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**Improving Energy Efficiency and Automating
Field Operations by Propelling Machinery
Using Stationary Power Source**

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ABSTRACT

Low energy conversion efficiencies, poor functional performance and soil compaction are deficiencies of present mobile tractor systems even though they are very versatile in adapting to field machinery operations. Inherent losses in transmitting power through soil-tire tractive methods is one of the primary causes of low energy conversion efficiencies and these losses can be more than half the energy supplied to the drive wheels in many conditions required for field machinery operations. Increasing weight on the drive wheels increases power transmission efficiency, but it also increases compaction of soil which has recently been recognized to adversely affect growth of plants and yields. Current field machinery operations depend on the skill of the operators; therefore, the number on items which can be sensed and controlled is limited to the operator. Many field functions need to be varied according to historical and real time data sensing to provide the optimum environment for growing a plant.

The goal of this research was to generate fundamental data on alternative farming methods based on principles which can optimize production per unit of energy consumed. The alternative emphasized in this research was based on merging principles of the early cable towing systems with modern principles of linear move irrigation systems and automation. This technique (AMPS) can provide a system where the power unit remains stationary at the side of the field while the implement is towed through the field. The entire system is indexed across the field for successive passes. The specific objectives of this research were:

1. Evaluate alternative principles of propulsion to optimize energy utilization efficiency of conventional field implements.
2. Evaluate principles for automating conventional field machinery operations using alternative machinery propulsion techniques.

A simulation model was developed for evaluating efficiencies and costs of AMPS compared to mobile tractor implement systems (MTIS). Results of various analyses using the model verified that AMPS can be more energy efficient and less costly per unit of area farmed than MTIS. Field efficiency is less for AMPS than MTIS but with an automated system, it may operate for longer periods.

Field tests with a cable towing unit using a tandem disk showed that overall efficiency was constant at 23.2 percent for three successive implement passes without indexing. This was an improvement in efficiency ranging from 32.3 to 120 percent when compared to three successive passes with a tractor system. Field tests also showed the need for sensing and guidance work.

Criteria for hitching implements to a cable towed system were developed using computer models and force analyses based on information obtained from studies on tractor towed implements. These models were verified in a soil bin using a 1/6 scale model implement. The equations of motion to model the path of an implement towed by a cable was also developed. These equations were then used to develop automated steering control for an implement using steerable rolling coulters.

Two laser techniques were evaluated for locating and controlling the offset and heading of both the AMPS system and individual tillage implements. These systems and algorithms to implement automatic control were evaluated to provide the accuracy needed in guiding and controlling the machinery operations of AMPS.

A field experimental AMPS was designed and constructed to provide a system with a 100 horsepower towing capacity and capable of towing implements up to 24 feet in width. Limited tests were made that showed that switches sensing joint misalignment could be used to directly control the individually powered truss wheels to provide adequate alignment for many machinery operations.

DESCRIPTION OF COOPERATION

This research was a joint effort of investigators at three institutions. Dr. Wayne LePori of the Texas Agricultural Experiment Station, Agricultural Engineering Department, Texas A&M University was the Principal Investigator of the project. Two cooperating investigators were from Israel: Mr. Amos Mizrach of The Institute of Agricultural Engineering, A.R.O., The Volcani Center; and Dr. Itzhak Shmulevich of The Agricultural Engineering Department, Technion, Israel Institute of Technology.

Each investigator had responsibility of independent research on specific aspects of the project. Use of the computer mail system (BITNET) enabled frequent contact and coordination of activities among the investigators. Also, each investigator was able to make at least one site visit to the other investigator's institutions for coordinating activities.

The major thrust of work in the US was on measurement of energy efficiency of cable towing; establishing fundamentals for hitching and guiding implements; and developing a discrete control system for automating an experimental cable-based system.

At the Technion in Israel, the major thrust of the work was on establishing fundamental principles for using a laser system for location and guidance of a multi-jointed mobile truss complex. A two dimensional model describing the dynamics of a multi-jointed mobile truss system was also developed using traditional control methods.

At the Volcani Center, the major thrust was on evaluating a low cost laser location and guidance technique. The technique would be used for both controlling indexing of multi-jointed trusses and providing the error signal needed for steering an implement. In addition, control algorithms compatible with the laser and cable system were developed.

CHAPTER 1

1.1 INTRODUCTION

The primary source of power for growing food and fiber in Israel and the U.S. is the wheeled tractor. The tractor is a mobile power source and this mobility is a distinct advantage in adapting it to different production practices. However, the tractor has the following limitations and disadvantages:

- * Compaction of soil due to multiple passes of heavy power units;
- * Inefficiency in transmitting power by tractive means;
- * Requirement of a skilled operator for efficient functional performance; and
- * Dependence on weather and soil conditions for adequate traction and transport of power unit.

The first two of these have become very significant in modern mechanized agricultural schemes.

Considerable increase in efficiency could be achieved by eliminating the dependency on soil-tire contact for power transmission that is used in present mobile tractors. The amount of power transmitted through a tractor tire is limited by the failure characteristics of the soil. The maximum tractive efficiency is near 80 percent, and in typical farming conditions, energy losses can be about half that delivered to the drive wheels. These losses have been characterized by Upadhyaya, et al. (1987). Evans and Gove (1986), have shown that the new rubber belt track for agricultural tractors has about 7 percent higher tractive efficiency at the same slip as a four-wheel drive tractor.

