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**Optimising the Performance of Shallow, High-Speed
Mouldboard Ploughs**

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ABSTRACT

The aim of the project was to undertake experimental and theoretical research, to enable a better understanding of the design of modern mouldboard ploughs. Using this knowledge to optimise the performance in terms of width, depth and speed of operation to enable a more efficient cost saving operation. This would strengthen the presence of the mouldboard plough in the modern primary tillage machinery line-up and make it more competitive against other tillage systems.

Soil bin and field studies were undertaken to determine the effect of operating depth, width and speed on the forces and movement of the soil. This was to determine if manufactures, especially Kverneland; had followed the suggestions of previous researchers with the design of their number 8 mouldboard or an improvement in design was needed to enable high-speed operation. Not only was the design found to operate well at over a range of speed up to 10km/h but also provided good inversion at width/depth ratios up to 4:1.

The experiments showed that depth had the greatest effect on the horizontal forces, followed by the width. Speed had the least affect on the draught force with only a 7.0% increase when increasing from 4.5 km/h to 10 km/h. This is very significant in improving the operation of and cost saving associated with high-speed plough operations.

These studies indicated two critical issues that face manufactures

- i) The difficulty of increasing the furrow bottom width to accept wider tractor tyres. This problem was tackled with a re-design of the mouldboard assembly and further testing proved successful. The experiments showed that the actual furrow bottom width produced by the mouldboard could be increased for no additional increase in the horizontal force, both under controlled soil bin and field conditions.

ii) The ability of the skimmer to operate at increased ploughing speeds. This problem was addressed by conducting soil bin and field studies on the standard manure skimmer. The forces were measured for a range of depths, speeds, rake angles and approach angles allowing an understanding of how pitch and yaw of the skimmer body affect the forces and the soil flow.

The horizontal force studies were conducted under soil bin conditions and showed that both a reduction in the horizontal force and a better control of the soil flow could be achieved with the modification of the skimmers operating configuration. The skimmer field studies used a modified skimmer to investigate the improved soil and trash flow characteristics at higher speeds.

Mathematical models have been developed to predict both the horizontal forces on the mouldboard assembly as a whole, the isolated horizontal mouldboard forces and also the horizontal force of the standard manure skimmer. The prediction was based on Mohr-Coulomb soil theory and inertia effects, with the ability to predict geometrical change for the skimmer as well as depth and speed effects. Both the mouldboard and the skimmer prediction show a good representation of the measured horizontal forces with R-squared values of 97.2% and 65.4% respectively.

Finally the work rate of different size mouldboard ploughs was examined and the cost of operation investigated. Methods to reduce the cost of operation were highlighted and the overall cost compared to other tillage systems for a given working period and worked area. The increase in speed was seen as the most beneficial way of increasing the work rate and reducing the cost associated with the ploughing operation. Mouldboard ploughing was shown to be cheaper than minimum tillage up to 125ha (hectares) and cheaper than discing up to 275ha, whereas shallow high-speed ploughing was cheaper than minimum tillage up to 225ha and always cheaper than discing up to a limit depending on workdays.

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***There's nothing new under the sun, but
there are lots of old things we don't know.***

-- Ambrose Bierce

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LIST OF SYMBOLS

Soil Related

γ	Bulk Density	kN/m ³
γ_p	Particle Density	kN/m ³
c	Cohesion,	kN/m ²
ϕ	Angle of Shearing Resistance or Internal Friction	deg
v_s	Volume of sample	m ³
m_s	Mass of oven-dry soil	g
v	Internal volume of cylinder	m ³
p	Porosity	ratio
v_s	Volume of pore space	m ³
v_p	Volume of soil sample	m ³
τ	Shear Stress	kN/m ²
σ	Normal Stress	kN/m ²
u	Water Pressure	kN/m ²
$\tau'_{\max}$	Soil shear strength at the soil-tool interface	kN/m ²
c_a	Soil-interface adhesion	kN/m ²
m	Rupture distance ratio	Dimensionless
q	Surcharge pressure	kN/m ² (assumed zero)
δ	Angle of soil-interface friction	deg

Tillage Tool Related

d	Depth of tool from soil surface	m
w	Width of tool in work	m
α	Rake angle from forward horizontal	deg
N	Dimensionless number	

Suffixes to N

γ	Gravitational	
c_a	Cohesive and Adhesive	
q	Surcharge	
β	Soil shear plane angle	deg

Force Prediction Related

Ht	Total Horizontal Force	kN
Hp	Horizontal Point Force	kN
Hs	Horizontal Share Force	kN
Hm	Horizontal Mouldboard Force	kN
He	Force due to Potential Energy	kN
Hcs	Horizontal Cutting Side Force	kN
Hms	Horizontal Mouldboard Side Force	kN
Hl	Horizontal Landside Force	kN
d_p	Depth of point	m
w_p	Width of point	m
d_w	Depth of wing	m
w_w	Width of wing	m
v	Velocity	m/s

CHAPTER 1 INTRODUCTION

The mouldboard plough as a primary tillage implement has a fundamental purpose, which is to manipulate the soil by mechanical forces. This is the same with any tillage implement, the difference being the amount and way in which the soil manipulation is carried out. The mouldboard plough has one of the most complex shapes of all tillage implements and its development has been mainly due to empirical methods. These subtle cut and try methods of development have seen the basic mouldboard design remain the same for almost 100 years. Modern production ploughs have seen slight variations in the design of the mouldboard; these include critical tail angle variation, approach angle or mouldboard curvature and size variation, but the operation and work produced have remained the same.

There are many advantages associated with the use of mouldboard ploughs for primary cultivation. These include total soil inversion, which provides near to 100% trash and crop residue burial. This also provides a valuable method of controlling weeds that establish before, during and after cropping, especially perennial weeds species. The inverted soil also provides an idea basis for a new seedbed. Additionally the soil is loosened and aerated during the process which can allow essential air and water to penetrate the top layer of soil to aid organic matter break down.

Since the industrial revolution Agriculture has not seen such hard times, the even increasing cost of inputs and the ever diminishing returns for goods such as crops. Times like this necessitate the use of ever increasing amounts of technology and knowledge to combat the diminishing margins involved in the agricultural industry.

The labour availability for farm operations is continuously decreasing, the supply of energy is getting more critical and the environmental laws are indirectly requiring the farmer to manage more organic matter (debris) in the top few inches of soil. Many new and some revived minimum tillage (scratch tillage) practices that do not include the use of mouldboard ploughs are being used on modern farms.

However, due to the necessity of inverting the soil for control of insects, diseases and weeds and due to the ease with which the soil can be manipulated the mouldboard plough will be used widely in the foreseeable future.

The mouldboard plough was once thought to be one of the best primary tillage implements and in many situations still is, but over the last few years has begun to lose some of its stature within the agricultural machinery line-up. This is mainly due to alternative high output minimum or no-till tillage and seeding machines. The mouldboard plough is considered as slow and costly due to its perceived inherent high draught force incurred by the way it is used.

To combat this problem an increase in output is necessary, to increase the output of a mouldboard plough additional furrows were commonly added. The addition of furrows generally requires the need to increase tractor horsepower. This increases the work rate to a certain extent but means that the work output of the plough is dependent on the size of tractor.

This will always be the case to a certain extent but if the output of a given size plough could be increased without the need to increase the tractor size this would be beneficial. To do this the amount of work done by the plough has to be increased for no extra draught force requirement from the tractor. Previous work that has been carried out on plough design and draught force requirement of ploughs shows that if the depth of ploughing is reduced the draught force of the plough for the given soil properties is reduced. Due to a reduction in draft force, it would then be possible to increase the forward speed and/or working width of the ploughing operation. This would again increase the draft force but as long as the reduction from reduced, depth was greater than the increase from forward speed; the plough could have a greater output for no greater increase in tractor power.

As Academician V.P.Goryachkin said, ploughing is the 'most important, most time consuming, costliest and heaviest' operation in agriculture. Tens of millions of man-hours and millions of tons of fuel are expended every year on ploughing. Gyachev, (1985). With current plough design and power available, the possibility of increasing the plough output is more possible than ever before.

Use of higher speed would permit us to increase the productivity of labour (at the cost of using high-power high-speed tractors). To reduce the amount of metal used too simplify servicing and to improve the manoeuvrability of the unit Gyachev, (1985)

The maximum speed of acceptable ploughing (assuming available power) is determined by the ability of a plough to make a furrow that will conform to the surface of a given tillage tool and to produce the desired soil break-up, inversion and coverage of debris Reaves *et al.*, (1975).

1.1 Objectives

1. To develop an understanding of the soil flow over mouldboard ploughs at speeds higher than those commonly used in a practical situation. Particularly at shallow depths.
2. To determine the minimum operating depth for a mouldboard plough whilst maintaining the quality of work.
3. To investigate the possibility of increased furrow width at shallow working depths, determining whether the ratio of width to depth can be changed whilst maintaining soil inversion, residue burial and a satisfactory surface finish.
4. The proposal and (time permitting) evaluation of a prototype design that enables shallow high-speed operation of the mouldboard or increased furrow bottom width, which may include other soil engaging parts.
5. To determine the operating advantages and disadvantages that may arise from ploughing at increased forward speeds and/or furrow bottom widths.
6. To investigate the possibility of applying mouldboard design features to current skimmers in order to improve their performance, especially at higher speeds.

1.2 Outline Methodology

To gain an understanding of the principals of the mouldboard plough in operation some basic investigations will have to be made.

1. How does depth effect the forces involved and the soil flow
2. How does width effect the forces involved and the soil flow
3. How does speed effect the forces involved and the soil flow
4. Can the plough be made more efficient
5. What are its limiting factors and can these be changed

To do this the best place to start would be a controlled environment such as the indoor soil bin, this removes much of the variability of a field condition which allows repeatability. Additionally it is very easy to obtain measured values of forces and furrow profiles, although this is a good starting point it also has some disadvantages such as limited space and no variation in surface condition i.e. trash or residue. For this the field situation will be needed were an infinite variety of conditions can be encountered depending upon the choice of soil type to the choice of previous crop.

Methods of measuring soil properties such as moisture content, bulk density, cohesion, shearing resistance, surface roughness, soil throw and surface residue may be needed to help determine results from experiments.

A visit to the plough manufacturer's design and development centre would be useful to discuss their current developments and ensure that any research is not duplicating work already carried out. Additional ideas may also arise from such a visit.

The use of video footage during field experiments will enable both current and any modified plough components to be monitored and examined closely. These can also be viewed many times once the experiments are over, without having to return to the field. Being able to watch the soil engaging components of a mouldboard plough in

operation can be very difficult due to the danger involved with moving machinery, especially when higher speeds are involved.

To enable economic studies to be carried out the value of new and used machinery will have to be obtained along with work rate and efficiency data. Some of this can be collected from manufactures information and the second hand market but some will have to be calculated. Additional information about farmers buying and selling habits of machinery and implements, along with their view on various tillage practices including the mouldboard plough as a primary tillage implement will be monitored.

CHAPTER 2 LITERATURE REVIEW

2.1 History

Ploughs and ploughing techniques of various forms have been around since before Roman times, even though the principle behind the process of ploughing the land has remained largely the same, technology and materials have allowed improvements in many areas. These range from materials used to produce the mouldboard to methods of pulling and attaching the plough, down to more specific design changes.

It was not until the mid 1800's that steel was first used in place of wood or cast iron for the manufacture of the mouldboard to aid soil scouring; this was the first of many major revolutionary changes that made the mouldboard plough we recognise today. During this time, many people tried to describe the shape of these new steel mouldboards using theoretical analysis; but in 1880 E. Perels, a professor of agriculture at the university of Jena, characterised the analytical method of development using theory as completely fruitless. A. Foppl, a famous professor of mechanics in Munich, called this a surprising reproach, because ploughing, as a mechanical process is one of the most important of human labours. The reasons he stated for the failure of the theory were:

1. Difficulties caused by the large variety of soils and soil properties;
2. Lack of interest by mechanical scientists at that time;
3. Lack of contact and interaction between science and practical experience in agriculture.

This was the situation in 1898, when Goryachkin started his work in Russia. His idea was that the shape of the mouldboard should match the mechanical requirements of plough performance. Introducing 3-dimensional coordinates, he tried to give values to a mold line most suitable for a special purpose. His goal was to determine the quality

of the performance of a certain plough on a certain soil and design a plough for a certain theoretical purpose.

In the 1900's the use of the wheeled tractor as a power unit took over from the more popular steam ploughs of that time by using converted horse ploughs that were light and manoeuvrable, and with the advent of the Ferguson linkage system in the 1920's the plough was at a height of performance it had never seen before.

Since this time, plough manufacturers and researchers alike have strived to increase the performance of the mouldboard plough by understanding its operating characteristics in terms of soil forces, component shapes and quality of work produced.

To undertake research on mouldboard ploughs in relation to increased speeds, increased widths and varying depths, the previous attempts of researchers must be reviewed. This chapter will summarise previous work that relates to the mouldboard plough in terms of increasing output through operational speed and operating width, and the effects of these as well as depth on the operating forces and quality of ploughing produced.

