the instrumentation installation on the cane harvester.

4.2.2 Chopper System

Two different measurements were required to monitor the chopper system power consumption. The first was the hydraulic pressure supplied to the system and the second was the flowrate of oil through the system.

To measure the pressure required to drive the chopper motor the transducer was attached to the hydraulic delivery line between the pump and motor. Due to the cost of the transducers, only one of the four chopper motors was monitored. Better result may be possible if all or more than one are monitored.

An unexpected result encountered during installation, was that the feed train rollers of the harvester were incorporated in the same hydraulic system as the chopper motors. For practical reasons these systems could not be separated. Therefore and all the power measurements of the chopper system also include power consumption from the feed train rollers. It was unknown how this addition would affect the end results. It must be kept in mind that the chopper results presented later in this thesis do contain effects from the inclusion of the additional system.

The oil flowrate through the chopper motors was measured by speed sensors, recording the rate of motor revolution. Assuming negligible leakage, oil flowrate was calculated by the rate of revolution multiplied by the motor capacity.

4.2.3 Elevator System

The elevator system used the same measurements as the chopper system. One of two hydraulic motors which drive the elevator was monitored. Figure 4.3 shows this motor along with the pressure transducer. Again due to the expense of the pressure transducers, only one of the two motors could be monitored. Better results maybe possible if both motors are monitored.

The speed sensor for this system was located at the lower end of the elevator, measuring the angular speed of an idler sprocket.

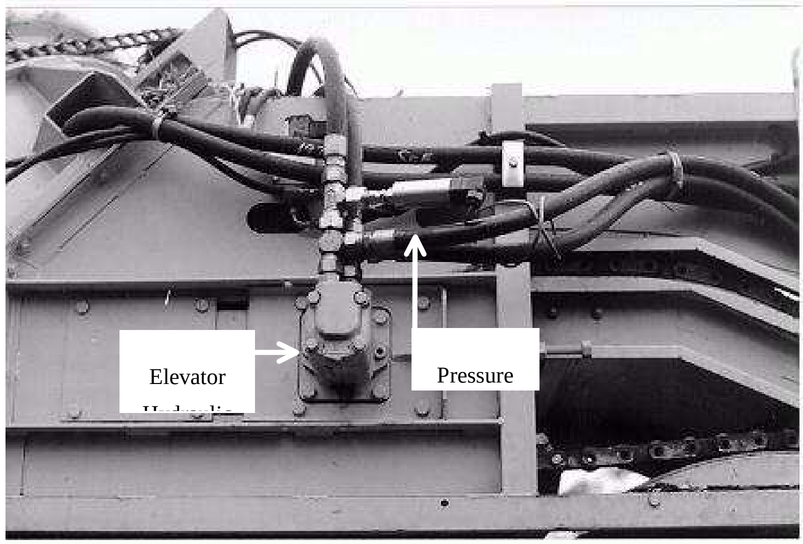


Figure 4.3. Elevator motor with pressure transducer.

4.2.4 Speed Measurements

4.2.4.1 Engine Speed

The harvester engine speed was also monitored, purely for analytical purposes. This signal could be used to reduce noise and improve results, during signal analysis. A great deal of work went into designing and fabricating a part to digitally measure this engine speed. Appendix E is a general assembly drawing of this part. The part was screwed into the engine housing, where it was keyed to a drive shaft. The part incorporated a magnetic pickup which delivered a electronic pulse. Each pulse indicated two engine cycles.

4.2.4.2 Ground Speed

The harvester ground speed was monitored using the sensor incorporated in the RIMIK Cane Loss Monitor. For this measurement, a magnetic pickup indicated every half revolution of the harvester's front wheel.

Chapter 5 : FIELD MEASUREMENTS

5.1 Field Trip

The 3rd to the 5th of June were spent in Bundaberg fitting the instruments to the harvester. The following three days were spent carrying out tests to obtain the required data. The Bundaberg Bureau of Sugar Experiment Station (BSES) provided all personnel and equiptment, which included the AUSTOFT harvester and a specialised weigh truck. Robert Dick, an agricultural engineer with BSES, was the major force behind this assistance.

5.2 Conditions

The three days of testing represented a variation in the harvesting conditions. These variations included differences in weather conditions and changes in crop variety and quality. Day one of testing consisted of a fine dry day, harvesting a crop of variety Q146-2R. This crop yielded heavily at approximately 120 t/ha and was harvested ‘green’. These crop conditions can be seen pictured in Figure 5.1. For reference purposes later in the thesis, this crop will be defined as ‘Field One’.

Day two and three of testing were carried out on a different field to day one. The crop variety for these two days was Q146-3R, which was harvested ‘burnt’ and also yielded approximately 120 t/ha. Differences in weather conditions were experienced during harvesting. These were wet drizzly conditions on day two and then dry conditions for day three. The crop can be seen pictured in Figure 5.2. For reference purposes, this crop will be defined as ‘Field Two’

The differences in the crop and weather conditions which occurred during testing, should not theoretically effect the results of the yield map produced for these fields. If the results of the tests do vary greatly over the three days, then this will indicate that these yield measurment techniques are susceptible to changes in environmental and crop conditions. If so, environmental conditions and crop conditions will have to be taken into account to achieve an accurate yield mapping system.

5.3 Procedure

5.3.1 Field Setup

The field was setup with three ‘witches' hats’ positioned equidistant along a single row of sugar cane. For day one this distance was 112.5 metres and for day two and three it was 130 metres. This distance was decided as the approximate distance required to fill up the weigh truck with sugar cane billets. From this setup each row of sugar cane provided two ‘test runs’ of data. For reference purposes, a ‘test run’ will be defined as the act of harvesting a single row of sugar cane, approximately 100 metres long (between the ‘witches' hats’) for data collection purposes.

5.3.2 Steps

The basic procedure for each test run was:

1. Start the Tape Recorder and stopwatch.

1. Begin harvesting cane from the first ‘witches' hat’ and drive at a preselected speed.

1. Note any irregularities in the crop along with their time of occurrence on a notepad.

1. Stop the harvester at the next witches' hat.

1. Stop the Tape Recorder.

1. Record the weight of sugar cane in the weigh bin of the truck.

1. Unload the weigh truck.

Figure 5.1. The green sugar cane crop harvested as Field 1.

Figure 5.2. Burnt sugar cane crop harvested as Field 2.

5.4 Field Trip Recordings

There were basically two types of field trip recordings. The first and most important were the data captured on the tape by the analog recorder. This data consisted of electrical signals relating to the physical quantities of elevator and chopper motor pressure and speed, along with the harvester's ground and engine speed. An example of this data is shown in this section.

The other type of data recorded in the field was hand written information pertaining to each experimental run. A summary of this data is shown in the following section.

5.4.1 Summary of Field Recordings

Table 5.1 and 5.2 give details of the test runs conducted in Field One and Field Two, respectively. This information includes the row number, the nominal ground speed of the run, the row length and the mass of sugar cane harvested.

The hypothesis being tested was whether the mass flowrate of sugar cane through the harvester was related to the power required to process it. To do this different mass flowrates of sugar cane had to be created. This was achieved by driving the harvester at a different speed for each test run. Assuming the crop yield was somewhat uniform over the field, each run will produce a mass flowrate roughly proportional to the ground speed of the harvester.

Note that the time to complete each test run is not shown in the tables below. These times were recorded with a stopwatch, but a more accurate time of harvesting was obtained during analysis using the chopper pressure signal. Figure 5.3 displays the distinct increase in pressure at the start of harvesting and then the decrease at the completion. During data analysis the time between this rise and fall was measured. This time period defines the harvesting period, which was used to obtain the average mass flowrate for each test run.

Also note that there are runs that have "none" as the row number. These are test runs which are described as 'free running'. 'Free running' is defined as the 'running' of all the harvester components as normal, but 'free' of any harvesting load. These runs provided valuable information about the power required to drive the elevator and chopper systems without processing sugar cane.

Overall, all these test runs provided approximately forty data points to prove or disprove the hypothesis that the mass flowrate of sugar cane through the harvester is proportional to the power required to process it.

Table 5.1. Summary of Field Recordings for Field 1.

Row No.	Run No.	Nominal Ground Speed (kph)	Plot length (m)	Harv. Mass (kg)
1	1.2	2.0	112.5	2023
1	1.3	2.0	112.5	1740
2	1.4	4.0	112.5	1770
2	1.5	4.0	112.5	1667
3	1.6	6.0	112.5	2058
3	1.7	6.0	112.5	1770
4	1.8	3.0	112.5	1960
4	1.9	3.0	112.5	1947
5	1.10	5.0	112.5	2050
5	1.11	5.0	112.5	1760
6	1.12	4.0	112.5	1940
6	1.13	4.0	112.5	1830
7	1.14	6.0	112.5	1799
7	1.15	6.0	112.5	1720
8	1.16	2.0	112.5	1529
8	1.18	2.0	112.5	2053
9	1.19	5.0	112.5	2023
9	1.20	5.0	112.5	1872
10	1.21	3.0	112.5	2082
10	1.22	3.0	112.5	1971

Table 5.2. Summary of Field Recordings for Field 2.

Row No.	Run No.	Nominal Ground Speed (kph)	Plot length (m)	Harv. Mass (kg)
none	2.1	0.0	0	0
1	2.2	5.0	150	2955
none	2.4	0.0	0	0
2	2.5	9.0	130	2897
2	2.6	9.0	130	2374
3	2.7	7.0	130	2337
3	2.8	7.0	130	2135
4	2.10	3.0	130	2227
5	3.1	3.0	130	2205
none	3.2	0.0	0	0
5	3.3	3.0	130	2043
6	3.5	7.0	130	2095
6	3.6	7.0	130	1930
7	3.8	9.0	130	2241
7	3.9	9.0	130	1950
8	3.11	5.0	130	2350
8	3.12	5.0	130	2089

5.4.2 Data Recorded on Tape

Figure 5.3 shows an example of the data captured on tape for each test run. The width of the graph represents the time to harvest the entire row and the voltage axis represents the voltages recorded on tape. The two pressure signals are recorded as a voltage which is proportional to the hydraulic oil pressure driving the hydraulic motors. It is interesting to note the apparent lag of the elevator response behind the chopper response. This is particularly evident at the start and end of the test run. During analysis, this lag was found to range between 2.5 and 3.5 seconds, depending on harvester ground speed.