One parameter affecting the amount of power which can be transmitted through tractive methods is the weight on the tire. As tractor power has increased, weight has also increased. This assists traction, but it compacts the soil which adversely affects crop production. Decreases in crop yields, as a result of compaction, are becoming particularly significant in certain soil types because of the increased sizes of tractors being used.

Non-tractive techniques have been developed in attempts to overcome the problems of traction limitations. These methods include rotary tillers, vibrating tools, powered disks, gantry-type systems, and cable towed implements. Each method has unique characteristics, but the gantry type systems and the cable systems overcome soil compaction problems and increase efficiency where most of the other methods generally increase energy use (LePori, 1985).

1.2 OBJECTIVES

Cable towing as a non-tractive alternative propulsion technique for field machinery operations was of particular interest in this project. The primary goal of the project was to generate fundamental data on alternative farming methods based on principles which can optimize production per unit of energy consumed. The specific objectives were to:

- (1) Evaluate alternative principles of propulsion to optimize energy utilization efficiency of conventional field implements.
- (2) Evaluate principles for automating conventional field machinery using alternative machinery propulsion techniques.

1.3 HISTORICAL PERSPECTIVE

Cable farming systems were one of the earlier mechanized farming methods. In the late 1800s, self-propelled steam engines that were too heavy to move through the field were used with winches to pull implements. A wide variety of implements were developed to use with the winch system and included cultivators, ridgers, mole plows, land levelers, and planters. However, the most common implement was the balance plow. Except for a few tools such as scrapers, all the implements required an operator to ride the implement for steering.

The balance plow consisted of two sets of facing moldboards which were balanced in the middle by a pair of wheels. While one set of plows was operating, the other was elevated at a 30° angle. At the end of the furrow, the plows were reversed by tilting the unit; one set being raised while the other was lowered. The implement was steered by a ploughman riding on the plow. Brakes in the wheels provided the mechanism for steering.

In most of the implements, steering was primarily dependent on a significant portion of the implement's weight being carried by a steerable pair of wheels. The requirement that a person be seated on the implement is unacceptable in modern agriculture due to safety and economic considerations. Although some of the techniques and machines developed in the early cable systems are relevant, most are not directly applicable to modern systems. The principles developed for the early cable plowing systems must be adapted and modified to make them acceptable for current farming systems.

The popularity of cable systems began to decline by 1915 when lighter diesel engines became available to power mobile tractors. This enables light power units to be developed that could travel through the fields. The diesel engine was also more efficient than the steam engine and was not adopted into cable drive plowing systems. However, the primary reason attributed to decline of the cable systems was that they were cumbersome to move and operate.

Bond (1923) characterized cable systems as being superior to traction drive tractor systems:

"Mechanically, this is a better system than direct traction, as the engine remains stationary while pulling the plough, and therefore, a high proportion of the work done in the cylinders is utilized in actual tillage. In the direct traction systems, from one-third to two-thirds of the power generated by the engine is absorbed by unproductive work of driving the tractor itself over the ground.... In cable tackle, the only loss of this kind is about one-sixth involved in winding-in of the cable.... The mechanical disadvantage of direct traction is emphasized when the tractor is called upon to work against a gradient, on soft ground, on wet soil, or in work requiring high implement speed.... Agriculturally, the cable tackle has advantages in that the engines do not compress the soil or the subsoil; it can work on stubbles too hard for the tractor wheels to grip or too soft or wet to carry the weight of the tractor;...."

These characteristics apply as well in terms of modern agricultural systems as they did when they were written.

A recent development in modern agriculture is the mobile sprinkler irrigation systems. These systems move large irrigation pipe across the field supported above the crop using a series of connected trusses on powered wheels. The initial systems traveled in a circular pattern around a center pivot. More recently, systems have been developed which move laterally across the field with the system maintained in a near straight line. The principles used in these linear move systems offer potential for merging with cable plowing techniques to form a new concept for performing most of the functions required for growing field crops.

An alternative which would provide an automated system for machinery operations similar to the irrigation systems could offer many advantages over current production systems. Such systems have the potential for introducing what might be termed high technology, integrated machinery farming systems. Schafer (1983) describes a Japanese gantry system as being on the cutting edge of research in automation. It can manage all field operations electronically, including soil analysis, and eliminate wheel traffic from the field. Such sophisticated systems are still in the future in terms of viable commercial systems, but some concepts developed through research on these types of systems is being applied.

Special variability of crops in a field has been measured and mapped in a few instances (Bae, et al. 1987). Ability to adjust for some of the suspected causes of this variability is being implemented. For example, application of fertilizer is being varied as dictated by soil tests.

Numerous opportunities exist for use of sensing and control to provide entirely new farming techniques. Benefit of achieving precise control must be evaluated through fundamental and field research with alternative machinery systems.