2.2 Plough Research 1930 Onwards

Considering the mouldboard plough as the primary tillage implement that it is, there are some basic mechanical functions that it has to achieve and can be classified by its action on the soil; these were highlighted by Nichols *et al.*, (1932) as being

1. The breaking or cutting loose of the furrow slice.
2. The pulverisation of the furrow slice
3. The inversion of the furrow slice.
4. The covering of trash and weeds.

These mechanical functions are the basic principles that distinguish a mouldboard plough from any other primary tillage implement and still hold true today.

One of the first descriptions of how the mouldboard plough turns the furrow slice was described by Bailey, (1750) and can be seen in Figure 2.1, as used by Söhne, (1985) at the 1st International Conference on Soil Dynamics.

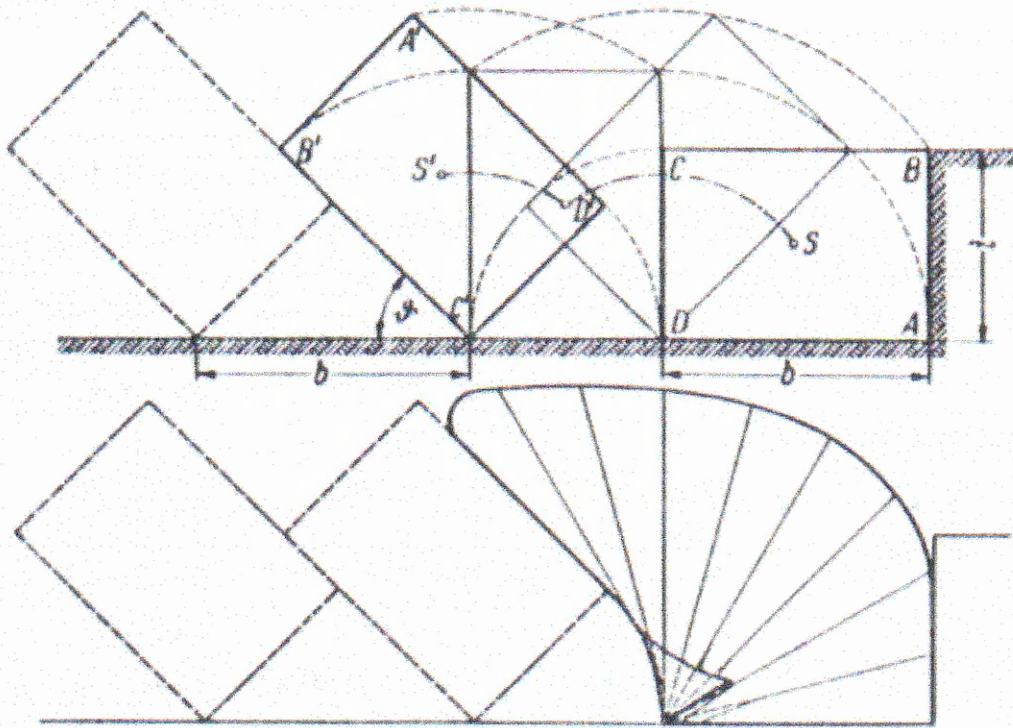


Figure 2.1, Bailey's Theory of a Stiff Soil Beam

This was described as the “push over” action when described by Bounsfeld, where the furrow slice firstly is turned about point “D” and then about “C” until the slice lays against the previous furrow. A great deal of subsequent work has also been based on this principal of soil turning although slightly varied such as Kermis, (1978) who used it as a starting point for a theoretical approach to high-speed plough design.

This principal was described as incomplete by Nichols, (1934) because it does not consider the soil reaction. At this time Nichols, (1934) described the two major paths of failure of the soil during reaction to the mouldboard body. These were named Primary and Secondary shear planes. The primary shear planes are produced by the shin and extend forward entirely across the furrow at 45 degrees to the direction of travel, see

Figure 2.2. These were discovered to be of constant angle and act in a similar way to that of a vertical wedge. The secondary planes occur at 90 degrees to the primary but do not occur until the furrow falls in inversion.

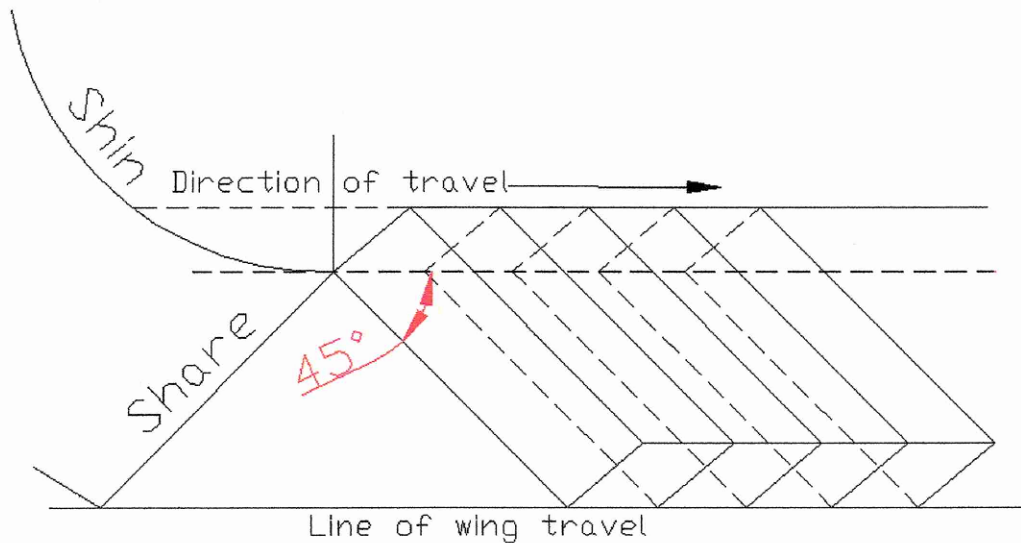


Figure 2.2, Diagram Showing Relative Position of Primary Shear Planes in the Unturned Furrow Slice

Early work carried out on mouldboard ploughs was that of Randolph, (1938), who considered that although previous work had been carried out on the forces acting on plough bodies, the results did not correlate between workers. Many times the question was asked, “What is the average draught of a mouldboard plough in different soil types”. They recommended that the soil in any tillage study should be treated as a dynamic material if the tests are intended for correlation, because the soil condition is always changing.

Randolph, (1938) conducted field tests on a 14-inch mouldboard plough in several soil types and found there to be a great variation in the forces required. The 14-inch general-purpose body used was found to have the lowest force per unit area at 6 inches (150mm) depth. The speeds of the tests were not taken above 6 mile/h (9.6 km/h) and the force was found to increase with the speed, but the relationship was not discovered. The effect of width of cut was only considered for one soil type and tended to have

little effect on the draught force, but increased the side forces; this was thought in part to be due to the force required to shear over the uncut portion of the furrow slice, commonly known as the hinge.

During these tests it was also noted that the landside increased the draught significantly due to a frictional effect and this was much dependant on the soil type. A rolling wheel type landside was said to reduce this force.

The influence of speed on tillage implements has always been of interest and an area of much research; one of the first papers was by McKibben, (1952). This was related to the performance characteristics of many tillage implements including mouldboard ploughs, highlighting advantages and disadvantages of increased operation speeds.

The main advantages are cost savings in implement and tillage operations, the power of the tractor may be more efficiently used, utilizing, high forward speeds and lower drawbar pull saving scarce materials. In addition, the size of implement to handle a given area is inversely proportional to the speed of operation and the weight of the implement is increased as the implement is widened. These advantages added to the ease of handling and manoeuvring of smaller lighter combinations have important benefits under certain conditions.

The disadvantages at this time started with the impact loads that can be encountered by rocks, stones and stumps. Their recommendation was that break pins, cushion springs and over-load devices were applied, which were successful. However, fields should be cleared of obstructing stones and obstacles to improve this situation. Modern mouldboard ploughs are all fitted with some type of overload device usually a shear bolt but often auto-reset. The investigation of the effect of speed on plough draught began as soon as tractors achieved higher speeds because of the amount of traction energy required for this tillage operation. From this very early stage, it was obvious that the draught of tillage implements increased with an increase in speed.

There was found to be more breaking up of the soil at higher speeds. However no one developed a generally accepted method to measure such differences at this time, so it was not possible to evaluate the advantages and disadvantages.

McKibben, (1952) determined that the plough may be designed to give the desired placement of the furrow slice at any selected speed; this will be different if the operating speed is greatly changed from that for which it was designed. The possibility of adjustable mouldboards was mentioned as a way to overcome the variation in speed.

They also considered that the increase in speed of tillage implements was similar to the economic law of diminishing returns, as each increment in increased speed will bring about a smaller benefit in the saving of time and materials than the preceding one. The benefits of increased field speeds are still worth striving for because the present speeds were twice that of the horse from which tractor development started, thus we are now saving at least half the time and materials which would be required at horse speeds. This is a greater saving than can ever be made again.

Likhoedenko, (1963), examined the ploughing speeds possible with standard plough bodies of the time, without a reduction in quality of work or increase in draught force was noticed. Some recommendations for mouldboard to work at 9 – 10 km/h were made from this work; Defined values of α (rake angle), θ (Approach angle) and L (length from share edge to the top of the mouldboard) must apply to a mouldboard designed for a certain speed range. The agronomic values of the ploughing operation were also considered, these being that the plough should turn the top layer of soil and displace it to the furrow bottom, convey the lower layer to the top and break it up into a fine structure to form a compact ploughed surface.

Work was continued in the search for high-speed plough bodies by Prihoda, (1964) who showed that trying to plough at increased speeds with standard plough bodies increased the draught force and the cost of the operation, which is just as unacceptable as the deterioration in agronomic quality achieved by using such bodies at speed.

He suggested that a body should be developed that satisfies the following demands.

1. The draught should be the same or ultimately less, at a speed of 7 - 8 km/h than that of existing plough bodies at speeds of 3.5 - 4 km/h at which the work of the plough bodies is at an optimum. These demands arise from the need to preserve the relationship between the drawbar pull required and the rate of work achieved. This relationship is a basic factor in assessing the economics of ploughing.
2. The agronomic demands made on plough bodies must be maintained with the new body at working speeds of 4 - 8 km/h so that they can be immediately used with existing tractors. By developing plough bodies which will meet these basic requirements it will become possible to achieve higher rates of work, maintain or shorten the agronomic ploughing period, use the higher efficiency of wheeled tractors (which are more advantageous at higher speeds) and possibly also reduce the weight of the plough.

Prihoda, (1964) considered that most energy is used for raising the centre of gravity of the inverted slice, so that if this can be reduced the energy will be decreased. A reduction in the speed of inversion reduces the pressure upon the working surface of the plough body, due to lower dynamic resistances when turning the furrow slice; this leads to less friction on the working surface of the body. The energy needed to overcome this pressure resistance is thereby reduced as well.

To reduce the energy Prihoda, (1964) said it was better to accelerate the furrow slice only in the region close to the upper point of reversal of the path described by the centre of gravity of the furrow slice, rather than in the region where the centre of gravity of the soil slice still describes an upward path. On the other hand, if the agronomic point of view is considered then it was found better to accelerate the furrow slice in the zone where the centre of gravity is still described as upward travel.

Further increases in ploughing efficiency can be expected, provided that the introduction of better hydraulic control of the 3-point hitches on tractor can improve the draught characteristics and thereby improve the conditions for introduction of high-speed ploughing. Prihoda, (1964) considered that the possibilities of high-speed ploughing should be assessed in terms of work rate and direct costs to determine the overall economy of the ploughing operation.

As the possibility of high-speed tillage was investigated further the benefits became realised. This investigation also brought about the need for reducing the draught force required at the increased working speeds. Quickstad, (1971) reviewed several high-speed tillage implements and methods of reducing the draught. These included oscillating the tool and reducing the friction between the surface of the tool and the soil to reduce the resistance either by a low friction coating or air lubrication. Both methods can reduce the resistance but a break through in the wear resistance of coatings hold the best chance in this area.

The other possibility to reduce the draught Quickstad, (1971) recommended varying the working shape of the tool, the requirement being that the tool should produce the same form and soil break-up as the conventional tools at slower speeds. A reminder is made that the soil acceleration force is proportional to the square of the velocity, and for this reason the shapes must be changed for high-speed. Work carried out at the National tillage Machinery Laboratory in 1968 designed for high-speed, showed approximately the same draught at 6 miles/h as a regular bottom at 4 miles/h. It was thought that increasing the speed of tillage operations is paramount because increasing the productivity is the ultimate goal.

Quickstad, (1971) estimated that 250 billion tons of soil is tilled on 360 million acres each year. The energy required to accomplish this task is very great and it points up the need to reduce tillage energy. He considered that this was the reason that minimum tillage, optimum tillage and zero/no-till are increasing in popularity.

As it is known that the force required to pull a mouldboard plough increases as the forward speed is increased but it is not known how this effects the specific pressures that are acting on the individual components of the plough. Korotkevich, (1972) carried out experiments over four speeds to determine the variation in pressure on the plough share and mouldboard. His findings were that the pressure diminished, as you move further away from the cutting edge and also as the distance from the point was increased. As the speed was increased, the pressure distribution did not increase linearly at each point measured with the increase in speed. The pressure increased greatest at the point and least at the heel of the share.