The other signal in Figure 5.3 represents the ground speed measurement of the harvester. The time between the electrical spikes indicates the time for half a revolution of the harvester front tyre. From these time increments ground speed can be calculated.

Note that the other speed signals of the engine, chopper and elevator are not shown in this figure. Their appearance is given clearly in Figure 5.4.

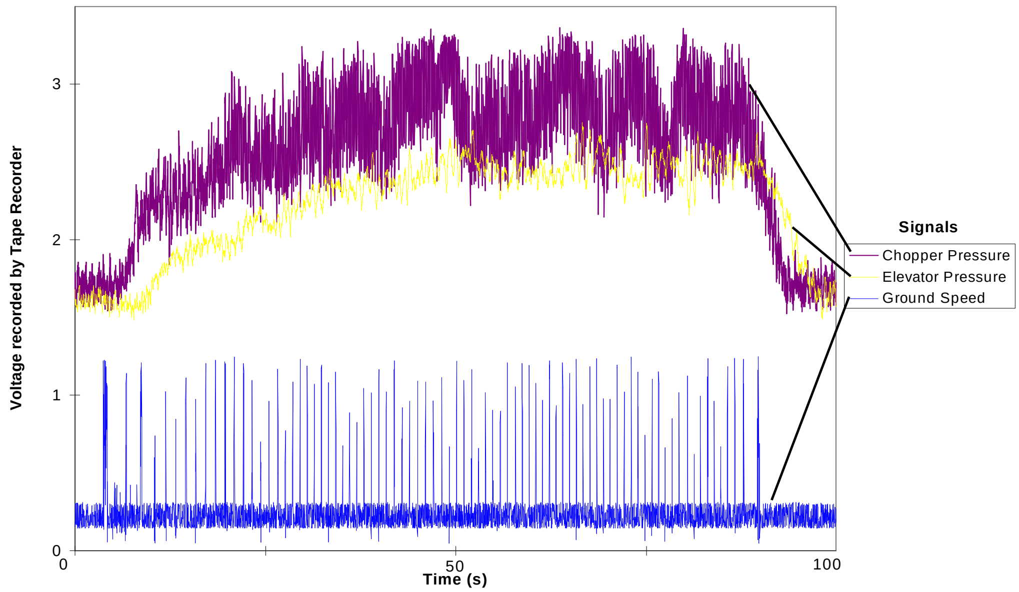


Figure 5.3. Example of the data captured on tape by the recorder for each experimental run.

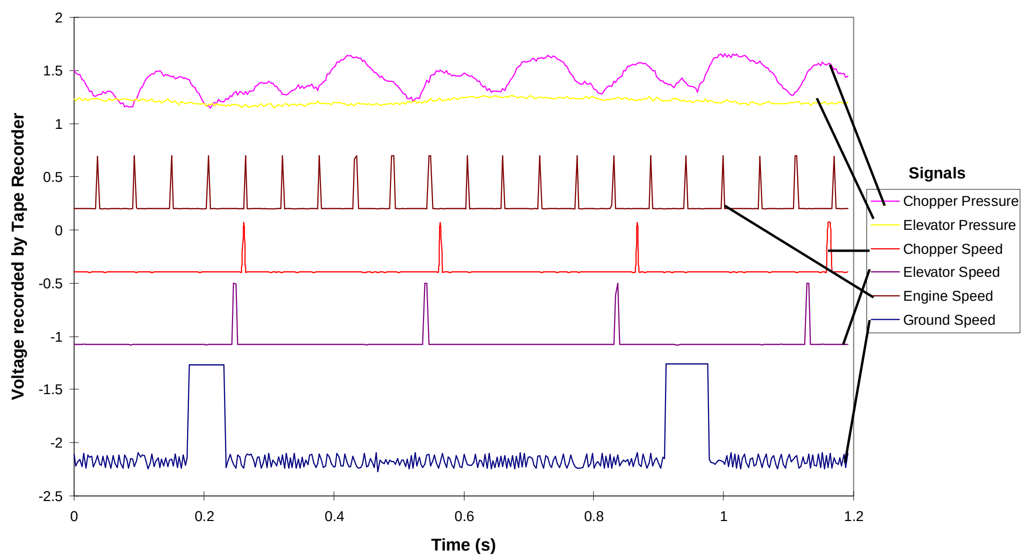


Figure 5.4 A example of a slice of the data (1.2 seconds long) captured on tape.

Figure 5.4 is an enlargement of a small section of Figure 5.3, representing only 1.2 seconds of data. This figure shows all the signals recorded on tape. Again the pressure signals can be seen at the top of the graph. The elevator signal remains steady while the chopper signal appears similar to a sinusoidal wave. The other signals measuring the various speeds, clearly show the voltage spikes depicting the measurement of a revolution. The engine speed signal appears to indicate a revolution time of about 50 milliseconds, while the elevator and chopper speeds appear to occur roughly every quarter of a second. During this particular time period the harvester tyre rotated half a revolution in approximately 0.8 seconds.

Chapter 6 : SIGNAL DIGITISATION AND ANALYSIS

The data recorded in Bundaberg provided the information necessary to make an informed decision about the chosen methods of yield measurement. The next step was to transform the abstract tape recordings to meaningful results. The analysis stage of this project provided these results by signal processing of the recorded data. Before this analysis could be carried out, the analog signal was digitised to permit processing by a computer. These two steps of signal digitisation and analysis are explained in this chapter, so the reader is aware of the process of obtaining the final results.

6.1 Signal Digitisation

To implement signal processing strategies, with a computer, it is necessary to digitise the signal. Digitisation refers to the conversion of a continuous-time (analog) signal into a discrete-time signal. The transformation is performed by an analog-to-digital (A/D) converter. The A/D converter changes a voltage amplitude at its input into a binary code representing an amplitude value closest to the amplitude of the input (Oppenheim and Schafer, 1989)

A major determinant of the digitisation process is the rate of sampling. For this project, the rate was decided in relation to the speed signals. It was these signals for which the rate of sampling had the greatest effect on accuracy; particularly the engine, chopper and elevator speeds. These speed signals were composed of electrical pulses lasting for three milliseconds in length. This means the voltage signals were ‘high’ for three milliseconds marking every revolution (see Figure 5.4). Therefore, to capture ever pulse, sampling had to occur at least at (1.0s/0.003s) 333 Hz. At this rate however, the engine speed signal, which produced pulses at a rate of approximately 20 Hz, would have an unacceptable error of 6% (20Hz/333Hz). To reduce this error to an acceptable limit of 2% a sampling rate of 1000 Hz was chosen.

Implementing this digitisation rate proved to be very difficult. The greatest problem was the sheer quantity of numbers that were produced. A quick calculation shows that for each run which lasts approximately 100 seconds with six channels produces 600 000 numbers. This introduces two problems both relating to computer power and memory requirements. Firstly, these numbers have to be saved in some form and secondly, each of these numbers have to be analysed to obtain results. To achieve this rate of digitisation considerable computing power was required. This power was difficult to obtain for an undergraduate engineering project at the University of Southern Queensland.

Initially a 286AT machine was trialed but the maximum digitisation rate available was 50 Hz; obviously this was inappropriate. A 486SX-33 machine was then trialed, but it also could not handle or deliver the require rate. After extensive investigation, appropriate data acquisition equipment was found. The most important equipment consisted of a 486DX2-66 computer containing 8 megabytes of RAM and a data acquisition card. This machine was important in providing the necessary computing power to digitise the signals at the desired rate of 1 kHz.

The problems with digitisation did not stop with the use of this computer. The software available at the University of Southern Queensland Faculty of Engineering was also found to be inappropriate. The software could not handle the digitisation rate required. The only option left was to develop or write software to do the job. This software along with the equipment used to digitise the data is briefly explained in the next subsections.

6.1.1 Digitisation Equipment

The equipment required for digitisation is shown in Figure 6.1. The Tape Recorder operated like a normal household tape player with play, rewind, fast forward and stop. These functions were used to position the tape at the required data and then reproduce the signals at the output connections. These signals were delivered to the computer via electrical cables. The two thin lines, in Figure 6.1, to going the computer via the oscilloscope, are the ground speed signal and the chopper signal. These signals were observed on the oscilloscope to confirm the start and completion of each test run. The other four signals were relayed directly to the data acquisition card.

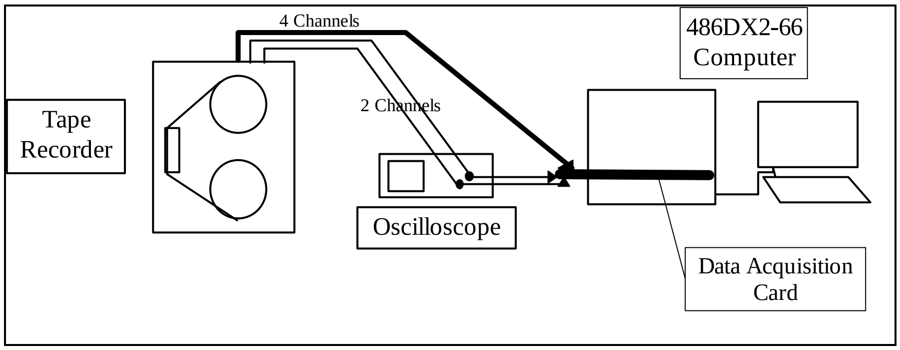


Figure 6.1. Digitising Equipment set up for Data acquisition.

The data acquisition card was a PCI-20428W-1 Low Cost Multifunction Board produced by Intelligent Instrumentation. The card was configured for 6 single ended analog input channels operating in the voltage range of $\pm$ 10V, with 12 bit A/D resolution and with a possible 100 kHz throughput. The 12 bit A/D converter produced binary numbers having a decimal equivalent of 0 to 4096 (2^{12}) for the $\pm$10 volt input range. This produced a maximum digitisation error of 0.0049 volts. The signals were coupled to the acquisition card by a termination panel at the rear of the computer.