Results emanating from research on alternative systems will be invaluable in maintaining viable mechanized farming systems. The ability to precisely sense and control machinery functions will eventually enable interaction on an almost individual plant basis in the field.

CHAPTER 2

REVIEW OF NON-TRACTIVE TILLAGE METHODS

2.1 INTRODUCTION

As new technology is developed, it is important to review old concepts and practices to determine if improvements can be made. This is particularly important in research and necessary to maintain the open-mindedness essential for advancing the state of the art. Until recently, mechanization research was in danger of stagnation because of the unquestioning acceptance of the tractor as the central component of a mechanized system. A review of early mechanization work reveals several alternatives to the tractor and can provide concepts to combine with new technology which may provide improved methods of farming.

The objective of this paper is to review and discuss some of the non-tractive power transmission methods which have been developed for farming. Emphasis will be placed on cable concepts and a summary of current work on improving these concepts are discussed. Non-tractive methods can be reducing dependence of field operations on weather, and providing completely different farming options.

Non-tractive means of providing power to farm machinery for field operations can be broadly categorized as:

- (1) Rotary powered implements;
- (2) Vibratory implements;
- (3) Gantry-type systems; and
- (4) Cable towed implements.

In the first two, the tractor is, generally, still the source of power and works in combination with the implement. However, some gantry-type systems still depend on soil-wheel traction for power transmission.

2.2 ROTARY POWERED IMPLEMENTS

Rotary powered implements are those whose soil engaging parts are in forced motion. Some of the earliest proposals to replace animal power centered around rotary soil engaging devices, many of which have been described by Spence (1960). In 1813, Trevithick proposed a "steam-spade-tormentor" based on the rotary principle of operation. It consisted of a giant wheel rotating perpendicular to its direction of travel. Spiked teeth and spades attached to the wheel loosened the soil and formed uniform ridges and hollows. Numerous other ideas were presented during this period and relied on techniques ranging from mechanical spading to soil engaging screws. Some of the screw-type devices were more attempts at propelling large steam engines rather than in working soil.

During the mid-1800s, several rotary plows were developed which pulverized the soil and aided in propelling the power unit at the same time. Many of the principles developed in these early attempts which failed at that time are used in current rotary systems. Success in many cases was limited by the state of construction technology of that time.

Various methods of orienting the rotary elements, with respect to the ground surface, were tried and each had its unique characteristics. Bernacki, et al. (1972) have described the importance in relationship of the axis of machine rotation and direction of movement of the machine. By controlling the relative peripheral and translation velocities of the soil engaging tool, different degrees of soil pulverization can be obtained, although distinct relationships are difficult to establish. Hendrick and Gill (1971) have discussed interrelationships of three important rotary-tiller design parameters: (1) direction of rotation; (2) depth of operation; and (3) ratio of rotor peripheral and machine forward velocities.

One of the advantages of powered rotary tillage tools is the reduction in tractive effort or draft force of the implements, but one of the disadvantages is increased total power consumption per unit of area covered. Although the total power per unit area for rotary powered tools is from 2 to 3 times that required for pull-type implements, pull-type implements require more passes to achieve similar soil characteristics (Kepner et al., 1972; Sineokov, 1977). This increase in power is attributed to the increase in area of shear per unit volume of soil and the imparting of kinetic energy in the soil.

2.3 VIBRATORY IMPLEMENTS

Several types of implements have used vibration or periodic oscillations to decrease draft of implements and increase soil pulverization. Verma (1971) has provided an excellent review and summarized results from many studies on oscillating soil tools. His conclusions from the review were that oscillating tools provided advantages in: reduction of draft energy, improved soil breakup, reduced compaction, less clogging, less adhesion, improved wear characteristics of the tool, and general improvement of soil conditions. However, he noted that the principal problem with oscillation is that no reduction in the total power requirement was achieved, and in many cases, actually increased total power requirements.

Although complete understanding of the effects of tillage tool oscillation are to be determined, recent advances have been made. Spektor (1980, 1981) has presented analytical and experimental studies directed toward achieving minimum energy input for soil deformation using cyclical action. Scerbo (1974) describes the development of an orbital plow used to bury telephone cable. This technique has been widely implemented for installation of telephone cable, and it permits use of a lightweight machine. Draft power is drastically reduced, but total power remains relatively constant.

Tompkins and Bledsoe (1979) have applied vibration to furrow openers for minimum tillage planters. Their findings were similar to other oscillating tools in that it increased the ease with which the furrow opener penetrated the soil and produced more soil breakup than conventional fluted coulters. Draft power was reduced but total power requirements increased.

2.4 GANTRY-TYPE IMPLEMENTS

Several types of gantry systems have been proposed as alternatives to the present tractor system, but few have been implemented. The wide-frame carrier concept was proposed in 1860 by Grafton and similar concepts are presently being used today in controlled traffic studies (Spence, 1960; Gebhardt et al., 1982; Pratt, 1983). The current wide-frame systems still rely on traction to propel instruments, but permanent traffic lanes or roadbeds have increased tractive efficiency (Burt et al., 1984). The primary benefit of these systems is thought to be decreased soil compaction which will result in increased crop yields.