Therefore, the increase of speed led to an increase in the peak loads on the share. A similar thing was found with the mouldboard for which the pressure is not distributed evenly; the highest pressure is at the shin and across the bottom of the mouldboard. At higher working speeds this becomes even more unevenly distributed over the surface, the pressure on the shin increased and the pressure on the wing decreased. This is best explained by the dynamic pressure of the soil slice upon the mouldboard. At higher speeds the soil slice, dropping onto the shin of the mouldboard, is thrown to one side, without reaching its wing. Therefore a higher pressure was observed on the share and the shin of the mouldboard with increasing speed, and a lower pressure on the wing.

To try and overcome the problem of designing many different mouldboard shapes to suit different operating speeds Al-Jalil *et al.*, (1979) developed a spring-damper control system for a variable angle mouldboard plough; this was hoped to control the draught increase by controlling the lateral cutting angle as speed increases. The mouldboard was hinged about a vertical axis at the front, and the angle was varied as a function of the resultant side force, which increased with an increase in draught force. The plough was tested under field conditions at three speeds with a spring and then a pneumatic damper system. The spring system gave good results up to 9.7 km/h, the furrow profiles were observed and the pneumatic damper gave good results up to 12.7 km/h. The relative draught reduction compared to National Tillage Machinery Laboratory (NTML) rigid bodies was 44.4% at 12.9 km/h.

The variable angle plough limited the increase in the acceleration forces, which tended to throw the soil further to the side at higher speeds, and reduced the increase in draught associated with high acceleration forces. This plough design has not become commercial to this date, probably due to complexity of manufacture.

Most work has been concentrated on changes of plough force with speed because this is recognised as a way to increase the output of the plough, therefore understanding the force penalty of this is important. It must not be forgotten that soil type and depth both have significant effects on the force required by the plough.

As the depth of work is increased the horizontal force was expected to rise. This was found to be parabolic by Kaburaki, (1959) in both alluvial soil and in sand with a model plough. This relationship with depth was greater than that found by Getzlaff, (1953). Using bodies of different scales and different soil types it was found that the relationship with depth was linear between the 80 and 220mm and then experienced a sudden increase. This was also found by other researchers and led Kaburaki, (1959) to a uniform conclusion as to the relationship between draught resistance and depth of cut. It must be noted that all these investigation dealt with the energy requirement and the quality of work from an agricultural point of view was not considered.

A review of work by National-Institute-of-Agricultural-Engineering, (1971), (NIAE) found that after soil type, the depth of work was the most significant factor which increased the force requirement of tillage implements including mouldboard ploughs. Increasing the depth from 200mm to 300mm could more than double the draught force.

One major effect of reducing the depth of ploughing is stability, which was investigated by Plouffe *et al.*, (1995). It was doubtful whether current plough bottom design could adequately operate at ploughing depths of less than 150 mm. Plough stability is a major concern in shallower conditions. Lucian, (1992) stated that plough depth variations of less than 10 % should be maintained to achieve a uniform ploughed surface, which leads to proper vegetation burial.

Vertical forces acting on the plough can greatly influence its stability; these include the weight of the plough and the weight of the soil being lifted. Gebresenbet, (1989) reported that the highest pressure was at the share point and the wing in shallow conditions. As the depth of ploughing became less, so the amount of soil being lifted is reduced and the stability of the plough can be affected.

In more recent years the depth of work was considered again, but this time in terms of the quality and effect on yield. Hakansson *et al.*, (1998) determined from tests carried out in Sweden, that over a number of years, variation in ploughing depth had neither a positive nor negative effect on the yield. Therefore, if it is desirable to plough shallower than usual in an individual year to save time or cost, this can be done with no residual effects, except possibly the total control of perennial weeds.

2.3 Work Carried Out on High-Speed Plough Body Design

2.3.1 National Tillage Machinery Laboratory (NTML)

In 1939 the International Harvester Company developed the HSKA mouldboard plough bottom, designed to work at higher speeds. This mouldboard was a lengthened version of the KA mouldboard and the top was rolled forward to prevent soil throwing at high speed. From tests in controlled soil bins the increase in draught was not appreciable at speeds between 2 and 4.5 mph (3.2 and 7.2 km/h) and showed some advantages in quality of ploughing at speeds of 4 to 5 mph (6.4 to 8 km/h).

Comparative studies showed that the draught per square inch of furrow slice of a mouldboard plough was significantly less than the draught per square inch of the disc plough.

The years 1950 through 1954 saw some more mouldboard plough investigations at the NTML. Plough bottoms from John Deere showed little difference in shape and performance of their NGP (new general purpose) and their HS (high speed) bodies. These both worked well between 2 and 6 mph (3.2 and 9.6 km/h) but above 6 mph (9.6km/h) both threw the soil too far.

Draught verses speed curves were obtained. It was found that repeated shallow ploughing and vehicle traffic can form compacted layers in clay soils. It was shown that deep ploughing in the autumn was better than in the spring for the reduction of clod size at planting time.

Basic studies about mouldboard plough performance indicated that 60 – 65% of plough draught is used at 3 mph (4.8 km/h) to shear the soil, creating failure planes and 80% is used in the share section. Draught and performance tests showed the considerable influence of mouldboard geometry; these tests helped to optimise plough geometry and draught requirements as well as the quality of the ploughing process.

2.3.2 *National Institute of Agricultural Engineering (NIAE)*

Previous work was carried out by researchers at the NIAE, investigating the stresses and forces produced when an implement is pulled through the soil. These experiments were generally concerned with the average draught, but recent work has pointed out the need to include the transient loads particularly when stones are involved. The results show average loads, pinpoint the main variables, and indicate the magnitude of the forces. The forces acting on a mouldboard body are dependant on many variables, including the soil type and condition, the size, shape depth and velocity of the body in work [NIAE, 1971].

Experiments were carried out by Rogers *et al.*, (1956) on different mouldboard bodies in different soils. The ploughing depth was kept at a constant 150 mm whilst the speed was varied. The soil type had the greatest effect on the average loads; this was closely followed by the effect of the soil condition. The effect of speed on the draught of all three bodies was much the same up to 3 mph (4.8km/h) with an almost linear increase which was as much as 20 %. At higher speeds, the draught increased more rapidly, up to a 40 % increase. The speed had a much greater effect on the appearance of ploughing than the shape of the bodies.

2.3.3 *The Work by Söhne et al.*

A considerable amount of work was done by Walter H Söhne in the area of soil dynamics, especially looking at the possibility of high speed mouldboard ploughs. At the 1985 International Conference on Soil Dynamics he wrote, “Soil dynamics describes the relationship between high speed mechanical forces caused by vehicle tires, cultivation and earth moving implements and the resultant rapid response of the soil”. Söhne, (1985).

In Germany, extensive investigations were made by Söhne to develop mouldboard shapes for higher speeds. Over a period of years farmers moved from the horse to the tractor as their primary power source, the power available increased significantly and the speed at which operations could be carried out also increased. This was mainly due to the fact that this is the best way to transmit the power available with a given weight of tractor. This trend was going to continue for the foreseeable future, so as well as suiting the plough to three point operation, designers had to look closely at the shapes that are appropriate at the increased forward speeds.

Söhne, (1959) recognised this fact and predicted that an increase in ploughing speed would be necessary because of the increasing labour cost. The farmer will have to consider reducing the labour cost per hectare together with increasing the available horsepower per hectare. To apply the increasing power to the ground the operation will have to be carried out at increased speeds, which entails considerable difficulties. As well as the difficulties of slopes and heavy land, there is the increase in resistance due to increasing working speeds. This resistance is composed of one component that is relatively independent of speed and a second component stemming from the acceleration of the soil which increases with approximately the square of speed.

Söhne, (1959) determined that the traditional horse plough used at the increased speeds of the tractor produced a wider furrow and the soil was thrown too far to the side. The design of a high speed plough would have to produce the same furrow and cultivation corresponding to the horse plough work or to slow tractor work. So the following two requirements for high-speed plough bodies were established:

1. The power requirements should not increase too much with increasing speed, and
2. The furrow shape should not differ too much from the traditional one, in particular, the furrow should not be thrown too far, and the soil should not be conveyed too far to the side and distributed over the soil already ploughed. Both these requirements have the same basis; the greater the lateral transport of the soil, the greater the energy expenditure.

Many bodies were looked at by Söhne and compared to see if there were any suitable for high-speed operation. Using a light interception method the geometrical shape of several plough bodies, including various American high-speed bodies were photographed. From these photographs characteristic values such as the share cutting and intersection angles, the lateral directional angles, the convex curvature of the horizontal shape lines, and the twisting of the mouldboards were determined. An examination was made as to which of these parameters are of special importance for high-speed ploughing.

Some recommendations were proposed as to the best shape for a high-speed plough. There were bodies that were not suitable for high-speed operation; however, there were a number of tractor plough bodies that are already suitable for speeds of 7.5 to 9.0 km/hr.

The recommendations by Söhne suggested that a plough body for speeds up to 9 km/h should fulfil the following conditions:

1. The plough body must be relatively flat, elongated and pointed. The share intersection angle (δ) should be about 15 to 17° at the share point and about 8 to 10° at the share end;
2. The share cutting angle (φ_1) should be about 35 to 38°
3. The lateral directional angle of a horizontal mouldboard shape line at a height of 160 to 200 mm should be equal to the share cutting angle on the land side, and should decrease towards the end of the mouldboard to 23 to 27°, i.e., the horizontal shape lines must have a convex curvature;
4. In order to achieve satisfactory inversion with such bodies, they must be relatively strongly twisted;
5. The mouldboard upper edge should be raised higher towards the furrow side, in order that the soil is not thrown out over it at high speeds.

One year later Söhne, (1960) conducted more work on high-speed ploughing. Again his belief was that to increase the output of the mouldboard plough the speed was the best variable to increase. If the number of bodies were increased then the power and the weight of the tractor would have to be increased but if speed is increased, only the power need be increased.

Following his previous work, four body shapes were tested in three soil types for draught requirement, furrow formation, lateral transport of the soil and soil crumbling effects. From the measured values, the dynamic component of ϵv^2 can be derived and related directly to the lateral directional angle of the plough body. Clod and crumb analysis of dry soil showed very little difference between high and low speeds and no basic difference with body shape. At high speeds however there was a certain amount of soil separation of the ploughed soil, whereby the large clods reached the surface and the fine clods are spread out over it. It was found that machinery compaction had a great effect on the quality of ploughing at all speeds and all body shapes.

Söhne *et al.*, (1962) designing a body for high speeds; the method put forward was based upon the soil path curves on proven designs of plough body. There are a number of methods for representing by mathematical means empirically obtained and very varied plough body shapes, either as entire surfaces or as indicative shape lines. Such methods are only to be regarded as mathematical aids and not as functionally justified systems. The soil path method satisfies requirements to furrow shape and soil crumbling related to the lateral angle of elevation at the rear of the mouldboard, the cutting angle of the share and the share point angle which depends on the required maximum speed. The object was to produce a steady bending of the soil slice across the mouldboard, having regard to the prescribed boundary conditions.

Following all his work in the area Söhne recommended that in practical agriculture, 7 mph (11 km/h) still seems to be a kind of sound barrier for ploughing. This to some extent is still the case in modern day plough designs.

2.4 Force Prediction

One of the first researchers to consider the mathematics behind the forces acting upon a mouldboard plough was academician V.P.Goryachkin. The formula for the specific ploughing resistance $k = k_0 + \epsilon v^2$ turned out to be one of the most important. It correlates plough resistance to ploughing speeds (v). ϵ depends on the angle ϕ at the end of the plough bottom according to the formula $\epsilon = C(1 - \cos \phi)$, Söhne, (1960) used this in his work. This formula was then subject to many modifications over the years, Miltsev, (1974) describes the equation proposed by Sineokev G.N. which adds the frictional component of the landside and some effect for blunting of the share to this original formula. Oskoui *et al.*, (1982) used this equation also with meteorological data from cone index readings to predict plough draught.

More complex methods of predicting forces were undertaken by O'Callaghan *et al.*, (1965) and Gyachev, (1985) using mathematical theory to determine the force of the soil slice on the mouldboard plough, with the former reliant upon a computer algorithm to handle the large number of calculations. Other purely numeric examples of force prediction included that of Qiong *et al.*, (1986) based on equations of equilibrium.

Alternative methods of determining the forces of mouldboard ploughs include that of Desbiolles *et al.*, (1997), again using cone index readings but with a standard tine providing an index reference. Finally, work by Seig, (1982) started to make use of the widely understood modified general soil mechanics equation developed by Godwin *et al.*, (1977) to predict the forces on the plough share. Further work by Wheeler *et al.*, (1996) included a velocity factor to the modified general soil mechanics equation but this was not included in Seig's work. As the majority of force prediction models use few soil variables in their methods, Seig's approach using the modified general soil mechanics equation was considered to have potential for more complete and improved prediction. This can be seen in Chapter 7.