6.1.2 Software

As previously stated, the software available could not cope with the digitisation requirements. It was decided to customise a sample driver which came with the acquisition card. The driver code was adjusted until it produced the desired output data. An example of this data is shown in Table 6.1.

Table 6.1. Selection of a data file produced by the digitisation process.

File name: 2_3.dat					
GND Speed	Pressure CHO.	Pressure ELV.	ELV. Speed	CHO. Speed	ENG. Speed
0.880	1.059	0.920	0.286	0.280	0.054
0.880	1.129	0.907	0.286	0.280	0.056
0.880	1.233	0.925	0.286	0.280	0.056
0.880	1.005	0.849	0.286	0.280	0.056
0.880	0.933	0.931	0.286	0.281	0.056

0.880	0.984	0.946	0.286	0.281	0.054
0.880	1.089	1.027	0.288	0.281	0.056

6.2 Analysis Method

The products of the signal digitisation was a number of large data files with little meaning. The purpose of the data analysis work was to make sense of this data. Several types of analysis were employed to obtain useful results. The first and most important, was the calibration analysis, whose purpose was to find the relationship between the power consumption and the mass flowrate of sugar cane. Some analysis was also carried out in the frequency and time domains of the signals to determine any general trends in the data. Finally, the data was processed for the production of yield maps. The basics of each of these analysis steps are discussed in this section.

6.2.1 Calibration Analysis

The goal of the calibration analysis was to prove or disprove the hypothesis of the project, that there is a relationship between the material flowrate and the power required to process it.

There is no known technique available for the measurment of sugar cane flowrate. This means the calibration of the instantaneous power measurements with the instantaneous flowrate was not possible. Therefore the calibration was indirect. This was accomplished by calculating the average power required for each test run and comparing it to the average mass flowrate of sugar cane. The average mass flowrate was calculated by dividing the weigh truck measurement by the harvesting time. With these two results of average power and average mass flowrate for each run, over 35 pairs of data points were availible to determine the relationship between these variables. It should be noted that in general, the use of average values is only valid for linear calibration functions.

The calculation of the power averages was executed using a spreadsheet and this is explained in the following section.

6.2.1.1 Spreadsheet

The analog to digital conversion produced large data files for each test run. Each of these files had to be analysed to obtain the average power requirement. Some type of computer program was required to carry out these calculations. A spreadsheet was selected as the medium for this analysis. The reason for this selection was the ease of interface between the data and analyser. A spreadsheet can provide the capacity to easily edit and graph data. These points were critical for removing irrelevant data from the beginning and end of the test runs and also for observing any irregularities in the data.

The spreadsheet was written to analyse the data files in a series of steps. Each step carried out a particular function using macro's. Figure 6.2 shows the appearance of the spreadsheet. The calculations were carried out in the vacant cells shown in the lower half of the figure.

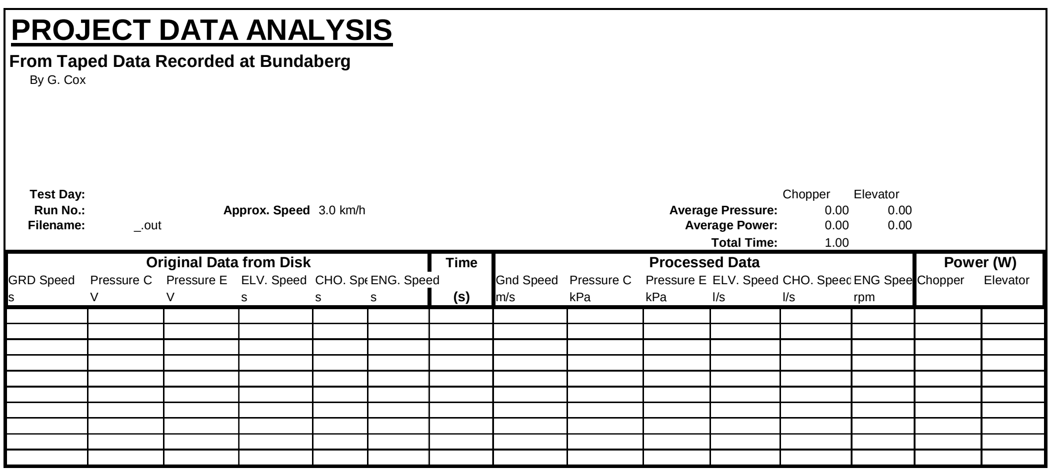


Figure 6.2. View of the spreadsheet developed to analyse the data.

A graphical example of the data produced by this spreadsheet is shown in Figure 6.4. Simple averaging of the power and pressure signals over the whole run was carried out to obtain the required calibration results. These results are given in the next chapter.

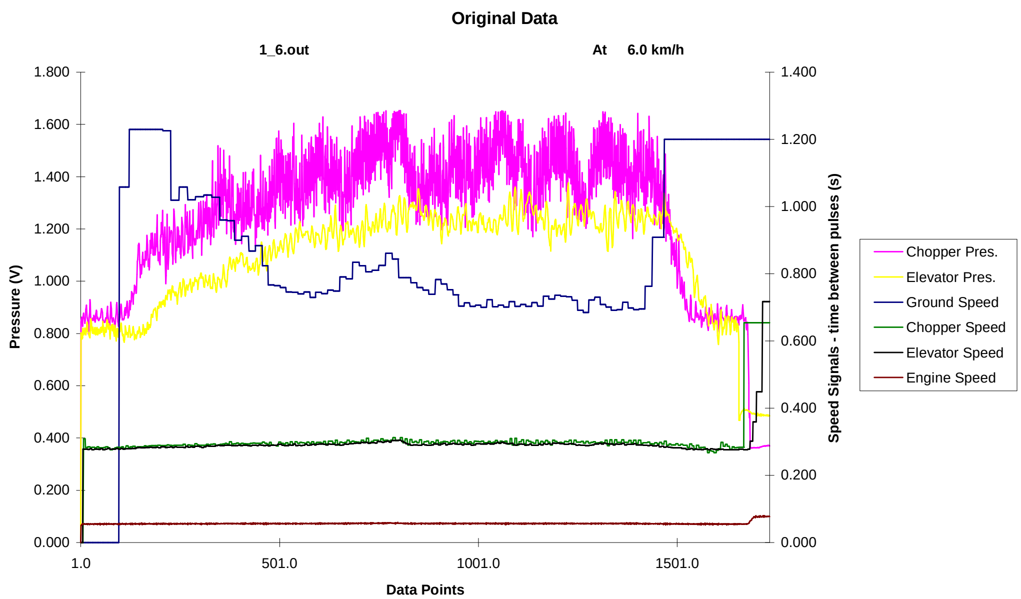


Figure 6.3. A graphical view of a data file produced by digitisation of an experimental run.

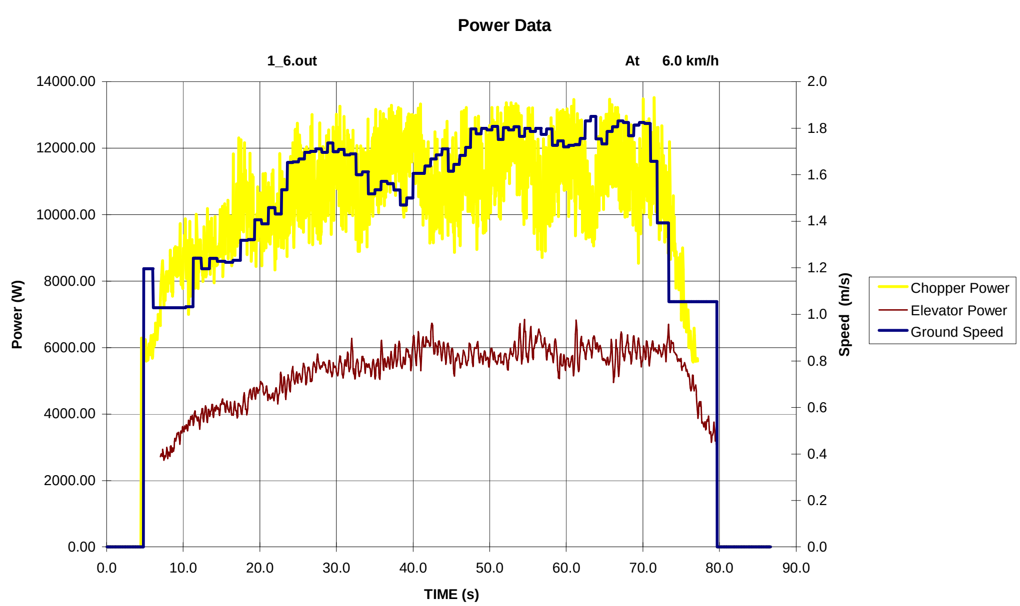


Figure 6.4. A graphical view of the power data produced by the spreadsheet, from the digitised data.

6.2.2 Spectral Analysis

Some simple analysis in the frequency domain was carried out on the recorded pressure signals. Frequency spectrums were calculated using the Fast Fourier Transform (FFT) function available in Microsoft Excel. Each FFT was carried out on 1024 data points, representing 51 seconds of signal. The results of this analysis are shown in the following chapter.

6.2.3 Yield Map production

Yield map production was not a requirement of this project, but all the data was available and out of interest yield mapping principles were applied. Field One results were the most suitable for this job, with a strong calibration function and data for a continuous area, 225 metres long and 10 rows wide.

The calculations were carried out using a modified version of the spreadsheet shown in Figure 6.2. The yield maps were reconstructed, run by run, using the pressure data along with the pressure calibration functions, given in the results chapter. The basic calculations required were:

1. Obtain the location data.

    a) Integrate the ground speed signal to obtain the distance travelled down the row.

    b) Correct this integrated distance by the known error at the end of the row.

2. Obtain the yield data.

    a) Predicte 'site' yields by applying the calibration results to the pressure signal data at every data point.

    b) Average the 'site' yield to obtain an average yield for every 10 metres along the row.