Chamen et al. (1980) and Matthews (1981) have both discussed gantry concepts and their advantages over conventional tractor systems. Wilton (1984) has proposed a center pivot gantry system to use electricity as the power source. Alcock and Jahns (1984) have developed and tested an automated spiral controlled traffic system similar to that described by Wilton. They found that an electrically powered tool frame could be accurately controlled from a center pivot irrigation system for spiral farming. Due to automation, they suggested that the power unit can be smaller and lighter than a conventional tractor; however, the power unit still depends on tractive methods to propel machinery.

2.5 CABLE TOWED IMPLEMENTS

Introduction of the cable system of farming was chiefly the endeavors of Mr. John Fowler in 1850 (Spence, 1960; Bonnett, 1972; Lane, 1980). These systems were the predominant mechanical means of tillage in England until the early 1900s. Many schemes for using cable were tried including the double engine system, the single engine system, the windlass tractor, and the windlass plow.

The double engine system used power units at each side of the field, and the implement was pulled back and forth between them. The single engine system used one power unit with one or more anchor wagons throughout the field. A two-way balance beam plow was generally used in both systems, so no turning of the implement was required to reverse the direction of plowing.

The windlass tractor system used a traction tractor which could lay out cable at high speeds, then winch the plow forward. In the windlass plow system, anchors were placed at the sides of the field and the power unit carrying a plow was winched back and forth between the anchors. These latter two methods were more or less experimental techniques.

Technology developed for steam plowing has played an important role in developing implements used in the modern era. These implements and

techniques such as the balance beam two-way plow are documented by Lane (1980) and Williams (1977). Other intriguing ideas such as the Boydell "railway" were tried during this period (Williams, 1977). The Boydell "railway" consisted of a number of flat plates loosely hinged around the circumference of the driving wheels. As the wheel turned, the hinged plates came down in succession to lie flat on the ground to give a continuous roadway for the wheel to roll on. The system allowed traction engines to exert more drawbar pull than conventional wheeled engines of the time.

The introduction of light and more efficient internal combustion engines eventually enabled traction or self-propelled power units to displace the cable systems. However, increasing concern about soil compaction and energy conservation has led to recent proposals for systems having their origin in the earlier cable-towed systems. Reese (1968) proposed a cable towing system that would use electricity as its power source. Permanent rails were proposed for the power units and implements were to be mounted on a frame supported by four low-pressure tires. Reese introduced the concept to stimulate thinking on alternative systems.

Dlubal (1979) proposed a large scale system (600-735 kn) based on the windlass tractor concept. No testing of such a unit was reported but a detailed analysis of its characteristics was developed and compared to conventional systems. Crossley and Kilgour (1983) have developed and tested an experimental winch plowing system for developing countries. This system is also based on the windlass tractor concept and illustrates how a small tractor can be used to pull higher draft loads when it does not depend on the wheel for traction. They showed that the unit could impart a draft force of three times the weight of the power unit, and it averaged 14.3 percent less fuel consumption per unit area as compared to conventional tractor operation.

2.6 SUMMARY OF NON-TRACTIVE METHODS

The review of non-tractive methods of supplying power for field machinery operations revealed that considerable work has been directed toward overcoming the inherent power losses of the tractive methods used in current tractors. The review also shows that considerable technology was developed for cable farming systems in the mid-1800s to early 1900s which were more energy efficient than traction-type systems. This cable-based technology has potential for being improved and integrated with other new technology to provide alternative systems which have the following characteristics:

- * Reduce energy requirements of field operations;
- * Reduce soil compaction;
- * Reduce influence of weather on field operations;
- * Provide a means of studying fundamental soil-machine-plant interaction studies;
- * Provide a basis for high technology integrated machinery farming systems.

CHAPTER 3

CABLE BASED FARMING SYSTEM

3.1 INTRODUCTION

Review of methods for non-tractive power transmission and initial analyses showed that a system based on cable towing can provide unique characteristics for growing crops. The merger of old and new technology provides a method having the following components:

- * Power unit for cable drive and electric generator;
- * Multi-jointed mobile truss for supporting cable and light implements;
- * Implement carrier for hitching, lifting, indexing, and reversing implements;
- * Anchor system for maintaining cable tension at the opposite end of the field from the power unit;
- * Sensing and control system for indexing mobile trusses and guiding implements.

A drawing illustrating the concept is illustrated in Figure 1, in Section 3.3.

A research unit based on this concept has been designed and constructed as shown in Figure 3.1. The power unit of the research unit is a tractor that has been mounted on a frame. The cable drive is a dual drum arrangement to provide an "endless" cable effect. The drums are designed to transmit 100 horsepower through the cable. The power unit also operates a generator which supplies electricity for indexing. Hydraulics of the tractor are also used to maintain cable tension and power jacks which are engaged to stabilize the power unit while pulling the implement.

Three mobile trusses, length of 102 feet each, are attached to the power unit through a short link forming a multi-jointed mobile complex. The truss joints are hinged for movement in two perpendicular planes and are supported by wheel trusses that allows movement in the third plane. A monorail is supported from the truss for cable support carriers and implement carrier. Each wheel is powered by a 2 horsepower electric motor for indexing. Switches are located at each joint for sensing misalignment and controlling indexing.