2.5 *Skimmer/Disc Coulter Forces*

There has been very little, if any, work carried out in the area of plough skimmers and other soil engaging parts related to the mouldboard plough. One of the few pieces of work were the experiments carried out by Tanner *et al.*, (1963) that separately measured the forces acting on the mouldboard body and the disc coulter, whilst ploughing under normal conditions and normal plough settings. This was done by measuring the total plough load with and without the disc and then subtracting one from the other to get the disc force.

Speed was chosen as the independent variable because it was known to have an effect on the draught force of plough body and coulter combinations and variation is easier to obtain than soil shear of ploughing depth in field conditions. In all cases the plough body contributed for about 80-85 % of the total draught and the draught of the disc coulter did not appear to vary much with different plough bodies. The vertical upwards force on the coulter was in all cases about twice the vertical downwards force of the body, so that while the body tried to go deeper, the net force on the body/coulter combination tended to prevent penetration. The coulter forces were independent of speed within the limits of the experiment and the dependable accuracy prevailing.

2.6 *Summary*

In summary, all the research agrees that the force required to pull the mouldboard plough increases with an increase in working depth. The rate of this rise depends upon the type and shape of the mouldboard and the soil type. Therefore a reduction in ploughing depth can be a means of obtaining a reduction in the force required to pull the mouldboard plough.

Likewise, the research shows that an increase in speed causes an increase in the draught force; this is also dependant on the shape and approach angle of the body and

the type of soil. Most research found the draught to increase with the square of speed, or to some power close to the square of speed. Along with the increase in draught force there has been found to be an adverse effect in the placement of the furrow slice.

As the speed is increased, the furrow profile moves further away from its original position. This is very dependant upon the type of body and the angle of approach, especially that of the mouldboard. The suggestions for high-speed mouldboards all conclude that the angle should be reduced to achieve the same soil throw as that of a normal mouldboard at slower speeds. These requirements usually conflict, as a body designed for high speed would produce an unsatisfactory furrow at slow speeds and visa versa. This has caused researchers to look at solutions such as variable angle mouldboards. At increased speed the pulverisation or break up of soil is increased especially when the soil is accelerated on the upward path of travel.

Increasing the speed was suggested as the best way to increase plough output, although width was found to have little effect on the force and therefore increased output maybe possible for a negligible force penalty.

Current plough design has developed in many different ways including a progression in mouldboard design to allow many different mouldboard options to be offered.

With the cost of power per kilowatt reduced and the average tractor size increased, the ability to work at increased speeds whilst maintaining driver comfort due to whole tractor and cab suspension is becoming more likely. The question has to be asked; “have the plough manufacturers followed the design proposals of the researchers such as Söhne, in terms of high-speed mouldboard design.”

CHAPTER 3 PRELIMINARY MOULDBOARD STUDIES

3.1 Pilot Studies, Width/Depth Relationships

3.1.1 Aim

To gain an understanding of the performance of a modern Kverneland mouldboard body and determine if the suggested shapes had been followed or re-design/modification was required.

3.1.2 Introduction

Although standard mouldboards have been tested under controlled soil bin conditions many times before, this was considered the best place to start any experimental work involved with a modern Kverneland mouldboard. As it was only possible to use one body, the sponsor suggested the No 8 was used. The No 8 mouldboard was especially designed by Kverneland in 1986 around the time the company introduced its vari-width option on ploughs; therefore the mouldboard was designed to work at different operating widths and depth/width ratio's. Testing this mouldboard would give an understanding of the mouldboard assembly as it was currently designed and configured, which would lead onto further testing both under controlled conditions in the soil bin at Cranfield University and in the field.

The area of most interest for the pilot studies was the width and depth ratio and configuration of the plough. It was considered that increasing the working width of the mouldboard plough would be one way of increasing the output and therefore reducing the cost of the operation.

Another reason for wanting to increase the width of ploughing was the increasingly wide tyres fitted to agricultural tractors. This was a problem highlighted by the

representative from Kverneland, although they had produced a vari-width plough to operate from 12-20" (305-508mm) the market still seemed to require wider furrow widths. Investigating furrow widths would help to determine if current plough designs have the potential of working at even greater furrow widths or are at their maximum width.

A width/depth ratio of 1.27 was the minimum that would ensure the furrow stayed turned after ploughing according to Goryachkin, (1968a). The maximum that is possible is of more interest when considering the maximum width of ploughing possible for a given depth. Work by Plouffe *et al.*, (1995) investigated two mouldboards with width/depth ratios between 1.6 and 4.4; from this they found that a width/depth ratio of three gave the best compromise between plough stability and vegetation burial.

3.1.3 Procedure

Work was carried out under the controlled conditions of the indoor soil bin facility at Cranfield University, to determine the minimum depth that could be achieved with the Kverneland No 8 mouldboard body at different operating widths, therefore testing the mouldboard body at different operating ratios of width to depth. These experiments would give a good understanding of the No 8 body working at many different operating parameters and its ability to produce a good quality of work at different operating widths and depths.

The experiments would compare the ability of the mouldboard body to not only cut and turn (invert) the soil but also compare the surface finish produced by the mouldboard at the different settings. It would also give a comparison of the elevation of the soil slice from its origin and the deviation of the soil to the side of the furrow.

Plouffe *et al.*, (1995) also found that the stability of the plough was compromised when the width/depth ratio was increased, this could also be observed with the Kverneland body. If it is possible to increase the width/depth ratio capable with the Kverneland No 8 body then what would its limit be and would this alleviate the problem of

needing wider furrow bottoms? A high width/depth ratio is needed because the increased width could not easily be achieved at greater working depth, with low width/depth ratios due to the increase in draught force.

In order to obtain the correct soil cutting over a range of widths the correct share has to be fitted to the mouldboard assembly. For this reason a controlled preliminary experiment was designed using only two share widths, which encompassed the whole range of width/depth ratios required.

A similar range to that used by Plouffe *et al.*, (1995) was thought to be suitable to test the Kverneland No 8 assembly. The two widths chosen were 355mm (14") using the standard 12" share and 508mm (20") using the standard 18" share.

The experiments that were carried out are given in Table 3-1. A randomised design was used and the experiments were carried out in a random order.

Test No	Ratio	Width (mm)	Depth (mm)	Test No	Ratio	Width (mm)	Depth (mm)
Test 1	1.75	355.60	200	Test 5	1.75	508.0	290
Test 2	2.25	355.60	160	Test 6	2.25	508.0	225
Test 3	3.00	355.60	120	Test 7	3.00	508.0	170
Test 4	4.00	355.60	90	Test 8	4.00	508.0	125

Table 3-1, Preliminary Experiment Variables

As can be seen from the Table 3-1 the experiments were arranged to have width/depth ratios from 1.75 to 4.00, using the two widths of 355.6 and 508mm. It was also possible to have common ratios for the both widths, which linked the experiment together and would show the limits of the mouldboard assembly at both wide and narrow settings as these were thought to be different. All tests were carried out at one

speed, which was nominally 4 - 5 km/h (1.25 - 1.38 m/s); this was considered an appropriate speed equivalent to normal field ploughing speeds.

3.1.3.1 Experiment Design and Layout

Due to the nature of the mouldboard plough action only one run was possible in each bin preparation. To simulate a true situation an open furrow was produced at one side of the soil bin, which gave the plough assembly an open furrow into which to turn the soil slice. Figure 3.1 shows the procedure of removing a section of soil along one side of the bin, known as a false furrow.

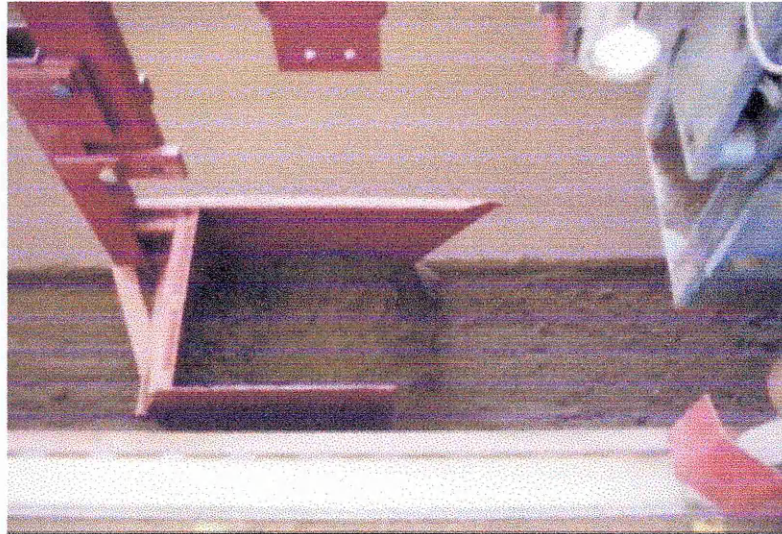


Figure 3.1, Removing False Furrow

The false furrow was removed to the same depth as the depth of test that was to follow; the false furrow can be seen in Figure 3.2



Figure 3.2, False Furrow Removed

Into this false furrow a pre-furrow was ploughed using the mouldboard at the corresponding test depth to provide the same open furrow profile as that left by the plough in a field situation. Figure 3.3 shows a pre-furrow being ploughed into the space removed by the false furrow tool, leaving a realistic furrow profile for the test to be ploughed into, as shown in Figure 3.4.



Figure 3.3, Ploughing a Pre-Furrow into the Removed False Furrow



Figure 3.4, Pre-Furrow, Leaving Correct Open Furrow Profile

This was needed to ensure that the soil slice being turned had an open furrow to fall into, as in a field situation. This would ensure no spurious forces were encountered by the soil being pushed into soil in the previous furrow or the side of the soil bin.

3.1.3.2 Measurements

The mouldboard assembly was attached to the soil bin processor via a two-dimensional Extended Octagonal Ring Transducer (EORT); this enabled the horizontal, vertical and resulting moment to be measured for each test. Calibration was carried out on the EORT using known static loads to match the gauges to the signal-processing unit; this was done for the three force measurement planes (horizontal, vertical and resulting moment)

Together with these force measurements a layer of chalk dust was applied to the surface of the soil to determine the soil movement and inversion of each plough setting; this can be seen in Figure 3.5



Figure 3.5, Chalk Dust on Soil Surface

This procedure enabled photographs to be taken after each test to determine the amount of soil inversion and the deviation of the soil slice from its original position. In addition, the furrow profile was measured using a profile meter, Figure 3.6. This gave an indication of the distance the soil was moved as a result of each plough setting. This could then be plotted in graphical format for comparison of each test setting.

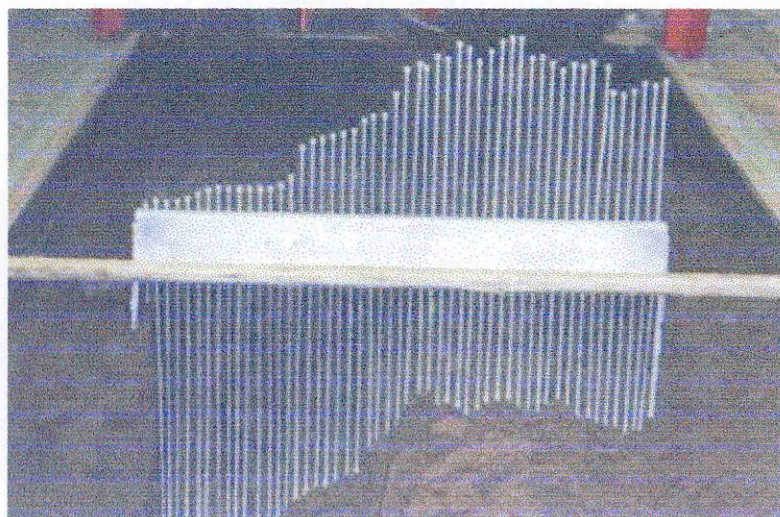


Figure 3.6, Library Picture of Profile Meter

3.1.4 Results of Width/Depth Relationships

The soil moisture content and bulk density (dry basis) were measured for each experiment as a measure of soil condition and consistency. An average of three samples gave the mean moisture and bulk density for each test carried out. These results can be seen in Appendix 1.1.

When the results from the eight tests were analysed and compiled into maximum, horizontal, vertical and resulting moments it was possible to show the results graphically. The graph below shows the maximum horizontal (draught) forces for the eight points measured.