This procedure produced 11 evenly spaced yield points for each 112.5 m long test runs. The yield calculations were carried out using both the chopper and elevator pressure data, and the yield maps produced from each of these techniques is shown in the next chapter.

Chapter 7 : RESULTS

Several different and interesting outcomes were produced by the signal analysis explained in the previous chapter. The results of the calibration, spectral and temporal signal analysis and yield map production are individually presented in this chapter.

7.1 Calibration

The analysis of each experimental run conducted at Bundaberg, produced an average mass flowrate of sugar cane during the run, along with the average operating powers and pressures of the chopper and elevator motors. These results are shown in table form in Appendix F. The relationship between these variables can be shown in an X-Y plot, where the independent variable of average mass flowrate is plotted along the X axis and the dependent variables of average hydraulic power or pressure are plotted along the Y axis. In this section these calibration results will be graphed to show the strong linear relationship that exists between them. Also, the calibration curves obtained by linear regression of these plots will be given.

7.1.1 Power Graphs

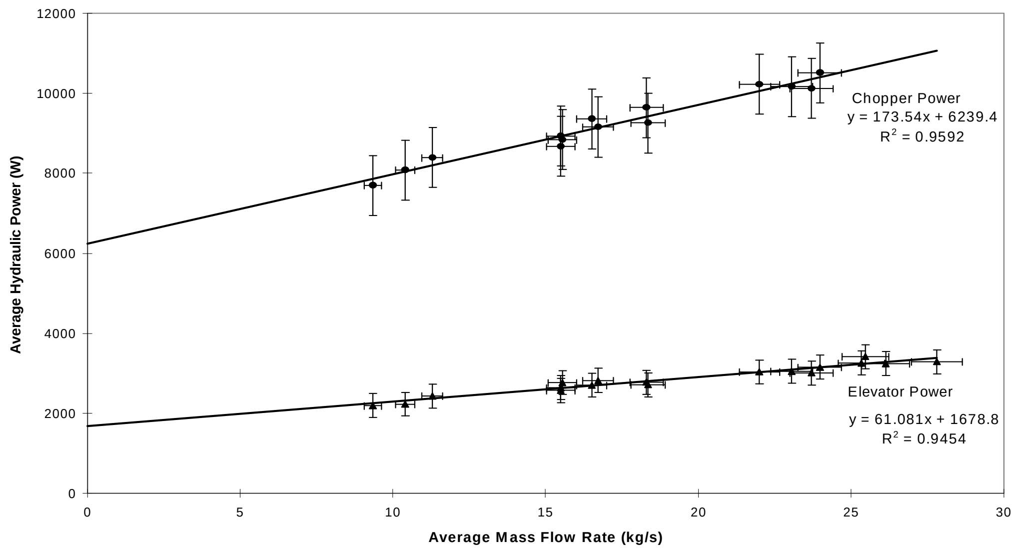


Figure 7.1. Calibration functions of average hydraulic power versus average mass flowrate of harvested sugar cane for Field 1.

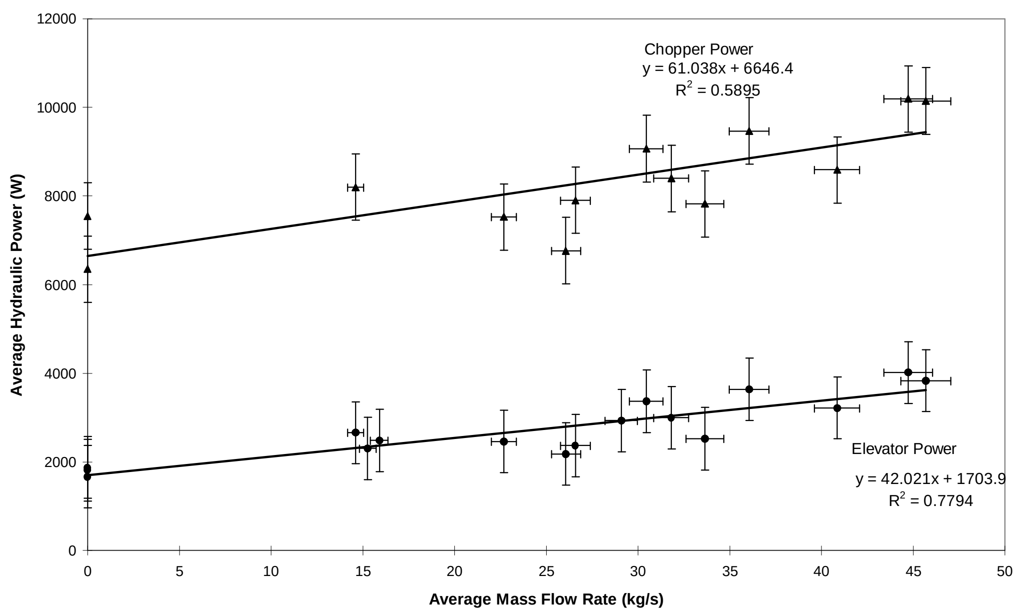


Figure 7.2. Calibration functions of average hydraulic power versus average mass flowrate of harvested sugar cane for Field 2.

7.1.2 Pressure Graph

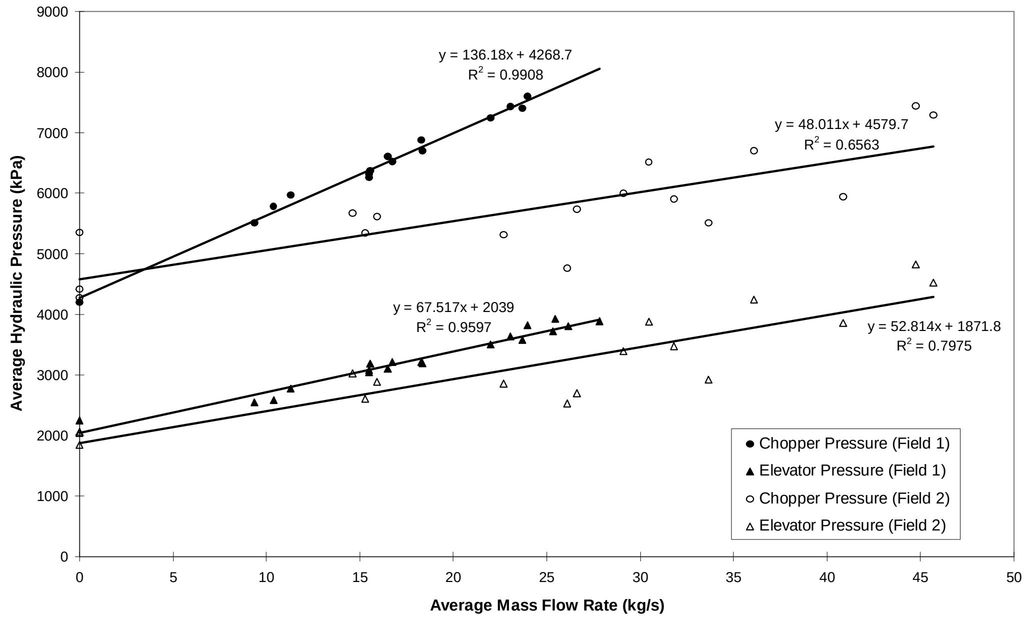


Figure 7.3. Calibration curves of average hydraulic pressure versus average mass flowrate of harvested sugar cane for both fields.

7.1.3 Calibration Coefficient and Statistic

Under the assumption of linearity, the relationship between the X-Y variables can be expressed as:

$$P = mF_r + b$$

where, P is the pressure or power measurement, F_r is the flowrate (kg/s) and m and b are calibration parameters. The calibration functions for each field are given below.

Note that the average absolute errors were calculated by the following equation:

$$\text{Avg. Abs. Error FS} = \left[\frac{\sum \frac{\text{verticaldeviation of data point from calibration line}}{\text{vertical scale of calibration line}}}{\text{No. of data points}} \right] x100$$

Table 7.1. Estimated flowrate calibration coefficients for Field 1.

Measurement Technique	Model	Regression Coefficients		Statistic			
		Slope, m	Intercept, b	R^2	Avg Abs. Error FS	Err. Bar P	Err. Bar F
Chopper Power	$P_c = mF_r + b$	173.5	6239	0.959	1.4 %	750 W	3 %
Elevator Power	$P_e = mF_r + b$	97.7	2686	0.945	2.1 %	300 W	3 %
Chopper Pressure	$p_c = mF_r + b$	136.2	4268.7	0.991	2.1 %	-	-
Elevator Pressure	$p_e = mF_r + b$	67.5	2039	0.960	4.6 %	-	-

Table 7.2. Estimate flowrate calibration coefficients for Field 2.

Measurement Technique	Model	Regression Coefficients		Statistic			
		Slope, m	Intercept, b	R^2	Avg Abs. Error FS	Err. Bar P	Err. Bar F
Chopper Power	$P_c = mF_r + b$	61.0	6646.4	0.589	17.1 %	750 W	3 %
Elevator Power	$P_e = mF_r + b$	67.2	2726.2	0.779	6.7 %	300 W	3 %
Chopper Pressure	$p_c = mF_r + b$	48.0	4579.7	0.656	13.1 %	-	-
Elevator Pressure	$p_e = mF_r + b$	52.8	1871.8	0.798	10.2 %	-	-

7.2 Spectral and Temporal Signal Analysis

The results of the spectral and temporal signal analysis were graphs showing some characteristic and variation of the measured signals. The first is a graph showing the variation in engine, chopper and elevator speeds throughout a typical experimental run. The other two graphs are typical spectral densities of the elevator and chopper pressure signals during harvesting.