The implement carrier is not shown in the figure and is discussed in Chapter 4. Housing for the computer used in the research is shown as the solid box in the upper left part of Figure 3.1. The sensing and control system will be discussed in Chapter 6.

Figure 3.1. Constructed AMPS multi-jointed mobile truss system

In this Chapter, two papers are presented that provide results of initial work on economic and energy evaluations of the cable towing concept. Additional economic information is given in Section 3.2 on comparing a specific set of conditions for a tractor system and the cable system. In Section 3.3, results of efficiency evaluations of cable towing are evaluated.

3.2 EVALUATION OF AUTOMATED CABLE-DRAWN TILLAGE SYSTEMS USING SIMULATION

3.3 EVALUATION OF A CABLE TOWING SYSTEM FOR FIELD MACHINERY OPERATION

APPENDIX A
RESULTS OF FORCE ESTIMATION PROGRAMS

```

*****
*****
*****
*****      FORCE ANALYSIS OF A CABLE DRAWN CHISEL      *****
*****
*****      4 m CHISEL      *****
*****      DEPTH = 15 cm (6 in)      *****
*****      SPEED = 9 km/hr (5.6 mph)      *****
*****
*****

```

```

*****
*****      INPUT VALUES      *****
*****

```

-----PLOW DIMENSIONS-----

XDIST1= 179 cm	YDIST2= 16 cm
XDIST2= 168 cm	
XDIST3= 102 cm	YDIST4= 66 cm
XDIST4= 85 cm	YDIST5= 78 cm
XDIST5= 20 cm	YDIST6= 78 cm
XDIST6= 112 cm	YDIST7= 78 cm
XDIST7= 203 cm	

ROCKSHAFT RADIUS	ROCKRAD= 84 cm
UNDER FRAME CLEARANCE	FRMCLR= 81 cm
PLOWING DEPTH	DEPTH= 15 cm
TIRE STATIC LOADED RADIUS	TIRERAD= 37 cm
WHEEL NUMERIC	WHEELNUM= 20
NO. OF ROWS OF TILLAGE TOOLS	NUMROW= 3
IMPLEMENT WEIGHT	IMPWT= 2200 kg

-----TOOL FORCES-----

NUMBER OF TOOLS ON ROW 1	NFR 1 = 4
VERTICAL TOOL FORCE - ROW 1	VFORCE 1 = 225 N
HORIZONTAL TOOL FORCE - ROW 1	HFORCE 1 = 2300 N
NUMBER OF TOOLS ON ROW 2	NFR 2 = 5
VERTICAL TOOL FORCE - ROW 2	VFORCE 2 = 225 N
HORIZONTAL TOOL FORCE - ROW 2	HFORCE 2 = 2300 N
NUMBER OF TOOLS ON ROW 3	NFR 3 = 4
VERTICAL TOOL FORCE - ROW 3	VFORCE 3 = 225 N
HORIZONTAL TOOL FORCE - ROW 3	HFORCE 3 = 2300 N

```
*****  
*****  
*****  
*****      FORCE ANALYSIS OF A CABLE DRAWN CHISEL      *****  
*****  
*****  
*****
```

HITCHHT cm	ANTITIP kN	DRAFT kN	VWHEEL kN	ROLLRES kN
30	3.32	32.04	21.18	2.12
35	3.92	31.99	20.58	2.06
40	4.51	31.93	19.99	2.00
45	5.11	31.87	19.39	1.94
50	5.70	31.82	18.80	1.88
55	6.29	31.76	18.21	1.82
60	6.88	31.70	17.62	1.76
65	7.47	31.65	17.03	1.70
70	8.05	31.59	16.45	1.64
75	8.63	31.53	15.87	1.59
80	9.21	31.48	15.29	1.53
85	9.79	31.42	14.71	1.47
90	10.37	31.36	14.13	1.41

```

*****
*****
*****
*****  FORCE ANALYSIS OF A CABLE DRAWN DISK HARROW  *****
*****
*****          4 m (12 ft) TANDEM DISK HARROW          *****
*****          DEPTH = 13 cm (5 in)                      *****
*****          SPEED = 9 km/hr (5.6 mph)                 *****
*****
*****

```

```

*****
*****          INPUT VALUES          *****
*****

```

-----PLOW DIMENSIONS-----

XDIST1= 145 cm	
XDIST2= 97 cm	YDIST2= 8 cm
XDIST3= 127 cm	
XDIST4= 151 cm	YDIST4= 58 cm
XDIST5= 33 cm	YDIST5= 56 cm
XDIST6= 231 cm	YDIST6= 56 cm
ROCKSHAFT RADIUS	ROCKRAD= 56 cm
UNDER FRAME CLEARANCE	FRMCLR= 71 cm
PLOWING DEPTH	DEPTH= 13 cm
TIRE STATIC LOADED RADIUS	TIRER D= 34 cm
WHEEL NUMERIC	WHEELNUM= 20
NO. OF ROWS OF TILLAGE TOOLS	NUMROW= 2
IMPLEMENT WEIGHT	IMPWT= 2900 kg