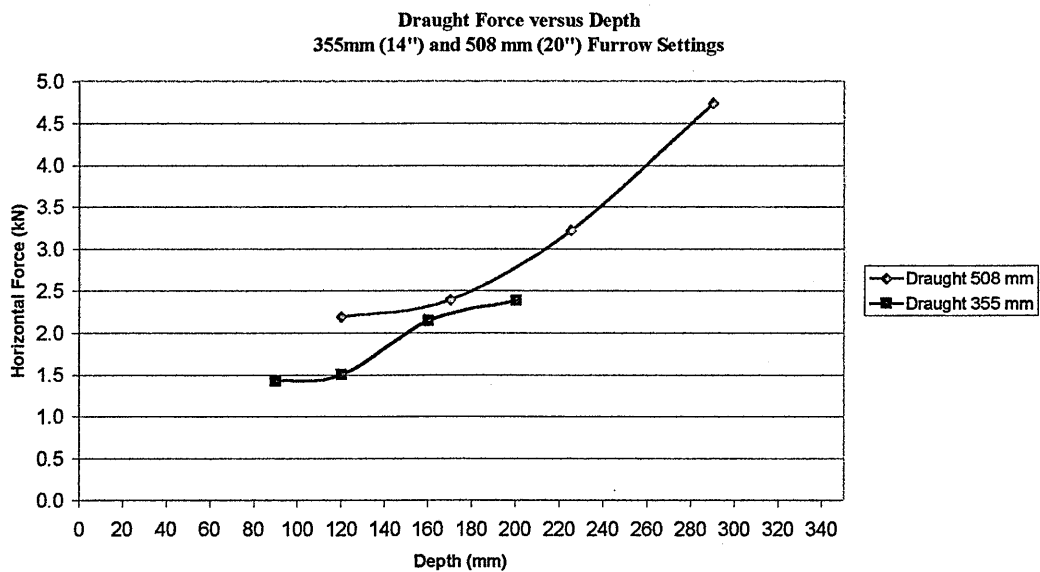


Figure 3.7, Horizontal Force, Two Share Widths Over Depth

As can be seen from the graph, the horizontal force increases with depth of operation for both the 355mm and the 508mm furrow width.

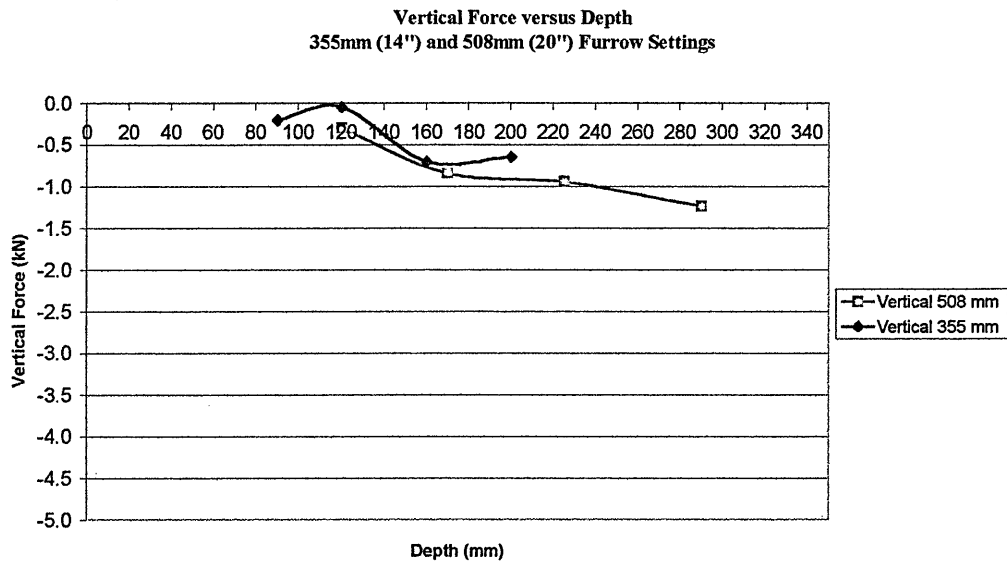


Figure 3.8, Vertical Force, Two Share Widths Over Depth

When considering the vertical forces shown in Figure 3.8 the values are considerably lower than those of the horizontal force, but both increase with the increase in depth.

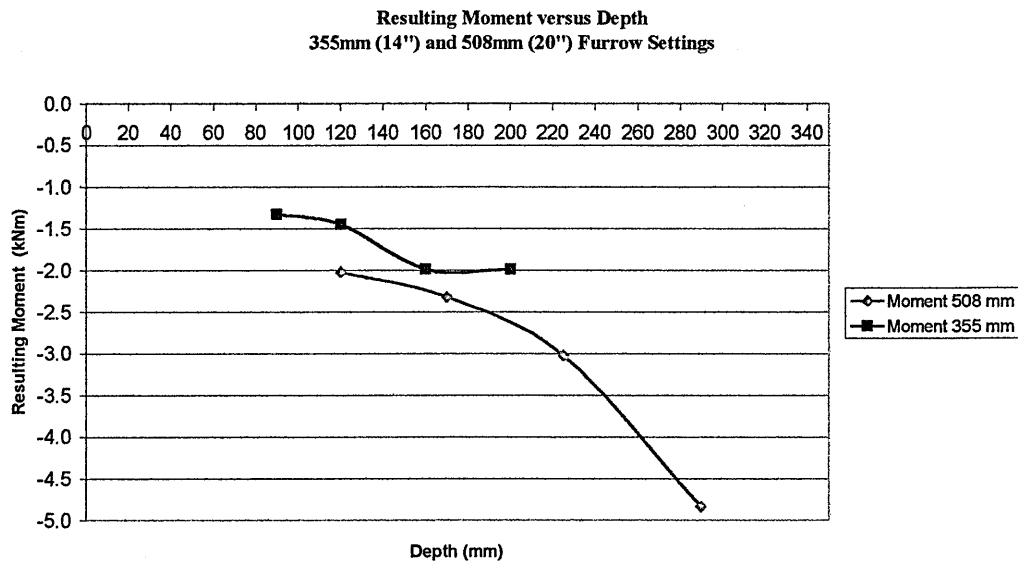


Figure 3.9, Moment Reaction, Two Share Widths Over Depth

Finally, looking at the moment reaction of the two share widths Figure 3.9; the values increase with the increase in depth and tend to mirror the horizontal force relationships

As these were preliminary tests only one replication was carried out, but the values for the 355mm furrow at 200mm deep was considered to be low for both the horizontal and vertical force and the moment reaction. The results for the 508mm (20") furrow seemed to be more consistent than those for the 355m (14") furrow settings.

To clarify the 355mm (14") data and curves an additional experiment was carried out at 355mm (14") width, with most interest in the data at 225mm depth.

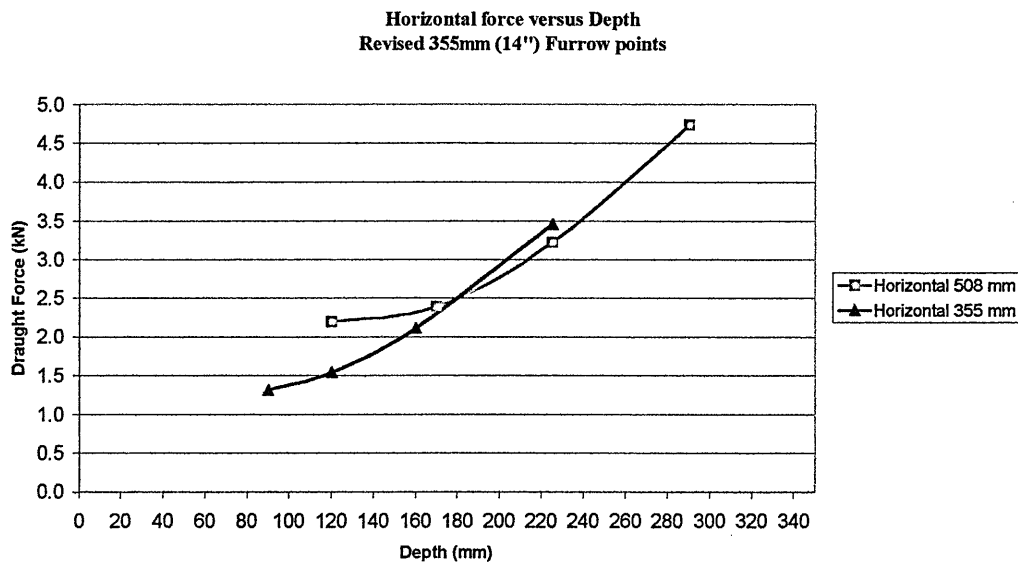


Figure 3.10, Horizontal Force, Revised 355mm Point

As can be seen from Figures 1.10 – 1.12, a more consistent relationship was obtained with the new data points at 355mm width, these increasing to a maximum at 225 mm deep.

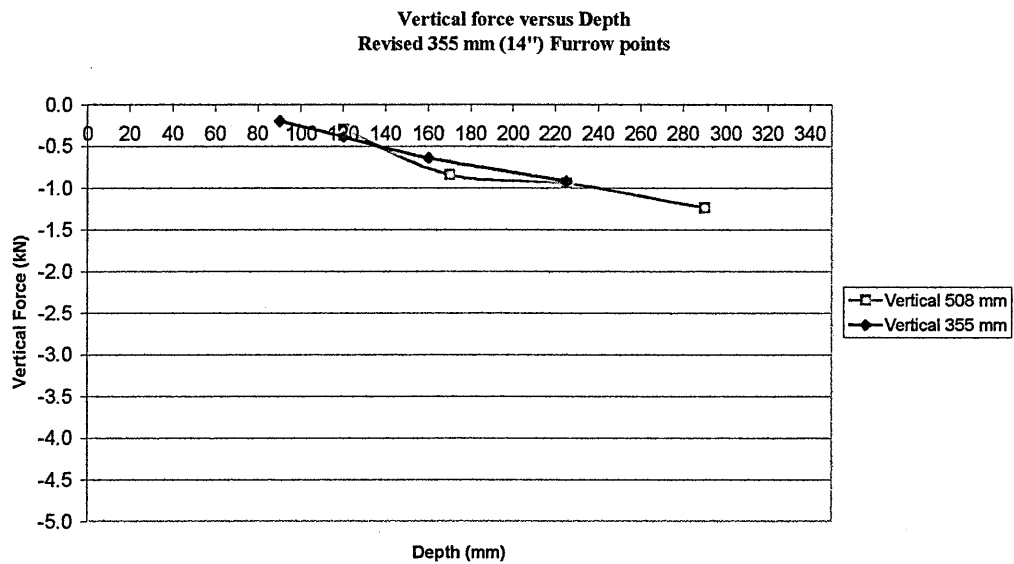


Figure 3.11, Vertical Force, Revised 355mm Point

This follows for the three measured variables of horizontal and vertical force and the resulting moment.

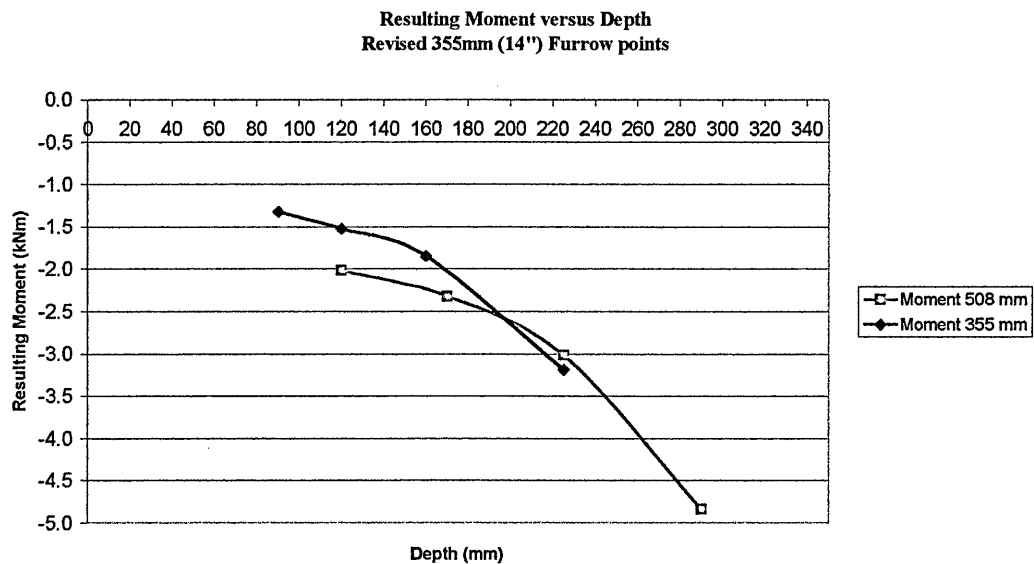


Figure 3.12, Moment Reaction, Revised 355mm Point

The point recorded at 355mm wide and 200 mm deep in the original experiment was thought to correspond with one of the layers that occur when the soil-bin is prepared for experiments. For this reason the forces measured at this depth were considered to be spurious when compared with the rest of the measured values in the experiment.

The revised point at 355mm wide and 225mm deep had a 19.7% increase in horizontal force over the 200mm setting and a 3.4% higher horizontal force than that the 508mm 225mm setting. This was mainly due to a 3.5% increase in the bulk density of the soil from when the 508mm experiment was carried out to the time of the revised 355mm experiment.

After the first test with the two furrow widths, it was decided to run an additional set of furrow widths. These were with a 406 mm (16 ") share working at 457mm (18") furrow width. Again, four width/depth ratios were chosen ranging between 1.75 and 4.0 to give four depths.

Table 3-2 below shows the configuration for the 457mm wide tests.