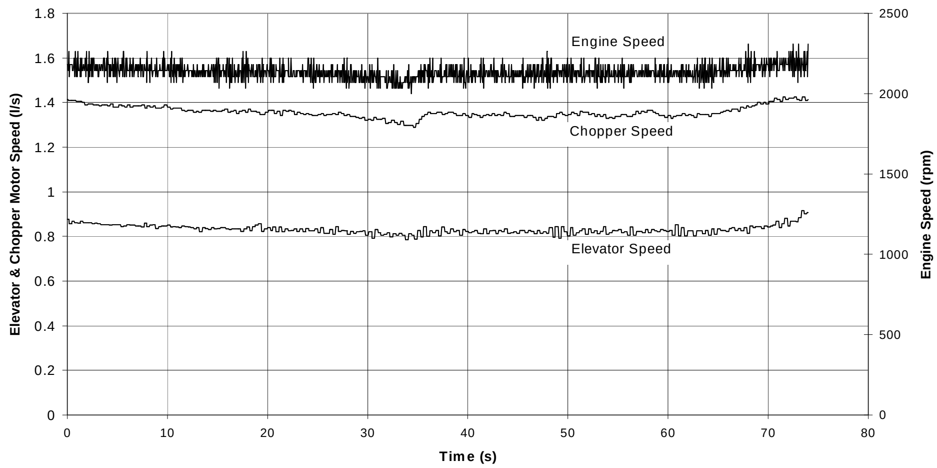


Figure 7.4. Graph of Elevator motor, Chopper motor and Harvester Engine speeds during a typical experimental run.

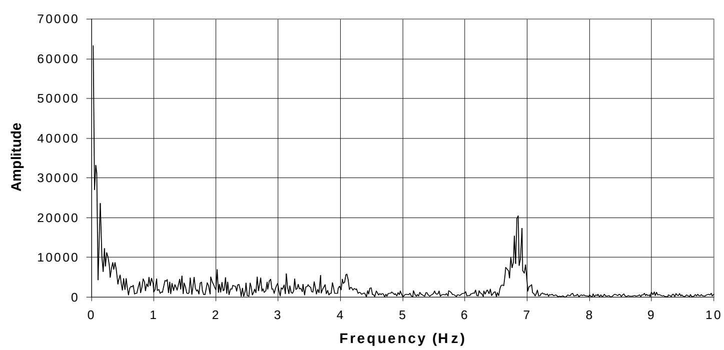


Figure 7.5. Frequency Spectrum of the Chopper pressure signal.

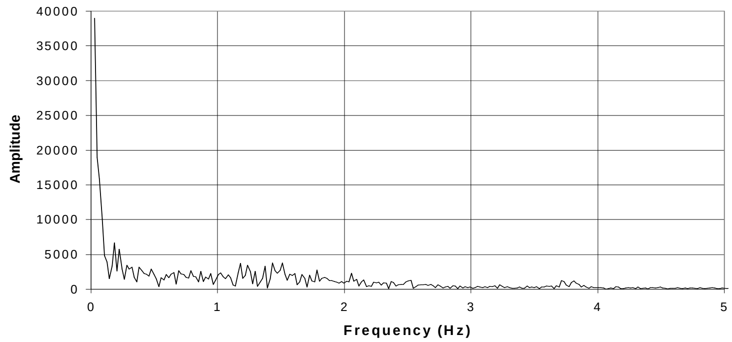


Figure 7.6. Frequency Spectrum of Elevator pressure signal.

7.3 Yield Maps

The yield maps were constructed for Field 1, using three different sets of data. The first, shown in Figure 7.7, was reconstructed using the elevator pressure signals of each row. The calculation of these yield measurements was explained in the previous chapter. Figure 7.8 is the corresponding yield map assembled using the chopper pressure data. These two maps have been plotted using a yield measurement for every 10 metres along each row.

The third map (Figure 7.9) was reconstructed from the weigh truck measurements. Masses of harvested sugar cane were measured for each half row length for Field One. These masses were simply averaged along the length of measurement to obtain an average yield. Therefore this map has been plotted using only a single yield measurement for every 112.5 metres along each row. This is the reason for the unnatural systematic appearance of the map. The main reason for this map is to provide a means of comparing the other two maps for general trends.

The yield data used to construct each of these yield maps is given in Appendix G.

Figure 7.7 Yield map produced using the Elevator data.

Figure 7.8. Yield Map produced using the Chopper data.

Figure 7.9. Yield map produced using the Weigh Truck data.

Chapter 8 : DISCUSSION

8.1 Calibration

The results of the calibration gave evidence of a linear relationship between the mass flowrate of sugar cane and the power consumption of the elevator and chopper system's of an AUSTOFT 7000 cane harvester. This result opens the way for the measurement of crop yield during harvesting, and subsequently the possibility of yield mapping.

Field One results gave the best indication of the linear relationship. For this field both the chopper and elevator systems gave a high coefficient of determination (R^2) of about 0.95. Field Two results are not as good because there were faults with the data acquisition system during testing. The power source for the Electronic Black Box appeared to be overloaded and this resulted in the pressure signals apparently being degraded by interference from the speed signals. The averaged pressure results for the Field Two runs were generally lower than they should have been due to this interference. Some runs were affected more than others, which resulted in the scatter of the data points. For Field 2 a general trend of increasing power consumption was still evident, but the scatter is much higher with R^2 down to 0.58 and 0.78 for the chopper and elevator respectively.

The results indicated a significantly high 'free running' power requirement for both systems. In both cases this power was approximately 60% of the full load power requirement, measured at maximum mass flowrate. This is due to the high friction losses that occur when moving the large masses. This outcome is exacerbated by fact that the power consumption is calculated using hydraulic system readings, and therefore the energy inefficiencies of the hydraulic motor are also included in the result. A lower 'free running' power measurement may be possible using torque transducer attached directly to the drive shafts, but this does not guarantee better results.

The graph shown in Figure 5.3 contains the pressure data points obtained for both days. Field One results are once again very good, with the Field Two having considerable scatter. This graph shows an interesting, but expected result. It appears the slope of elevator calibration line is relatively unaffected by the different conditions between Field One and Two. However the chopper calibration is effected considerably, with the slope of the Field Two line being less than a half of Field One. This may be due to the fault during data acquisition, but it is likely that most is due to the changes in crop condition. The most obvious change in crop condition was the green cane in Field One and the burnt cane in Field Two. The additional extraneous matter for Field One may have notably increased the power consumption for the chopper.

These results were expected from the chopper because the mass flowrate is indirectly measured using the assumption that chopping force is proportional to number of cane stalks being cut. As discussed in chapter three, there are other factor involved in this action. The elevator measures mass flowrate more directly using the power required to shift a mass. As discussed in chapter three there are only three variables of concern, the mass of cane, the coefficient of friction and the angle of the elevator to the horizontal. If the last two variables can be kept relatively constant then mass flowrate can be accurately inferred. This points to the use of the elevator system as the best option for the use in yield mapping for sugar cane.

One unsettling point on the pressure graph was the free running data point for the chopper, which occurred at zero mass flowrate and approximately 5500 kPa. This 'free running' point appears to be much higher than the other three 'free running' points at approx 4250 kPa. This can not be due to the problems with the Field Two data, because lower than actual pressure readings were expected. This reading was taken at the beginning of the day prior to any harvesting and the hydraulic oil was 'cold', resulting in higher than normal viscosity. This viscosity increase could produce higher power readings due to the additional power losses, however the elevator measurement at the same time does not back up this theory. It would be crucial in yield mapping operations that this base value remain constant. If this value changes the whole calibration curve would be displaced resulting in yield measurement errors. The variation in this 'free running' power, for both the chopper and elevator, may have to be investigated further to provide confidence in these methods of measuring mass flowrate.

Table 7.1 shows average absolute error of less than 5% for the data set. This satisfies the requirement given in chapter three of errors less than 5 to 10% suggested by Harvard

(1983), for yield mapping purposes. The best results were given by the chopper and elevator power readings with an average error of only 2%. The pressure results were also very good indicating that motor speed measurements may not be required for accurate yield measurements. These results will be discussed in the next section using the temporal results.

Table 7.2 shows the calibration curves for Field Two. Again, due to the errors during data acquisition the statistics are considerably worse than Field One, but the trends are still consistent.

The error bar values are given in the tables and shown on the power graphs. They are very large but are an indication of the pressure signal variations rather than the overall errors of the technique. These error bars represent the standard error obtained if a single instantaneous pressure reading is used to measure the material flowrate at the same instant. If however, the pressure signals are smoothed or averaged over, say 3 seconds, then the material flowrate measurement error would be significantly reduced. During yield mapping operations this would be accomplished using a slow moving average of the pressure readings.

The theoretical implications of these calibration results are that sugar cane mass flowrate can be successfully measure by the power consumption of the elevator and chopper systems. The practical application of this technology is the construction of yield maps for sugar cane agriculture. Therefore the major objectives of this project have been completed.

8.2 Spectral and Temporal Analysis

Figure 7.4 presents the engine, chopper and elevator speeds during a typical experimental run. At this ground speed of approximately 6 kph significant variation of all three speeds occurred, with the lowest speeds occurring at approximately half way. For the chopper and elevator, this speed was approximately 90% of the free running speeds shown at the start and finish of the run. All signals varied together in time as expected, due to load increases on the harvester. The engine speed decreased as the machine was loaded, and this led to a proportional drop in hydraulic motor speed. There may also be addition speed reductions owing to the increase leakages within the hydraulic motors at the higher operating pressure. This variation in motor speeds indicates that the linear functional relationship between mass flowrate and hydraulic pressure will not hold. This maybe particularly important at the higher flowrates where cane harvesters usually operate. For example, during the harvesting of Field One, the harvester driver was 'comfortable' at a speed of 6 kph. This corresponded to the relatively high mass flowrate of approximately 25kg/s. The possible reduction of the linear relationship for hydraulic pressure at the higher flowrates may indicate that the power measurements would be required to obtain sufficiently accurate yield measurements.

Note the square structure of the speed signals in Figure 7.4 indicate the error or resolution due to digitisation of the analog signals. This is particularly evident for the engine speed signal.

The frequency spectrum of the pressure signal exhibited some interesting results. The most obvious is the peak that occurs at 7Hz for the chopper signal. This is due to the cutting action of the rotary drum choppers, which rotate at approximately 3Hz and make two cuts every revolution. The amplitude of spectral peak would be related to the chopper blade sharpness. The magnitude of the peak would increase as the blades grow blunter with wear and higher chopping forces are required. The elevator frequency spectrum is smoother with no significant frequency above 2.5Hz. This difference between the chopper and elevator signals is also evident in Figure 4.3 where the elevator pressure signal is substantially smoother than the chopper signal.