-----TOOL FORCES-----

NUMBER OF TOOLS ON ROW 1	NFR 1 = 12
VERTICAL TOOL FORCE - ROW 1	VFORCE 1 = 1000 N
HORIZONTAL TOOL FORCE - ROW 1	HFORCE 1 = 1400 N
NUMBER OF TOOLS ON ROW 2	NFR 2 = 12
VERTICAL TOOL FORCE - ROW 2	VFORCE 2 = 660 N
HORIZONTAL TOOL FORCE - ROW 2	HFORCE 2 = 800 N

```

*****
*****
*****
*****  FORCE ANALYSIS OF A CABLE DRAWN DISK HARROW  *****
*****
*****
*****
*****

```

HITCHHT cm	ANTITIP kN	DRAFT kN	VWHEEL kN	ROLLRES kN
30	2.22	27.04	6.30	0.63
35	2.67	26.99	5.85	0.59
40	3.12	26.95	5.40	0.54
45	3.57	26.90	4.95	0.50
50	4.02	26.86	4.50	0.45
55	4.46	26.81	4.06	0.41
60	4.91	26.77	3.61	0.36
65	5.35	26.72	3.17	0.32
70	5.79	26.68	2.73	0.27
75	6.23	26.63	2.29	0.23
80	6.67	26.59	1.85	0.19
85	7.11	26.55	1.41	0.14
90	7.54	26.50	0.98	0.10

```

*****
*****
*****
*****      FORCE ANALYSIS OF A CABLE DRAWN LISTER      *****
*****
*****      SIX LISTER BOTTOMS      *****
*****      DEPTH = 11 cm (4.2 in)      *****
*****      SPEED = 6.75 km/h (4.2 mph)      *****
*****
*****
*****

```

```

*****
*****      INPUT VALUES      *****
*****

```

-----PLOW DIMENSIONS-----

XDIST1= 320 cm	YDIST2= 5 cm
XDIST2= 8 cm	
XDIST3= 31 cm	YDIST4= 47 cm
XDIST4= 74 cm	YDIST5= 53 cm
XDIST5= 6 cm	
ROCKSHAFT RADIUS	ROCKRAD= 66 cm
UNDER FRAME CLEARANCE	FRMCLR= 58 cm
PLOWING DEPTH	DEPTH= 11 cm
TIRE STATIC LOADED RADIUS	TIRERAD= 34 cm
WHEEL NUMERIC	WHEELNUM= 20
NO. OF ROWS OF TILLAGE TOOLS	NUMROW= 1
IMPLEMENT WEIGHT	IMPWT= 1600 kg

-----TOOL FORCES-----

NUMBER OF TOOLS ON ROW 1	NFR 1 = 6
VERTICAL TOOL FORCE - ROW 1	VFORCE 1 = 500 N
HORIZONTAL TOOL FORCE - ROW 1	HFORCE 1 = 2560 N


```

*****
*****
*****
*****      FORCE ANALYSIS OF A CABLE DRAWN LISTER      *****
*****
*****
*****
*****
*****

```

HITCHHT cm	ANTITIP kN	DRAFT kN	VWHEEL kN	ROLLRES kN
30	-1.14	17.74	19.83	1.98
35	-0.78	17.74	19.47	1.95
40	-0.43	17.70	19.12	1.91
45	-0.07	17.67	18.76	1.88
50	0.28	17.64	18.41	1.84
55	0.63	17.61	18.06	1.81
60	0.98	17.58	17.71	1.77
65	1.33	17.55	17.36	1.74
70	1.67	17.52	17.02	1.70
75	2.02	17.49	16.67	1.67
80	2.37	17.46	16.33	1.63
85	2.71	17.42	15.98	1.60
90	3.05	17.39	15.64	1.56

```

*****
*****
*****
*****  FORCE ANALYSIS OF A CABLE DRAWN CHISEL-DISK  *****
*****
*****          4 m CHISEL-DISK          *****
*****          DEPTH = 18 cm (7 in)      *****
*****          SPEED = 9 km/hr (5.6 mph)  *****
*****
*****
*****

```

```

*****
*****          INPUT VALUES          *****
*****

```

-----PLOW DIMENSIONS-----

XDIST1= 130 cm	YDIST2= 8 cm
XDIST2= 97 cm	
XDIST3= 127 cm	YDIST4= 63 cm
XDIST4= 158 cm	YDIST5= 64 cm
XDIST5= 27 cm	YDIST6= 78 cm
XDIST6= 122 cm	YDIST7= 78 cm
XDIST7= 211 cm	YDIST8= 78 cm
XDIST8= 300 cm	
ROCKSHAFT RADIUS	ROCKRAD= 64 cm
UNDER FRAME CLEARANCE	FRMCLR= 81 cm
PLOWING DEPTH	DEPTH= 18 cm
TIRE STATIC LOADED RADIUS	TIRERAD= 36 cm
WHEEL NUMERIC	WHEELNUM= 20
NO. OF ROWS OF TILLAGE TOOLS	NUMROW= 4
IMPLEMENT WEIGHT	IMPWT= 2650 kg