Test Number	Width/depth Ratio	Width (mm)	Depth (mm)
Test 1	4.0	457	110
Test 2	3.0	457	140
Test 3	2.5	457	180
Test 4	1.9	457	230

Table 3-2, Preliminary Experiments with 457mm Furrow

Once again, the moisture content and bulk density of the soil was taken. The mean moisture content was 10.41 % over a range of 6.13 to 11.87% and the mean bulk density 1.55 Mg/m³ over a range 1.42 to 1.69 Mg/m³. This gives an 8.4% increase in the mean moisture content and a 9.15% increase in the mean bulk density over the

values obtained for the previous tests, which can be noticed in the results. The mean results for all the preliminary experiment can be seen in Appendix 1.2.

With these additional points from the intermediate width, it is possible to view all the data points on one graph, as shown in Figure 3.13. The data points for the 457mm width fall slightly above those for the 508mm width from the first tests. This is considered to be due mainly to the increase in moisture content and bulk density of the soil between tests. The more important information obtained from the graph is that all three widths follow a similar trend of increasing draught force with an increase in depth. This relationship is fitted very closely by a second order polynomial curve as can be seen in Figure 3.14.

An additional method of viewing the results graphically is to compare the force required by each furrow setting to the amount (area) of soil moved, otherwise known as the specific resistance (SR). This method has been used many times in the past to compare tillage implement force data, including mouldboard ploughs.

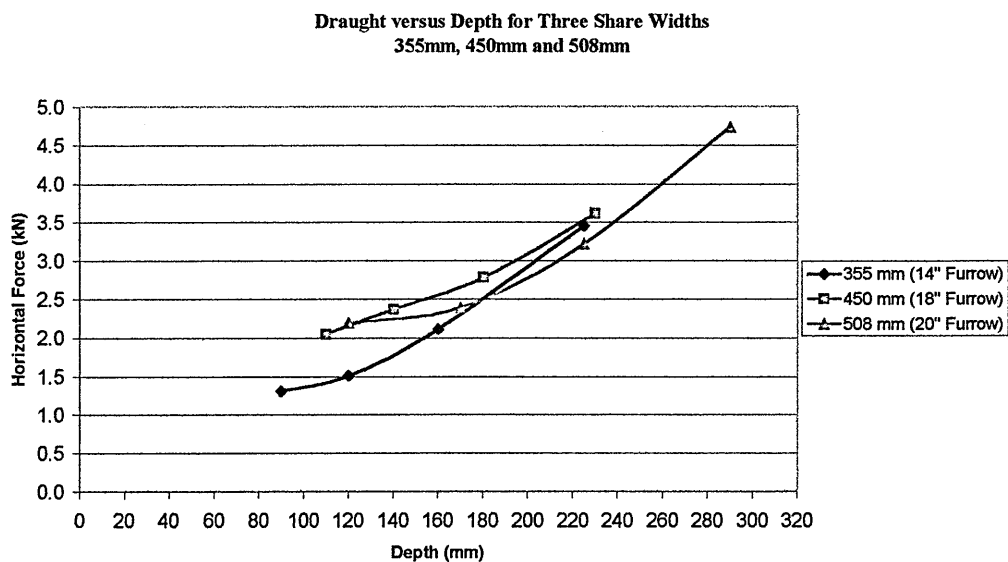


Figure 3.13, Horizontal Force Data for Three Furrow Widths

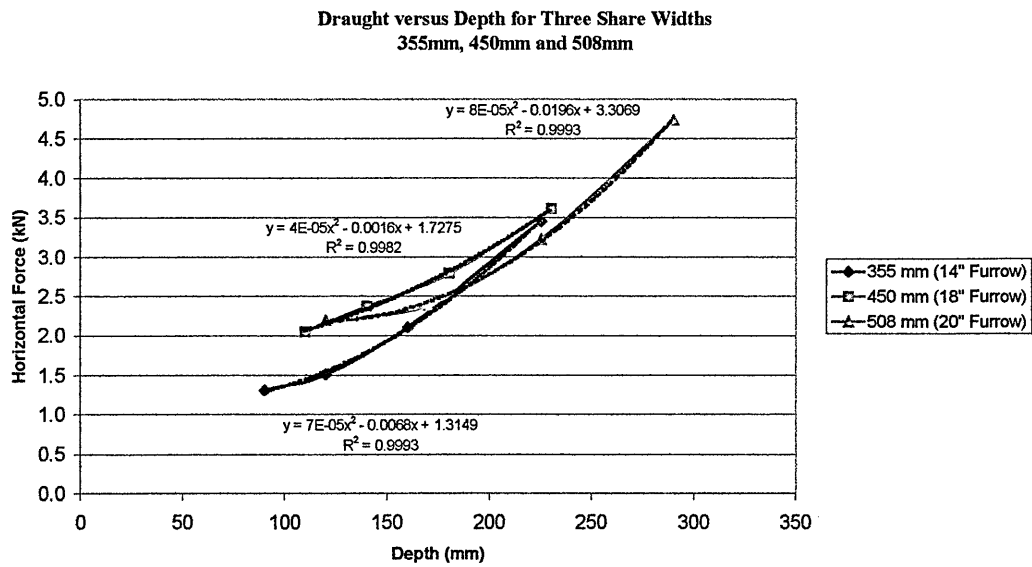


Figure 3.14, Second Order Polynomial Curves Fitted to the Measured Data

Figure 3.15 shows the horizontal force for the three widths tested, divided by the theoretical area of soil that is moved by each configuration, using the share cutting widths and the operating depths as the dimensions for the area calculation.

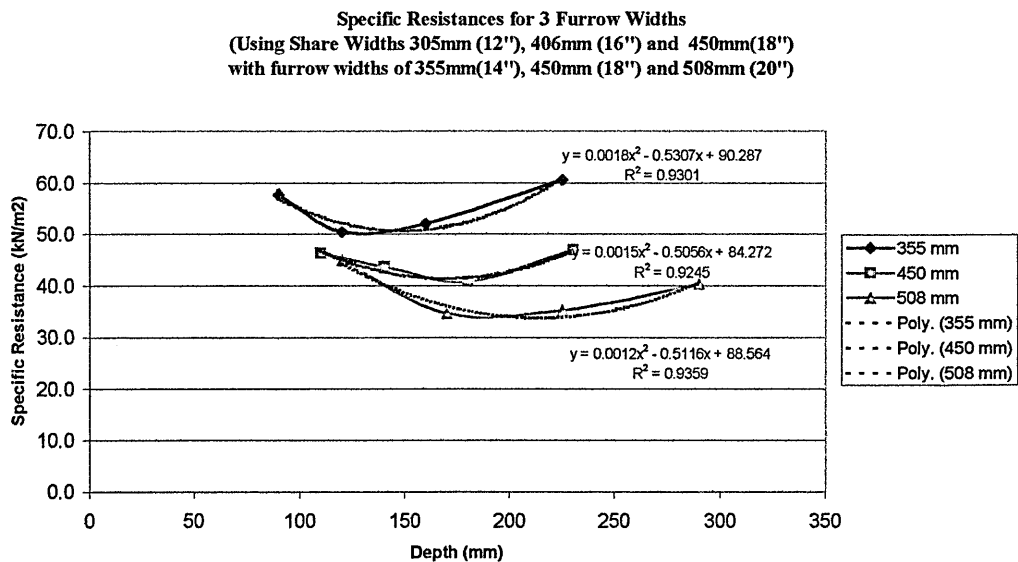


Figure 3.15, Second Order Polynomial Curves, Fitted to SR Data for Three Furrow Widths

The data in Figure 3.15 shows that there is an optimum depth of work for each of the furrow widths used; this increases as the width is increased. The minimum point on each of the curves being the point at which the least force is required to move the given unit area of soil. Using the fitted curves from the graph in Figure 3.15 the minimum specific resistance for the 355 mm furrow occurs at 150mm depth. This increases for the 457mm furrow to 170mm and likewise for the 508mm furrow the minimum specific resistance depth increases to 215mm deep.

The theoretical areas used in the calculation can be compared with those measured during the experiment using the soil profile meter for the 355mm wide furrow and the 508mm furrow. Figure 3.16 shows the profile measured for the soil bin after a 355mm wide test had been carried out. The shaded area is the theoretical area of soil that the width/depth setting should cut and move. As can be seen from the profile some soil has been failed on the land-side of the furrow and fallen back into the furrow bottom. Whereas on the open furrow side, the soil has been pushed to the extent of the theoretically cut width and left at the angle produced by the mouldboard.

This can be compared to a profile taken from the wider furrow setting (508mm) Figure 3.17, which again shows the shaded area as that of the theoretical soil area which should be moved by the furrow setting of 508mm wide and 170m deep.

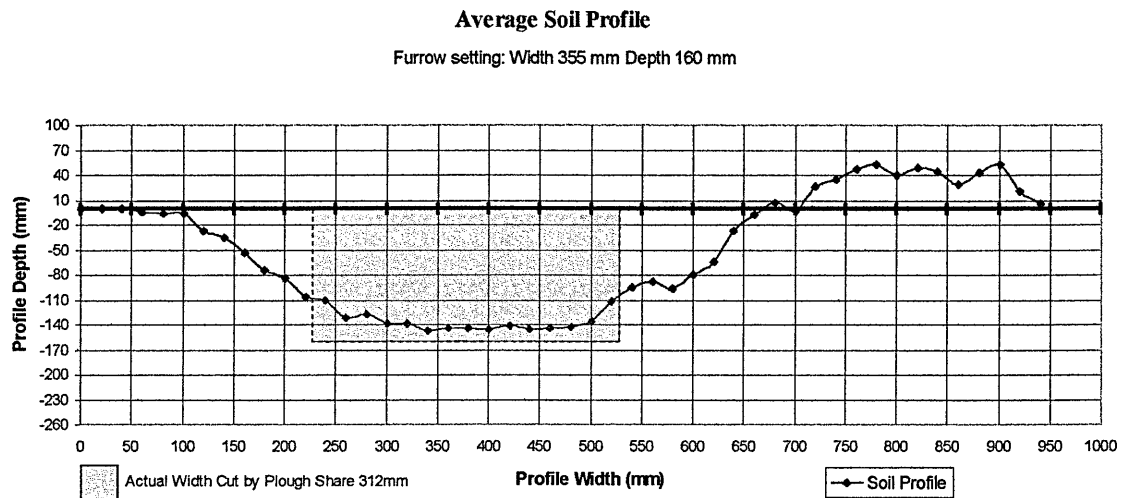


Figure 3.16, 355mm, Measured Furrow Profile

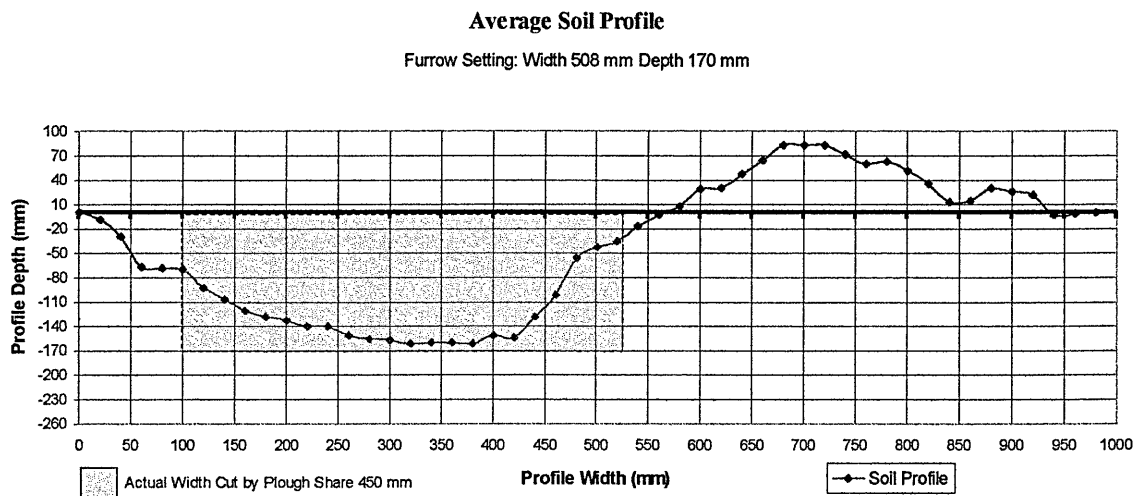


Figure 3.17, 508mm, Measured Furrow Profile

As in the previous furrow profile, some soil on the land-side has failed and fallen back into the furrow bottom which fills in the bottom corner of the theoretical area. In contrast to the 355mm wide profile, on the open furrow side the soil had not been

pushed to the extent of the cut width and was left partially across the bottom of the furrow. The profiles does, however slope away from the open furrow at the given mouldboard angle as for the 355mm wide furrow.

Finally, observations can be made of the soil throw and inversion achieved by each furrow setting by examining the chalk dust traces before and after each test run with the 355mm and 508mm wide furrows. Figure 3.18 to Figure 3.21 shows the soil surface and chalk traces before and after each test for the 355mm wide furrow setting.