8.3 Yield Maps

Yield mapping principles were applied to the data gathered during Field One harvesting. The maps generated from the chopper and elevator pressure data are very similar. The average absolute difference between the yield maps at each measurement point was substantial at 10%. This error is mostly due to the minor differences or inaccuracy in the yield calibration functions.

The maps appear to indicate a high degree of spatial variability. Although this variability can not be backed up with visual observations during harvesting, the weigh truck yield map also displays this significant variation.

It must be remember that the yield maps produced by the chopper and elevator should not look identical to the weight truck map. The weigh truck map is not a ‘yield map’ in the strict sense. It is constructed of yields averaged over 112m length of row, and although these average yields are very accurate, this map only has a spatial resolution of 112m along the row.

Even though the weigh truck yield map overall appears very different to the chopper and elevator maps, similar general trends are present. On all maps, higher yields occur along the full length of rows nine and ten and also with the first hundred metres of rows three, four and five. There are some areas in the maps that appear suspicious. These are the low yield measurements of below 90 t/ha, indicated as the white areas. Row one on the elevator map is the displays a relatively low yield measurement while the chopper and weigh truck maps show higher yields. This was probably due to apparent error in the calibration curve, which did not fit as well to the data points at the lower flowrates, at which this row was harvested. There also appears to be a slight valley across the yield maps at the halfway mark, 115m. This corresponds with the point where the harvester stopped on each row to weigh the harvested cane, which completed a defined ‘test run’. Due to the stopping and starting of the harvester at this point, the ground speed and hydraulic pressures varied too greatly to achieve accurate yield reading.

These yield maps are the first of their kind ever produced using instantaneous mass flow measurement during harvesting of sugar cane. This technique can open up a whole new realm of information to improve the management of sugar cane agriculture.

Chapter 9 : CONCLUSIONS

The main objective of this project, to develop the basic technology to enable the measurement of yield variability in sugar cane, has been achieved. The yield measurements can be done during the mechanical harvesting operation of a billet harvester. This development, when incorporated with a machine location method, enables the production of yield maps.

The Global Positioning System (GPS) appears the best location system for the location of cane harvesters during yield mapping operations. Specifically Differential GPS will provide the required accuracy with ease of implementation. Although there is a high initial outlay, the future improvement in its accuracy will enable its use in other agricultural practices.

Yield measurements during harvesting require the simultaneous measurement of material flowrate and travel speed. The power consumption of the billet harvester’s elevator and rotary drum chop system (chopper system), appeared to be the simplest option for mass flow measurement of sugar cane. There were concerns however, for the reduction in accuracy due to the influence of unwanted variables. For the elevator, variation in the coefficient of friction and the angle of the elevator to the horizontal, may produce significant errors to the yield measurements. The chopper system’s accuracy can be affected by changes in the extraneous matter, moisture content, plant maturity and the knife sharpness.

An experiment was designed to test if the hydraulic power consumption of the elevator and chopper system could be used to measure the material flowrate, for yield mapping purposes. The power consumption of each system was measured using the hydraulic oil pressure and speed measurements of appropriate motors. An AUSTOFT 7000 cane harvester was fitted with a series of transducers and field tests were carried out. For practical reasons, it was not possible to measure the hydraulic power on the chopper system separately, so the feed roller system was also included.

An extensive data processing scheme was followed to transform the raw transducer signals to power measurements. These results indicated that there was a strong linear relationship between the mass flowrate of sugar cane through the harvester and the power consumption of the elevator and chopper systems. High coefficients of determination, greater than 0.94, were found for both methods. Additional corrupted data produced the same linear relationship, but had lower coefficients of determination. The uncorrupted power results had an average absolute error, about the linear calibration function, of approximately 2%, over the full range of values. This result is well within the requirement for yield mapping application.

Hydraulic oil pressure at the elevator and chopper motors was also a strong indicator of material flowrate. Compared to the power results, the pressure results produced similar coefficients of determination and average errors. This outcome indicated that pressure measurements maybe as reliable as power measurements for the determination of mass flowrate. Therefore, speed measurement may not be required. Further analysis of the speed measurement however, indicate that at normal operating mass flowrates, the angular speeds of the hydraulic motors do decrease considerably. Therefore power readings, may be a better indicator of mass flowrates during normal harvesting conditions.

Even though both the chopper and elevator systems provided a strong linear relationship for mass flow measurements, the elevator would be the best option for application in a full yield mapping system. The reason for this is the variation of the chopper calibration function under different crop conditions. The calibration results indicate the slope of the linear calibration function decreased significantly between two fields, probably as a consequence of difference in conditions between a burnt and 'green' harvested crop. Under these same harvesting conditions, the elevator calibration function displays only a minor change.

Yield maps were produced using the calibration functions and the raw signals for both the elevator and chopper systems. The sugar cane plot, 225m long and 15m wide, showed a high degree of spatial yield variability. The general trends of the yield variation agreed with average yields calculated using harvested masses.

9.1 Further Work

Further work for the project could involve research into the factors that effect the accuracy of the elevator mass flowrate measurements. Some factors which could be investigated are:

1. Effect of changes in the coefficient of friction on the elevator floor. The coefficient may be affected by crop properties or wet conditions.

2. The possible variations in the elevator angle during harvesting and how much this affects the calibration function.

3. The possible variation in hydraulic pressure measurements resulting from fluctuations in hydraulic oil temperature.

Additional research is also required into the transportation delay of the harvester. The mass flowrate being measured at the elevator has a transportation delay from when it was cut by the base cutters. This delay must accurately be determined to produce consistent yield maps. During the testing for this project, the delay was approximately three seconds, measure from the chopper response, which was assumed to have no delay.

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Hall D, Academic Lecturer, USQ, Toowoomba, October 1995

Appendix A: Project Specifications

Development of technology for yield mapping in Sugar Cane

Honours Project Plan

Name: Graeme Cox

Supervisors: Assoc Prof Harry Harris; Dr Randolph Pax **USQ**

Mr Robert Dick **BSES**

Objectives: To develop the basic technology to enable the measurement of yield variability in sugar cane. This work is seen as the first step towards a full yield mapping system.

Research Plan:

(1) Undertake a literature review of the options available for the mapping yield variability in sugar cane at the field level. Particularly examine the possible use of remote sensing and harvester integrated measurement systems.

(1st-17th March 1995)

(2) Analyse, assess, and document the options for the measurement of the mass flowrate through a cane harvester.

(17th March-7th April 1995)

(3) Propose one or more techniques for measuring mass flowrate through a cane harvester.

(7-14th April 1995)

(4) Design the instrumentation to measure the flowrate using the chosen technique(s).

(14th-28th April 1995)

(5) Manufacture the selected instrumentation.

(28th April-30 June 1995)

(6) Implement the instrumentation on a harvester and carry out field tests of the techniques at Bundaberg in July, 1995.

(3-14 July 1995)

(7) Analyse, assess, and document the options for remotely sensing yield of sugar cane at the field level.

(4th August 1995)

(8) Analyse, assess, and document the options for harvester location, to include dead reckoning, local triangulation and GPS.

(18th August 1995)

(9) Analyse the field test results.

(18th August-22nd September 1995)

(10) Provide a report by November 1, 1995.

(1 November 1995)

Appendix B: Remote Sensing Review

Remote sensing is a technique using reflected information from earth. Using a recording instrument, such as a camera, spectral data from the plant is reflected back to the receiver and this information can be interpreted in many ways. There are several techniques used to gather data for remote sensing use. Of these the most commonly used and the most applicable to irrigation agriculture application is spectral sensing. Spectral sensing involves the measuring or recording of the reflected light from a source, such as an agricultural crop. The recording can take the form of a photograph, a series of photographs, video tape or other media. These measurements provide data relating to the light reflected by the crop, and this data can be interpreted to provide information about the condition of the crop. An example of the application of this technique, often used in farm management, is the association of a green crop as healthy and an off colour, such as brown, with unhealthy.

The extension of this method to separately measure and record different sections of the light spectrum is known as multispectral sensing. The visible and invisible light spectrum can be devised into different types, such as inferred, ultraviolet, red and green. By using optical filters, special film and other methods, these spectrum sections can be individually recorded. Multispectral sensing can provide additional data on which to obtain information about crop condition. Specifically, information about crop biomass can be obtained and from this crop yield maps can be devised. Drury (1990, pp 94) states that a semiquantitative measure of the density of plant cover can be given one of several vegetation indices. The vegetation indices in question is the ratio between very near infrared and red reflectance. This interpretation by Drury indicates that it may be possible to use these indices to measure sugar cane yield. Colwell (1983) however, states that spectral biomass techniques have been found to be accurate for low to medium biomass quantities, but are little value over 5000 kg/ha. This statement exempts sugar cane from this method because the typical yields for this crop is 100 000 kg/ha.

The assumption that this technique will not work for sugar cane is also supported by Kirchner and Lee-Lovick (1992) who little or no correlation between spectral signatures of sugar cane and it's yield. This work is the most comprehensive available in relation to remote sensing research carried out on sugar cane. From this paper there appears to be no merit in the use of remote sensing for yield estimation of sugar cane.

Although this technique does not work for final yield measurement of sugar cane, it could be used in the early stages of growth to find problems etc. Geoff Cox (1995, pers. comm.) believes this may be the most important time to get things right and so remotely sensed data may become useful in the future of sugar cane production.

Appendix C: Theoretical Elevator Load Calculations

Comparison of elevator load for different coefficients of friction and elevator angle.