-----TOOL FORCES-----

NUMBER OF TOOLS ON ROW 1	NFR 1 = 16
VERTICAL TOOL FORCE - ROW 1	VFORCE 1 = -900 N
HORIZONTAL TOOL FORCE - ROW 1	HFORCE 1 = 670 N
NUMBER OF TOOLS ON ROW 2	NFR 2 = 3
VERTICAL TOOL FORCE - ROW 2	VFORCE 2 = 225 N
HORIZONTAL TOOL FORCE - ROW 2	HFORCE 2 = 2300 N
NUMBER OF TOOLS ON ROW 3	NFR 3 = 3
VERTICAL TOOL FORCE - ROW 3	VFORCE 3 = 225 N
HORIZONTAL TOOL FORCE - ROW 3	HFORCE 3 = 2300 N
NUMBER OF TOOLS ON ROW 4	NFR 4 = 3
VERTICAL TOOL FORCE - ROW 4	VFORCE 4 = 225 N
HORIZONTAL TOOL FORCE - ROW 4	HFORCE 4 = 2300 N

```

*****
*****
*****
*****  FORCE ANALYSIS OF A CABLE DRAWN CHISEL-DISK  *****
*****
*****
*****
*****

```

HITCHHT cm	ANTITIP kN	DRAFT kN	VWHEEL kN	ROLLRES kN
30	0.41	32.75	13.21	1.32
35	0.97	32.70	12.64	1.26
40	1.53	32.65	12.08	1.21
45	2.09	32.59	11.53	1.15
50	2.64	32.54	10.97	1.10
55	3.20	32.48	10.42	1.04
60	3.75	32.43	9.86	0.99
65	4.30	32.37	9.31	0.93
70	4.85	32.32	8.76	0.88
75	5.40	32.26	8.22	0.82
80	5.94	32.21	7.67	0.77
85	6.48	32.15	7.13	0.71
90	7.02	32.10	6.59	0.66

```

*****
*****
*****
*****  FORCE ANALYSIS OF A CABLE DRAWN DISK HARROW  *****
*****  CONDITIONS TO MATCH MODEL TEST  *****
*****  4 m (12 ft) TANDEM DISK HARROW  *****
*****  DEPTH = 13 cm (5 in)  *****
*****  SPEED = 9 km/hr (5.6 mph)  *****
*****  SANDY SOIL  14 DEGREE ANGLE  *****
*****  H/V RATIO = 0.77  WHEELNUM = 15  *****
*****
*****

```

```

*****
*****          INPUT VALUES          *****
*****

```

-----PLOW DIMENSIONS-----

XDIST1= 126 cm	
XDIST2= 97 cm	YDIST2= 8 cm
XDIST3= 127 cm	
XDIST4= 151 cm	YDIST4= 58 cm
XDIST5= 33 cm	YDIST5= 56 cm
XDIST6= 231 cm	YDIST6= 56 cm
ROCKSHAFT RADIUS	ROCKRAD= 56 cm
UNDER FRAME CLEARANCE	FRMCLR= 71 cm
PLOWING DEPTH	DEPTH= 13 cm
TIRE STATIC LOADED RADIUS	TIRER D= 34 cm
WHEEL NUMERIC	WHEELNUM= 15
NO. OF ROWS OF TILLAGE TOOLS	NUMROW= 2
IMPLEMENT WEIGHT	IMPWT= 2840 kg

-----TOOL FORCES-----

NUMBER OF TOOLS ON ROW 1	NFR 1 = 12
VERTICAL TOOL FORCE - ROW 1	VFORCE 1 = 800 N
HORIZONTAL TOOL FORCE - ROW 1	HFORCE 1 = 616 N
NUMBER OF TOOLS ON ROW 2	NFR 2 = 12
VERTICAL TOOL FORCE - ROW 2	VFORCE 2 = 530 N
HORIZONTAL TOOL FORCE - ROW 2	HFORCE 2 = 408 N

```

*****
*****
*****
*****  FORCE ANALYSIS OF A CABLE DRAWN DISK HARROW  *****
*****
*****
*****
*****

```

HITCHHT cm	ANTITIP kN	DRAFT kN	VWHEEL kN	ROLLRES kN
15	0.81	13.63	11.08	1.33
23	1.18	13.59	10.71	1.29
30	1.55	13.55	10.34	1.24
38	1.92	13.51	9.97	1.20
46	2.28	13.46	9.61	1.15
53	2.65	13.42	9.25	1.11
61	3.01	13.38	8.89	1.07

APPENDIX B
SENSOR CALIBRATION PLOTS

CALIBRATION FOR DRAFT LOAD CELL

CALIBRATION FOR ANTI-TIPPING FORCE LOAD CELL

APPENDIX C

PLATE PENETRATION RESISTANCE OF THE SOIL

PLATE PENETRATION RESISTANCE OF THE SOIL

The diagram on the following page shows the locations in the soil bin where the penetrometer measurements were made. Locations 1-3 were in an area that was rarely disturbed by the model implement. Measurements 4-6 were made in the center of the path followed by the left half of the implement, and measurements 7-8 were in the path followed by the right edge of the implement. The most soil disturbance occurred at the edges of the implement.