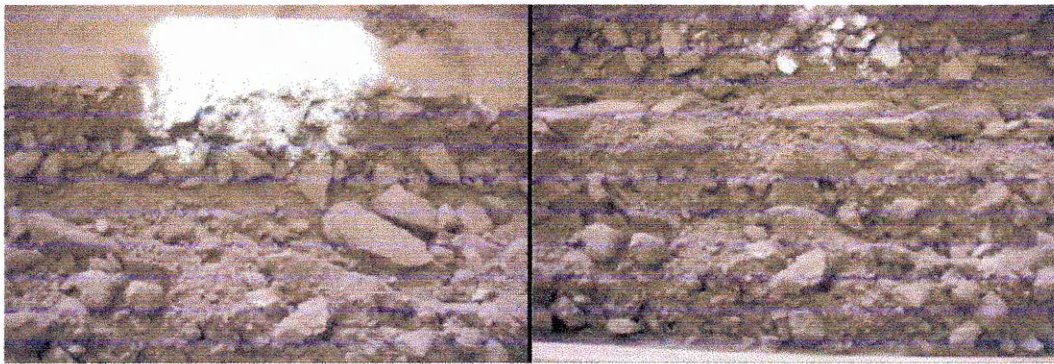


Figure 3.18, Before and After Photo, 355mm Wide, 200mm Deep

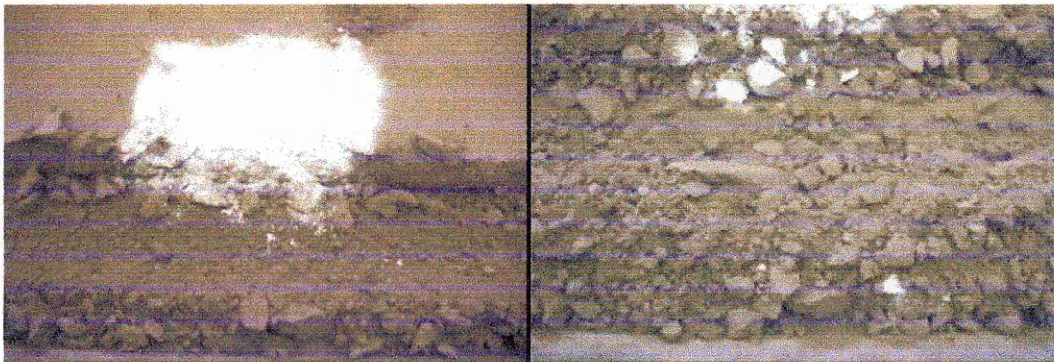


Figure 3.19, Before and After Photo, 355mm Wide, 160 mm Deep

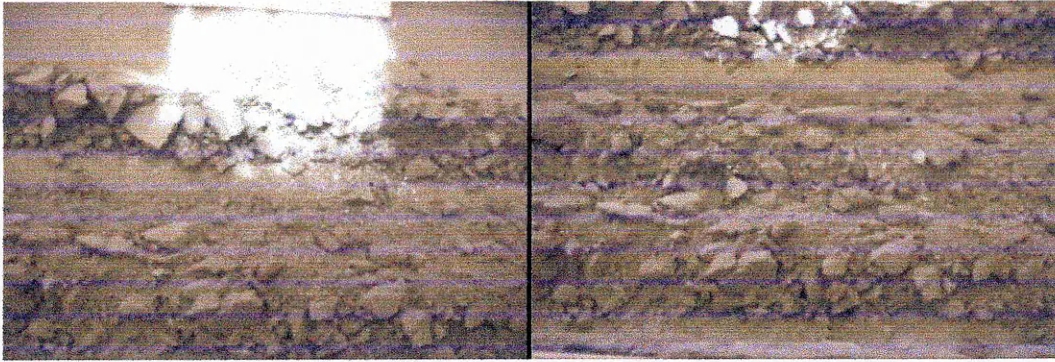


Figure 3.20, Before and After Photo, 355mm Wide, 120mm Deep

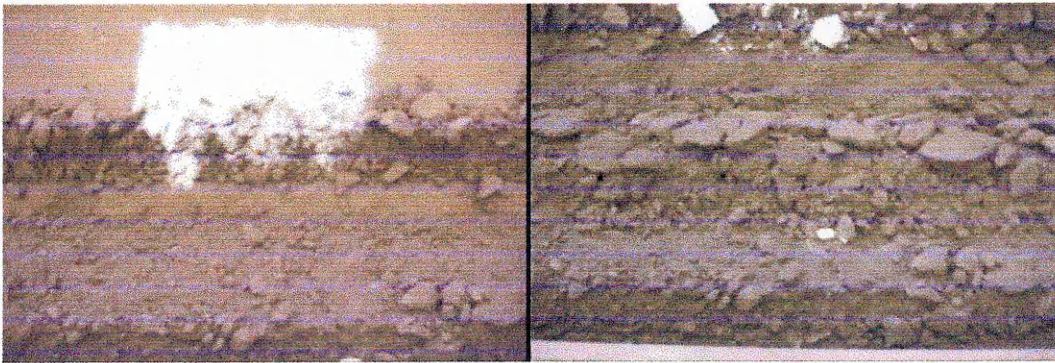


Figure 3.21, Before and After Photo, 355mm Wide, 90mm Deep

This can also be seen for the 508mm furrow width, Figure 3.22 through Figure 3.25

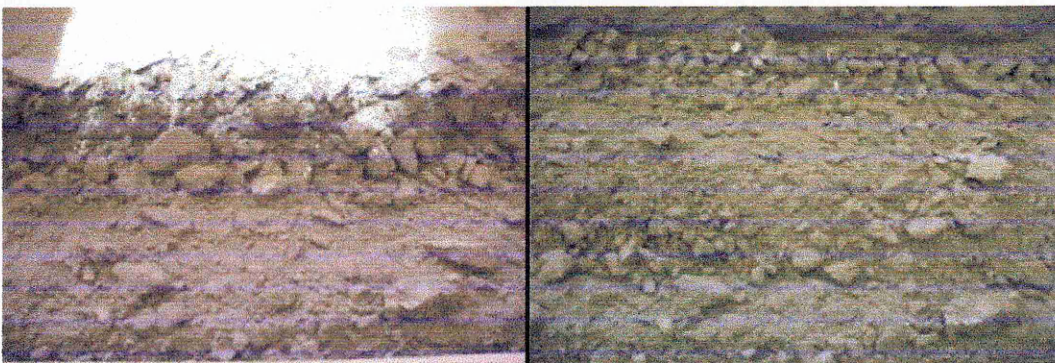


Figure 3.22, Before and After Photo, 508mm Wide, 290mm Deep

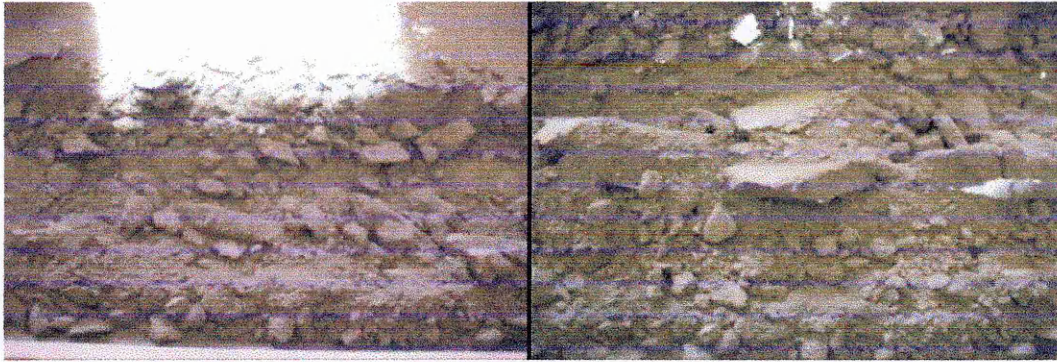


Figure 3.23, Before and After Photo, 508mm Wide, 225mm Deep

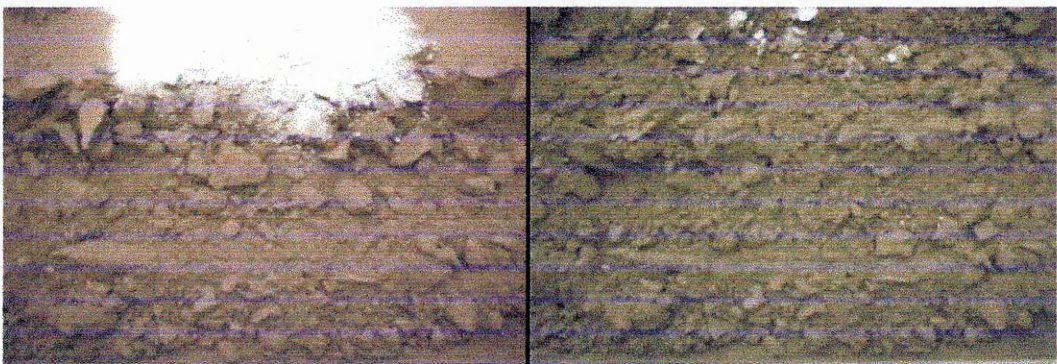


Figure 3.24, Before and After Photo, 508mm Wide, 170mm Deep

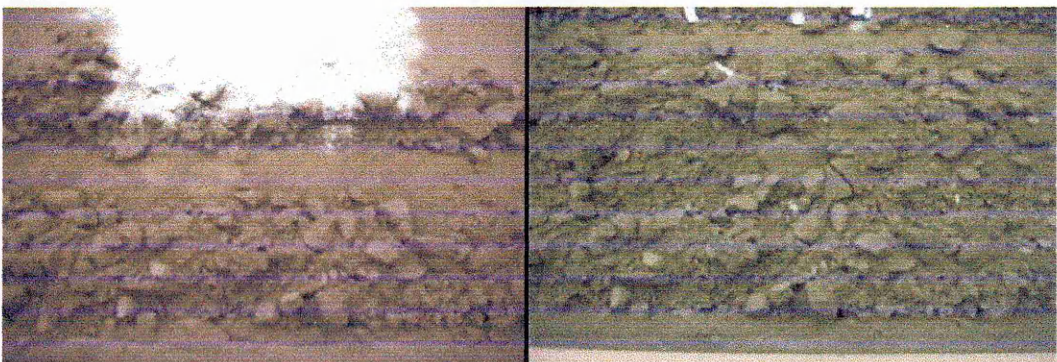


Figure 3.25, Before and After Photo, 508mm Wide, 120mm Deep

As can be seen from the photographs there is very little difference between the chalk burial at the lowest width/depth ratios and the highest width/depth ratios for either of the furrow widths. This is realistically only a 2-dimensional burial as the chalk dust lies perfectly flat on the surface, whereas arable trash or stubble will have some bulk and thickness.

3.1.5 *Summary.*

When testing the 355mm wide plough under controlled soil bin conditions at four depths that did not correspond with any layers that may occur from preparing the soil profile, the horizontal force increased consistently with depth. This was also the case with the 457 mm and 508mm width settings. This was as expected and follows theory and experimental work that has been carried out on numerous other tillage implements including mouldboard ploughs. There was a greater than linear increase response of horizontal (draught) force with depth for all three width settings, The force relationships overlapped at certain depth settings due to variation in soil strength and experimental error.

When the three different width settings were plotted against theoretical area disturbed the benefits of increased width were shown. The reason the specific resistance rises when the depth decreases is thought to be due to the frictional component of draught force that remains constant irrespective of depth. Therefore, as the depth decreases, the area gets smaller but there is the same amount of frictional resistance to pull the plough along in the soil. These effects give rise to a minimum value at some depth which is related to the width where the force component due to depth has increased too approximately the same as the frictional component and the area moved is an optimum. After this, as the depth is increased, the force component due to depth increases significantly with depth whereas the area moved increases linearly at a lesser rate. This means that the specific resistance curve rises and the force required to move the given area of soil increases.

Following these experiments, studies are required at increased speeds to determine the rate of increase of horizontal (draught) force due to varying speed. The optimum values from the specific resistance graphs, in terms of width and depth of work should be investigated because the optimal draught force requirement for a given amount of soil moved, is considered the point at which maximum efficiency of soil movement is

achieved. The only limitation would be that the depth at which this occurs might be too large to be able to increase the forward speed sufficiently to increase output.

As the graphs show, when the depth of operation is decreased the draught force decreases; this needs to be compared with results for increasing draught forces at increased forward speeds. Comparisons can then be made with the amount of draught force increase due to speed and the decrease due to depth. It will then be possible to determine exactly how much speed can be increased for no extra draught force requirement at any given depth.

One major observation made during the preliminary soil bin studies was that when the furrow cutting width (including correct share width) was increased from 355mm (14") to 508mm (20") the actual open furrow width left by the plough was not increased greatly, and was negligible for some configurations. Considering the profiles shown in Figure 3.16 and Figure 3.17, the increase in furrow width setting is 43% whereas the increase in furrow profile width is only 16%. This has implications on the open furrow space available for currently increasing widths of tractor tyres used for agricultural operations and the amount of re-compaction that occurs within the furrow bottom from such use.

It was shown from applying chalk to the surface of the soil before each test run that the Kverneland No 8 mouldboard body works well and achieves good soil inversion over a wide range of depths when used at both 355mm wide and 508mm wide. There was little variation in the amount of chalk covered throughout the range of tests carried out, but surface residue with increased bulk may cause problems at the shallower depths due to the limited volume of soil available for coverage.