Max. Pour Rate= 180 t/hr
= 3t/min

h= F. sin(α)
v= F. cos(α)
p= h + v.μ
Velocity= 1.9 m/s
Power= p*vel

Elevator Speed = 222 flights/min
F(per flight) = mass per flight.gravity
F(per flight) = 133 N
F(total) = 1326 (ten flights)

Table of Power (Power required to raise cane load in Watts)

μ α –>	0	10	20	30	40	50	60	70	80	90	100
0	0	426	839	1226	1576	1879	2124	2305	2415	2453	2415
0.1	245	667	1069	1439	1764	2036	2247	2388	2458	2453	2373
0.2	491	909	1300	1651	1952	2194	2369	2472	2500	2453	2330
0.3	736	1150	1530	1863	2140	2352	2492	2556	2543	2453	2287
0.4	981	1392	1761	2076	2328	2509	2614	2640	2586	2453	2245
0.5	1226	1633	1991	2288	2516	2667	2737	2724	2628	2453	2202
0.6	1472	1875	2222	2501	2704	2825	2860	2808	2671	2453	2160
0.7	1717	2117	2452	2713	2892	2982	2982	2892	2713	2453	2117
0.8	1962	2358	2682	2925	3079	3140	3105	2976	2756	2453	2075

Appendix D: Electronic Block Box Circuitry

Circuit diagram

Figure D.1 is the schematic representation of the electronics within the box. On the left of the figure, blocks representing the transducers are depicted. The outputs on the right are voltages which are applied to the recorder channels. Within these two points are the circuits necessary to supply power to the transducers and to condition the signals for recording on tape.

For the pressure transducers, labelled P1 and P2 in the figure, their 4-20 mA output signal had to be converted to a 0-3 Volt input to the recorder. This is facilitated by applying the current across a resister. By using Ohm's law, V = I.R, the voltage drop across the resister is proportional to the current flowing through it. This "load" resister is depicted in the figure by Rs. This voltage drop is exactly what is required by the recorder. The LM741 Operational Amplifier following the load resister simply adjust the magnitude of the voltage, using resisters R1 and R2, and also provides some buffering from interference. The output voltage is given by the formula Vo = i.Rs.R2/R1. Therefore by adjusting Rs, R1 and R2 the desired 0-3 Volt output can be made.

The pressure transducers were powered by 12V supplied by the a stable power source, via the black box.

The next output from the circuit was Vo1 the timer signal. This subcircuit basically uses a 555 timer chip to produce voltage pulses at a constant rate. This was to be used during data processing as a stable time base, but the Tape Recorder operated constant speed (within 5%), so this subcircuit was deemed redundant and not used.

What seemed to be the simplest signal, the speed signals, turned out to be the most over complicated interfacing. This circuit was designed for a 4 channel recorder. So with only one channel left after the two pressure signals and the time base, all speed signals had to be measured on this remaining channel. Basically, the remaining electronics shown in the circuit, condition the speed pulses so they can be recorded on a single channel by multiplexing. Due to the fact that no 4 track recorder ever existed, a 7 track recorder was used and none of this extra electronics are required. However because the circuit was already half completed some of the circuit was used to provide speed pulses of a constant 3 millisecond length.

To power the speed sensors a 78L05 chip was used to reduce the supply voltage from 12V back to 5V as shown in the figure.

Even though half of the components in the circuit are redundant for this project, they do exist on the circuit board and could be used if necessary for different situations.

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Appendix E : Digital Engine Tachometer

Appendix F : Calibration Results

F.1 Pressure Data

day 1

Run	Time	Mass	Avg. Flow	Avg Pc	Ave Pe	Linear Fit		% Error FS	
	(s)	(kg)	Rate (kg/s)	(bar)	(bar)	Pc	Pe	Pc	Pe
	5	0	0.00	4198.422	2244.672	4269	2024.90	2.08	13.92
2	194.5	2023	10.40	5781.1	2581.2	5683.54	2728.68	2.87	9.34
3	186.2	1740	9.34	5508.4	2543.5	5539.892	2657.21	0.93	7.20
5	101	1667	16.50	6601.7	3099.8	6513.673	3141.69	2.59	2.65
6	74	2058	27.81		3885.4	8051.27	3906.69		1.35
7	69.5	1770	25.47		3920.5	7732.597	3748.14		10.92
8	126.5	1960	15.49	6313.3	3044.6	6376.194	3073.29	1.85	1.82
9	125.7	1947	15.49	6254.2	3080.1	6375.539	3072.97	3.57	0.45
10	85.5	2050	23.98	7595.7	3823.2	7529.819	3647.25	1.94	11.15
11	80	1760	22.00	7238.50	3498.70	7261	3513.51	0.66	0.94
12	105.7	1940	18.35	6699.50	3193.70	6765.121	3266.79	1.93	4.63
13	100	1830	18.30	6870.80	3214.90	6757.8	3263.15	3.33	3.06
14	71	1799	25.34		3714.60	7714.972	3739.37		1.57
15	65.8	1720	26.14		3797.80	7824.015	3793.62		0.26
18	181.9	2053	11.29	5962.80	2770.30	5803.953	2788.58	4.68	1.16
19	85.35	2023	23.70	7398.60	3581.20	7492.527	3628.70	2.76	3.01
20	81.2	1872	23.05	7426.90	3633.90	7404.369	3584.84	0.66	3.11
21	124.5	2082	16.72	6518.20	3214.50	6543.313	3156.44	0.74	3.68
22	126.8	1971	15.54	6368.80	3187.90	6383.006	3076.68	0.42	7.05
Day 2									
1	38	0	0.00	5348.94	2045.92	4579	1872.00	24.32	5.84
2	111.1	2955	26.60	5730.91	2698.67	5855.688	3276.36	3.94	19.40
4	38.5	0	0.00	4412.839	2057.781	4579	1872.00	5.25	6.24
5	64.75	2897	44.74	7438.806	4826.454	6726.583	4234.34	22.50	19.88
6	51.95	2374	45.70	7282.899	4526.56	6772.494	4284.84	16.12	8.12
7	69.45	2337	33.65	5507.417	2921.84	6194.205	3648.73	21.70	24.41
8	70.1	2135	30.46	6512.279	3877.049	6040.912	3480.10	14.89	13.33
10	152.4	2227	14.61	5664.608	3021.254	5280.417	2643.56	12.14	12.68
day3									
1	138.6	2205	15.91	5606.44	2879.95	5342.636	2712.00	8.33	5.64
2	44.15	0	0.00	4273.31	1848.47	4579	1872.00	9.66	0.79
3	133.75	2043	15.27	5340.56	2607.96	5312.189	2678.51	0.90	2.37
5	65.85	2095	31.81	5902.39	3475.39	6106.107	3551.82	6.44	2.57
6	66.35	1930	29.09	5994.54	3392.62	5975.232	3407.86	0.61	0.51
8	54.85	2241	40.86	5939.55	3854.72	6540.13	4029.24	18.97	5.86
9	54.05	1950	36.08	6694.60	4246.22	6310.73	3776.90	12.13	15.76
11	90.1	2350	26.08	4753.61	2528.22	5830.942	3249.14	34.03	24.21
12	92.05	2089	22.69	5306.71	2852.40	5668.321	3070.25	11.42	7.32
							av err	13.13824	10.28934
							std dev	9.039299	7.953845

F.2 Power Data

day 1									
Run	Time	Mass	flow rate	Ave Pc	Ave Pe	Linear Fit		% Error FS	
	s	kg	kg/s	(W)	(W)	Pc	Pe	Pc	Pe
	5	0	0.00			6239.4	1678.80		
	5	0	0.00			6239.4	1678.80		
2	194.5	2023	10.40	8075.247	2228.042	8044.394	2314.11	0.29	2.73
3	186.2	1740	9.34	7692.614	2191.469	7861.095	2249.59	1.60	1.84
5	101	1667	16.50	9357.345	2701.297	9103.669	2686.94	2.41	0.45
6	74	2058	27.81		3285.875	11065.69	3377.51		2.90
7	69.5	1770	25.47		3416.25	10659.05	3234.39		5.76
8	126.5	1960	15.49	8931.099	2641	8928.241	2625.19	0.03	0.50
9	125.7	1947	15.49	8672.258	2568.625	8927.406	2624.90	2.43	1.78
10	85.5	2050	23.98	10508.62	3155.715	10400.3	3143.32	1.03	0.39
11	80	1760	22.00	10222.45	3035.045	10057.28	3022.58	1.57	0.39
12	105.7	1940	18.35	9253.684	2710.978	9424.524	2799.87	1.63	2.82
13	100	1830	18.30	9639.571	2775.484	9415.182	2796.58	2.14	0.67
14	71	1799	25.34		3256.50	10636.56	3226.47		0.95
15	65.8	1720	26.14		3246.31	10775.7	3275.45		0.92
18	181.9	2053	11.29	8394.127	2427.364	8198.046	2368.19	1.87	1.88
19	85.35	2023	23.70	10122.16	3004.843	10352.71	3126.57	2.19	3.86
20	81.2	1872	23.05	10164.77	3052.351	10240.22	3086.97	0.72	1.10
21	124.5	2082	16.72	9156.432	2823.794	9141.491	2700.25	0.14	3.91
22	126.8	1971	15.54	8839.875	2766.886	8936.934	2628.25	0.92	4.39
							ave err	1.36	2.07
day2									
1	38	0	0.00	7548.53	1812.21	6646.40	1703.90	23.46	2.82
2	111.1	2955	26.60	7903.66	2366.71	8269.87	2821.56	9.52	11.83
4	38.5	0	0.00	6345.81	1874.565	6646.40	1703.90	7.82	4.44
5	64.75	2897	44.74	10191.58	4015.888	9377.32	3583.97	21.17	11.23
6	51.95	2374	45.70	10142.45	3835.124	9435.70	3624.17	18.38	5.49
7	69.45	2337	33.65	7821.272	2523.531	8700.34	3117.91	22.86	15.46
8	70.1	2135	30.46	9066.795	3372.937	8505.40	2983.71	14.60	10.12
10	152.4	2227	14.61	8201.708	2658.885	7538.34	2317.95	17.25	8.87
day3									
1	138.6	2205	15.91		2488.181	7617.46	2372.42		3.01
2	44.15	0	0.00		1663.563	6646.40	1703.90		1.05
3	133.75	2043	15.27		2301.01	7578.74	2345.76		1.16
5	65.85	2095	31.81	8397.36	2999.32	8588.31	3040.79	4.97	1.08
6	66.35	1930	29.09		2933.32	8421.88	2926.21		0.18
8	54.85	2241	40.86	8588.76	3219.71	9140.22	3420.75	14.34	5.23
9	54.05	1950	36.08	9465.12	3638.86	8848.51	3219.92	16.03	10.89
11	90.1	2350	26.08	6765.56	2177.25	8238.40	2799.90	38.30	16.19
12	92.05	2089	22.69	7528.15	2462.66	8031.61	2657.53	13.09	5.07
							ave err	17.06	6.71