A 5.08 cm (2 in) diameter by 6.4 mm (1/4 in) thick aluminum plate was pressed into the soil at a constant rate of 2.09 cm/s to a depth of 11 cm. The force on the plate was recorded every 0.1 seconds. Two sets of tests were run to determine the effect of working the soil. Before the first set 3 leveling operations were performed to allow some soil consolidation to occur. Before the second set the implement was run 3 times with a leveling operation following each run. The second set of measurements was taken 0.5-1 m away from the first set.

The nine graphs on the following pages show the results of the measurements. The numbers beside the graphs correspond to the location where the measurements were made. The lines without symbols represent the first set of data and the lines with symbols represent the second set.

LOCATIONS IN THE SOIL BIN WHERE MEASUREMENTS WERE MADE

(1)

(2)

(3)

(4)

(5)

(6)

(7)

(8)

(9)

APPENDIX D
ANALYSIS OF VARIANCE OF MODEL TESTS

ANTI-TIPPING FORCE

ANALYSIS OF VARIANCE PROCEDURE

DEPENDENT VARIABLE: ANTTIP

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	22	1319.17721975	59.96260090	1129.30	0.0001	0.998393	1.5151
ERROR	40	2.12388888	0.05309722		ROOT MSE		ANTTIP MEAN
CORRECTED TOTAL	62	1321.30110863			0.23042834		15.20840844

SOURCE	DF	ANOVA SS	F VALUE	PR > F
HEIGHT	6	1307.41027036	4103.83	0.0001
TENSION	2	8.05984839	75.90	0.0001
REP	2	0.00534045	0.05	0.9510
HEIGHT*TENSION	12	3.70176055	5.81	0.0001

GENERAL LINEAR MODELS PROCEDURE

DEPENDENT VARIABLE: ANTTIP

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	3	1315.27416497	438.42472166	4291.90	0.0001	0.995439	2.1015
ERROR	59	6.02694366	0.10215159		ROOT MSE	ANTTIP MEAN	
CORRECTED TOTAL	62	1321.30110863			0.31961162	15.20840844	

SOURCE	DF	TYPE I SS	F VALUE	PR > F	DF	TYPE III SS	F VALUE	PR > F
HEIGHT	1	1305.28507743	12777.92	0.0001	1	249.45839395	2442.04	0.0001
TENSION	1	7.80876745	76.44	0.0001	1	5.82155522	56.99	0.0001
HEIGHT*TENSION	1	2.18032009	21.34	0.0001	1	2.18032009	21.34	0.0001

STD ERROR OF ESTIMATE

PR > |T|

T FOR HO:
PARAMETER=0

PARAMETER	ESTIMATE	PR > T	STD ERROR OF ESTIMATE
INTERCEPT	5.40954886	0.0001	0.22802865
HEIGHT	1.64450386	0.0001	0.03327809
TENSION	-0.14628794	0.0001	0.01937812
HEIGHT*TENSION	0.01306526	0.0001	0.00282801

DRAFT FORCE

ANALYSIS OF VARIANCE PROCEDURE

DEPENDENT VARIABLE: DRAFT

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	22	2928.39536893	133.10888041	462.39	0.0001	0.996083	0.5130
ERROR	40	11.51492118	0.28787303				
CORRECTED TOTAL	62	2939.91029011					
					ROOT MSF		DRAFT MEAN
					0.53653800		104.59605143

SOURCE	DF	ANOVA SS	F VALUE	PR > F
HEIGHT	6	2881.26502751	1668.13	0.0001
TENSION	2	7.10982090	12.35	0.0001
REP	2	0.98690427	1.71	0.1931
HEIGHT*TENSION	12	39.03361625	11.30	0.0001

DRAFT FORCE

11:17 TUESDAY, OCTOBER 6, 1987 5

GENERAL LINEAR MODELS PROCEDURE

DEPENDENT VARIABLE: DRAFT

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F	R-SQUARE	C.V.
MODEL	3	2852.33358854	950.77786285	640.53	0.0001	0.970211	1.1648
ERROR	59	87.57670157	1.48435087		ROOT MSE		DRAFT MEAN
CORRECTED TOTAL	62	2939.91029011			1.21833939		104.59605143

SOURCE	DF	TYPE I SS	F VALUE	PR > F	DF	TYPE III SS	F VALUE	PR > F
HEIGHT	1	2833.26553040	1908.76	0.0001	1	485.80219624	327.28	0.0001
TENSION	1	6.32162405	4.26	0.0435	1	18.06762894	12.17	0.0009
HEIGHT*TENSION	1	12.74643408	8.59	0.0048	1	12.74643408	8.59	0.0048

STD ERROR OF ESTIMATE

PR > |T|

T FOR HO:
PARAMETER=0

ESTIMATE

PARAMETER

INTERCEPT	118.59534375	136.44	0.0001	0.86923086
HEIGHT	-2.29490956	-18.09	0.0001	0.12685399
TENSION	0.25771493	3.49	0.0009	0.07386816
HEIGHT*TENSION	-0.03159020	-2.93	0.0048	0.01078019

8/10/87 11:17 AM
DRAFT FORCE