Appendix G : Yield Map Data

G.1 Chopper Data (t/ha)

Distance											
Down row											
0	row 1	row 2	row 3	row 4	row 5	row 6	row 7	row 9	row 9	row 10	
5	127.677116	104.8	79.51694	83.30669	98.97836	81.27672	55.43598	90.954	101.7757	108.6608	
15	122.690865	104.8	110.345	116.1498	129.3683	111.6628	85.93707	75.53127	110.543	143.6449	
25	142.992428	104.8	105.0409	108.336	121.6921	120.7056	91.98009	51.99816	106.1727	120.5915	
35	139.207983	104.8	113.3198	123.9691	132.0769	119.2671	87.51486	74.11495	116.0739	131.7267	
45	152.365832	104.8	149.9339	105.9053	150.0396	127.8774	113.9429	82.93836	121.6827	135.9101	
55	143.517846	104.8	113.0182	134.9837	138.1285	124.9691	118.44	127.3486	142.6012	115.4237	
65	140.633616	104.8	115.478	134.9479	141.5027	112.3027	100.6084	130.2309	120.0213	128.8987	
75	147.516001	104.8	120.0364	111.7138	112.6284	114.5106	111.5262	129.8254	122.8125	114.1812	
85	102.749467	104.8	119.8211	120.7498	121.2083	103.0453	99.06885	134.3554	119.7941	119.8397	
95	117.146229	104.8	112.472	113.396	115.8015	100.1366	93.54711	149.8748	120.567	116.1532	
105	109.13447	104.8	119.3098	121.2503	115.0065	99.36411	113.1991	135.204	115.3759	134.0285	
115	98.1755652	102.3883	119.6639	101.4547	100.6304	94.86607	59.80976	134.3073	100.917	127.756	
125	136.702802	102.7588	115.7643	121.0156	110.3072	105.5907	96.67839	135.8704	114.7641	134.3619	
135	118.4441	112.6822	119.3053	119.7923	113.7491	120.3398	99.3097	148.2866	117.4697	143.3375	
145	98.6860937	101.9936	116.1454	110.255	116.5272	118.6816	106.7239	143.9981	114.1131	129.2931	
155	102.329674	118.4186	102.814	107.3367	102.959	116.2172	91.56775	133.0285	115.9157	119.6429	
165	84.9855145	107.6585	95.21728	109.3689	96.20157	104.7355	98.82109	129.2759	111.5603	114.5802	
175	90.9857451	105.6112	76.17112	121.3265	106.48	112.0295	91.81614	125.8746	120.5019	101.2532	
185	95.0910391	111.7582	68.74899	110.1756	99.02067	112.6755	84.15484	135.2076	117.0616	99.01224	
195	111.595793	107.3348	87.18143	106.2604	109.2146	120.4814	77.97058	142.4977	110.8171	110.0183	
205	101.493129	87.72016	90.10949	118.3889	106.461	120.8598	94.26823	127.4751	101.0848	93.85661	
215	98.9761696	95.16462	121.9697	115.2872	113.1527	122.9361	105.3172	140.0284	122.5788	136.5316	**Ave Yield**
sum	2583.09748	2306.289	2371.383	2515.37	2551.135	2464.531	2077.638	2678.226	2544.204	2678.703	**112.5935**

G.2 Elevator Data (t/ha)

0	row 1	row 2	row 3	row 4	row 5	row 6	row 7	row8	row 9	row 10	
5	86.20922	104.8	77.9029	84.51656	100.6494	79.71613	59.52911	75.94473	92.25393	117.3961	
15	79.89756	104.8	109.8539	122.1169	124.4279	105.9023	92.78237	54.11857	107.1006	140.4718	
25	98.88664	104.8	120.9628	110.155	130.2352	114.3779	95.38548	45.05598	98.18727	129.773	
35	100.2642	104.8	126.7099	120.4247	135.5815	115.5206	92.81355	58.84466	111.8585	138.6189	
45	101.2503	104.8	161.6595	111.5469	145.1732	127.1033	117.423	68.31087	120.9668	133.6953	
55	107.5936	104.8	143.1905	136.9518	136.6681	122.0412	119.9425	109.4048	131.1789	121.2409	
65	102.4786	104.8	132.3539	128.468	130.3045	111.0322	113.7219	121.8316	118.5946	135.596	
75	110.3513	104.8	138.8685	106.4744	120.6585	105.8001	117.6432	97.3508	127.2676	122.2313	
85	81.82079	104.8	137.3175	116.1865	125.5536	92.22044	108.4942	117.4086	125.8438	128.1569	
95	88.86888	104.8	133.3268	110.2529	124.024	93.54451	106.1709	118.9034	127.8981	118.0243	
105	84.68954	104.8	146.0553	113.5994	120.2816	96.10799	125.7258	121.1942	122.7171	148.9637	
115	72.16236	90.18472	125.5826	106.2182	97.62813	88.7296	74.0743	121.3952	104.2268	142.0766	
125	110.5985	89.64988	134.928	125.1466	107.7114	93.26076	104.42	123.8988	116.5723	136.8389	
135	101.6891	96.3289	143.777	124.2281	108.7306	102.866	105.8041	128.0407	127.1256	161.4649	
145	87.68054	100.3102	150.0099	115.4917	116.5065	108.1145	116.9911	124.5886	121.1041	137.9379	
155	74.20659	110.6481	132.4375	113.8688	100.7647	105.6665	106.9924	120.184	116.4669	133.2857	
165	71.66419	100.496	115.1642	115.2059	98.41913	96.83256	119.4481	110.1905	114.4051	126.7087	
175	75.05013	97.47987	97.35507	114.487	109.4731	104.1971	104.7608	109.3854	122.4102	117.1919	
185	79.41197	97.4145	78.31961	114.8147	97.79571	106.0922	101.8864	109.9552	116.493	112.8828	
195	83.75104	100.8386	95.53591	114.9472	108.82	107.9926	91.13451	113.582	107.0461	118.2766	
205	86.67913	78.99103	112.9136	122.1084	103.6776	110.1471	105.5266	112.7964	92.1728	106.3621	
215	84.55617	89.02266	138.367	121.0868	111.7577	111.3098	119.4785	129.0268	117.5615	146.4323	**Ave Yield**
	1969.76	2204.164	2752.592	2548.296	2554.842	2298.575	2300.149	2291.412	2539.451	2873.627	**110.604**

G.3 Weigh Truck Data (t/Ha)

Distance										
Down row										
0	row 1	row 2	row 3	row 4	row 5	row 6	row 7	row 9	row 9	row 10	
5	119.881481	104.8889	121.9556	116.1481	121.4815	114.963	106.6074	90.60741	119.8815	123.3778	
15	119.881481	104.8889	121.9556	116.1481	121.4815	114.963	106.6074	90.60741	119.8815	123.3778	
25	119.881481	104.8889	121.9556	116.1481	121.4815	114.963	106.6074	90.60741	119.8815	123.3778	
35	119.881481	104.8889	121.9556	116.1481	121.4815	114.963	106.6074	90.60741	119.8815	123.3778	
45	119.881481	104.8889	121.9556	116.1481	121.4815	114.963	106.6074	90.60741	119.8815	123.3778	
55	119.881481	104.8889	121.9556	116.1481	121.4815	114.963	106.6074	90.60741	119.8815	123.3778	
65	119.881481	104.8889	121.9556	116.1481	121.4815	114.963	106.6074	90.60741	119.8815	123.3778	
75	119.881481	104.8889	121.9556	116.1481	121.4815	114.963	106.6074	90.60741	119.8815	123.3778	
85	119.881481	104.8889	121.9556	116.1481	121.4815	114.963	106.6074	90.60741	119.8815	123.3778	
95	119.881481	104.8889	121.9556	116.1481	121.4815	114.963	106.6074	90.60741	119.8815	123.3778	
105	119.881481	104.8889	121.9556	116.1481	121.4815	114.963	106.6074	90.60741	119.8815	123.3778	
115	103.111111	98.78519	104.8889	115.3778	104.2963	108.4444	101.9259	121.6593	110.9333	116.8	
125	103.111111	98.78519	104.8889	115.3778	104.2963	108.4444	101.9259	121.6593	110.9333	116.8	
135	103.111111	98.78519	104.8889	115.3778	104.2963	108.4444	101.9259	121.6593	110.9333	116.8	
145	103.111111	98.78519	104.8889	115.3778	104.2963	108.4444	101.9259	121.6593	110.9333	116.8	
155	103.111111	98.78519	104.8889	115.3778	104.2963	108.4444	101.9259	121.6593	110.9333	116.8	
165	103.111111	98.78519	104.8889	115.3778	104.2963	108.4444	101.9259	121.6593	110.9333	116.8	
175	103.111111	98.78519	104.8889	115.3778	104.2963	108.4444	101.9259	121.6593	110.9333	116.8	
185	103.111111	98.78519	104.8889	115.3778	104.2963	108.4444	101.9259	121.6593	110.9333	116.8	
195	103.111111	98.78519	104.8889	115.3778	104.2963	108.4444	101.9259	121.6593	110.9333	116.8	
205	103.111111	98.78519	104.8889	115.3778	104.2963	108.4444	101.9259	121.6593	110.9333	116.8	
215	103.111111	98.78519	104.8889	115.3778	104.2963	108.4444	101.9259	121.6593	110.9333	116.8	**Ave Yield**
	2452.91852	2240.415	2495.289	2546.785	2483.556	2457.481	2293.867	2334.933	2538.963	2641.956	**111.3007**

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