3.2 Pilot Field Studies, Mouldboard Trash Burial

3.2.1 Introduction

Following the soil bin studies that made use of a chalk covered surface to examine soil inversion it was considered that further studies should be carried out. Unfortunately, the soil bin has a perfectly smooth surface condition and it would be very difficult to recreate an arable stubble condition to any degree of accuracy. For this reason, the best way to test the ability of the plough to bury surface residue and trash is to carry out field tests. Once again these tests were preliminary and were to aid the understanding of the plough operation in a field situation subjected to different operating variables.

A set of field experiments was carried out to determine the ability of the Kverneland No8 mouldboard to handle trash and surface residue at various plough configurations. The variables were depths and widths of a similar range to those selected for the soil bin tests. In addition, variation in speed was added because this was considered to affect the performance in terms of work quality of the plough. From these field tests the limits of the plough/mouldboard combination at each test configuration were to be observed for further study.

The field site chosen was winter barley stubble, which unfortunately, had not been baled due to difficult weather conditions. Therefore it was spread from the windrows and left on the surface, resulting in the surface residue being at an above average level. This would not have been the first choice of experiment site because rather than simulating the common surface trash condition (either chopper or removed) for arable stubble it was a worst-case scenario. The experiment was also carried out during January when weather conditions were not ideal but due to the previous season and the land available this was the first opportunity to conduct the tests.

The soil type of the field site selected was found to be of a sandy clay consistency from a soil texture determination test. The break down showed approximately 50% clay, 32.5% sand and 17.5% silt. Even though the soil had a high amount of clay it also contained a high amount of small stones; this meant that scouring on the mouldboards was not a problem.

For the purpose of the field experiments a Kverneland two-furrow reversible competition plough was used, with the competition bodies replaced with No8 bodies the same as used for the soil bin tests. This plough was fitted to a Massey Ferguson 6180 4WD having an engine power of 95 kilo Watts.

At the time of this experiment another project was taking place, which involved using the lower link draught sensing pins to measure horizontal force on any implement attached to the tractor link arms. This measurement system was under evaluation but it was considered useful to gain some data of the horizontal forces required by the plough operating under different configurations, so the data logging equipment and instrumentation was set up in the tractor. Unfortunately after the data was collected and analysed it was found that the resolution was not sufficient to determine any difference between no-load and the loads applied by the two-furrow plough operating at the various settings.

3.2.2 *Procedure*

The planned experiment was to test two different widths, these being the standard 355mm (14") and the maximum width available from Kverneland that is 508mm (20"). Three different speeds were to be tested, these being 4.5 km/h, 7.5 km/h and 12 km/h or the maximum possible with the available power from the Massey Ferguson 6180. The final variation was the depth of work; the plough was tested at 175-200mm (7-8") in the control test, and depths of 150mm (6") and 120mm (4.5") were also chosen to compare the ability of the plough to cover trash.

These tests would highlight the ploughs limits in terms of performance and quality of work, both for the minimum depth that ploughing could be carried out at under high trash conditions and also to determine if speed would be limiting within the range available from the given tractor on the quality of work.

The initial test variables can be seen in Table 3-3. Three strips of the field were ploughed for each test number to enable an adequate area of ploughing for comparison purposes; this also ensured that the plough was working against the same open furrow width and depth for at least two of the lengths of the field.

Test No	Speed (km/h)	Width (mm/inch)	Depth (mm/inch)
Test 0	4.5	355/14"	205/8"
Test 1	4.5	355/14"	175/6-7"
Test 2	7.5	355/14"	175/6-7"
Test 3	10	355/14"	175/6-7"
Test 4	4.5	508/20"	175/6-7"
Test 5	7.5	508/20"	175/6-7"
Test 6	10	508/20"	175/6-7"
Test 7	7.5	508/20"	115/4.5"
Test 8	12	508/20"	152/6"

Table 3-3, Initial Field Experiment Variables

Firstly the plough was set up to a standard configuration, this being 355mm (14") wide and 200mm (8") deep. Once at the test site the plough was used a few times up and down the field, this ensured it was working satisfactorily and that the quality of work was of a reasonable standard. Additionally this allowed a check to determine if an acceptable ploughed finish could be obtained in the given conditions. Using the plough at this common configuration also allowed a control strip to be ploughed so that when the plough set-up was changed the quality of work could be compared with the control work.

It was found that the depth of ploughing was very difficult to control under field conditions and small setting changes of 25mm would not be possible to maintain. For this reason a depth of approximately 175-200mm (7-8") was chosen for the standard plough depth and also used for the tests that were initially 150-175mm (6-7"). This was considered a common plough setting, which would be used by many operators.

The tests began at the standard 355mm (14") furrow, 175-200mm (7-8") deep and 4.5 km/h. The speed was then increased in two increments, firstly up to 7.5 km/h and then to 10 km/h. For these tests, the same widths and same depth were maintained as much as possible with position control linkage setting.

For the next test the width was increased from 355mm (14") to 508mm (20") and the speed reduced again to its lowest value with the depth remaining constant. This width setting was then repeated at each of the three speeds.

The next test was to vary the depth of the plough, reducing it from 175-200mm (7-8") to approximately 115mm (4.5") and the intermediate speed of 7.5 km/h was used. The final test was carried out at as high a speed as possible, which was 11km/h, the maximum speed maintainable with the tractor.

3.2.3 *Results*

3.2.3.1 *Observations From Initial Field Tests*

As the tests were set-up to determine the reduction in quality of work when using the plough at the different configurations, observations of each ploughed section were imperative. Comments were made on each one in terms of depth, width and speed the pictures of each plough configuration can be seen in Appendix 1.3.

Ploughing speed:

- 1) The difference in ploughing quality between 4.5 km/h and 7.5 km/h was not noticeable. This was the case for both the 355mm and the 508mm width.
- 2) At 10 km/h the quality of work was similar to that of the slower speeds but its consistency began to reduce, due to the clay nature of the soil. On some occasions the soil would hold together in a continuous spiral and turn a full 360 degrees after leaving the back of the mouldboard. This left the soil clods standing with the trash facing upwards again, which was not the desired effect. This rolling effect was slightly more pronounced at the wider of the two furrow widths.

Ploughing depth:

The depth of work had the most effect on the quality of soil inversion and trash burial achieved by the Kverneland plough. This was most noticeable with the wider furrow, when the depth was reduced from 150-175mm (6-7") to 115mm (4-5"). The quality of work achieved is highly dependent on the amount of trash that needs to be buried, due to the proportions of clean soil in the furrow profile and the amount of trash. The depth of work therefore directly affects this ratio of clean soil to trash, and has more effect on the trash buried than the width. If the width is increased, the amounts of trash are increased proportionally to the amounts of clean soil. Subsequently if the depth of ploughing is decreased then the amounts of trash can remain the same but the amount of clean soil available in the given furrow profile will be reduced. This then affects the ploughs ability to achieve total trash burial even if the soil is inverted.

Ploughing width:

The ploughing tests that were conducted at 508mm (20") were of most interest in terms of trying to increase the area ploughed and to provide a wider furrow to accept wide tractor tyres. A reduction in depth would be most useful at the 508mm (20") furrow setting as a method of reducing the draught requirement, which could be offset against the increased working width.

3.3 *Summary.*

The Kverneland No8 mouldboard is a good general-purpose mouldboard that works well over a range of widths, depths and speeds. The Kverneland No8 mouldboard was capable of burying trash at speeds in excess of 7 km/h. At approximately 10 km/h the mouldboard reached its limit in terms of effective trash burial, for the particular field conditions, moisture content and level of trash.

The depth of plough operation greatly affected the trash burial capabilities. Most of the tests showed that the depth would have to be kept at approximately 150mm (6") in arable stubble just to provide enough soil to bury the previous crops residue. The minimum depth that can be sustained depends greatly on the amount of trash to be buried.

Additional observations taken from the fieldwork were that the actual width of the furrow bottom remained approximately the same irrespective of the furrow width setting of the plough although the actual cut width of soil increased, the furrow bottom width was very similar, this has two major effects on the quality and finish of the ploughing. Firstly, if the tractor used to pull the plough is fitted with wide tyres, commonly specified on many farms primary tractor, the last furrow of each plough bout is driven over. This re-compacts the soil in the open furrow that has just been ploughed and leaves a depression that has to be filled by the first furrow of the

following bout. Getting the first furrow to fill this depression is not always possible and consequently the finished surface ends up with compacted furrows on every bout.

The second problem with having the same width mouldboard for various width furrows is that soil profile and soil consolidations are different. As the mouldboard does not move the soil any further to the side when using a 508mm (20") furrow width, it is not pushed up against the previous furrow to the same extent as when using a 355mm (14") setting. This means that with the 508mm (20") furrow setting the soil is spread more thinly over the width and is more likely to settle over time, leaving an uneven surface finish. If the mouldboard was matched to the furrow width setting, an identical furrow profile and furrow consolidation could be obtained at all furrow widths. This would also allow the bottom of the open furrow to be wider, enabling the use of wide tyres so eliminating unwanted compaction.

CHAPTER 4 MOULDBOARD SOIL BIN STUDIES

4.1 *Aim*

The aim of this experiment was to extend the work carried out in chapter 3 and investigate the variation of speed on the draught force of different width and depth mouldboard plough setting under controlled soil conditions, in order to establish a relationship. In particular to examine the effects of speed in terms of increasing plough performance.

4.2 *Introduction*

In earlier work all the soil bin experiments had been carried out at one speed, even though the depth and the width had been varied. To enable a relationship between the depth, width and speed of the Kverneland No8 body experiments were needed to test the mouldboard at different widths and depths over varying speeds. Previous soil bin tests carried out to determine the draught force of varying widths shares, showed some variation in draught force results. This was due to the different soil properties at the time of testing, which caused the draught to be higher on the 457mm (18") furrow width than on the 508mm (20") furrow.

To ensure that the soil bin properties remained the same for all of the tests, the experiment had to be carried out in soil bin preparations that followed each other and followed the same procedure. This would ensure that the soil properties did not affect the results.

With the additional information gained from these experiments it will be possible to determine which of the three variables being tested has the greatest effect on the

draught force of the plough. This will help to determine the best way to increase the output and efficiency of the mouldboard plough.

As the furrow width is an important factor the experiments concentrated on this and, therefore, the majority of the tests were carried out using the 508mm (20") furrow width.

From previous soil bin experiments, choosing a share width and applying the depth/width ratio of the furrow determined the depths, but this caused some problems. The soil bin is prepared in layers of 50 mm. If the depth of the ploughshare happened to coincide with the depth at which two layers joined, the soil failure was totally different than if it was cutting through the middle of a layer. For this reason the depth settings for this set of soil bin experiments were chosen so that they were directly in the middle of the layers of soil. These were 125, 175 and 225mm depths.

The speed was a very important variable to be tested and the higher speeds were of more interest than the slower ones. The maximum speed of the complete soil bin-processing unit was found to be 10 km/h after some speed calibration tests. This was not as fast as was first desired to test the plough but was chosen as the top speed for several reasons:

To test the mouldboard at speeds any higher than 10 km/h only the small section of the soil processor would have to be used. This would mean disconnecting it from the soil processing section for each test. Once the small piece of the processor is disconnected from the main part, it becomes very unstable due to its light/weight construction. This was considered unsuitable for connecting the mouldboard because of the high force that may be involved at increased depth or speeds. Another problem with the small section of the processor is the attachment method and depth control. These are very basic and depth control is coarse so were considered not suitable.

After all these possibilities, it was decided to use a maximum speed of 10 km/h using the whole processor unit, which made the test more straightforward and reliable. Two

slower speeds could then be chosen to provide a total of three speeds for the experiment

The final variable is the width of share fitted to the mouldboard assembly; these come in standard widths from 305mm (12") to 457mm (18"). Three different widths were chosen to give three different furrow widths. A 305mm (12") share is used for a 355mm (14") furrow, a 406mm (16") share for a 457mm (18") furrow and the widest share 457mm (18") for use with the 508mm (20") furrow.

Once again some kind of false furrow was needed to simulate the previous furrow of a plough. Rather than remove the false furrow as was done in the previous soil bin experiments with a special attachment a process much like that used in the field when ploughed lands were opened was adopted. This was to use the mouldboard to produce the correct open furrow profile over two pre-test runs. The first pass was done at half the working depth of the test that was to follow; the next run was then done at test depth and in the middle of the bin. This left enough room for a full ploughing width at 508mm to be ploughed as the test run, which was a much quicker procedure because the mouldboard assembly did not have to be removed each time before a test.

4.3 Procedure

A set of experiments was set up for the three important variables. These were three widths of share to give the following furrow widths: 355mm (14"), 457mm (18"), and 508mm (20"). Three depths 125mm, 175mm, 225 mm corresponding with the middle of any prepared layers in the soil profile, and finally three speeds of 4.5km/h, 7.5km/h and 10 km/h. As the widest furrow was of most interest in terms of increasing the plough output, this width was tested at all 3 depths and speeds. It was only necessary to test the narrower two shares at one depth and one speed because they were of less importance and some data had been collected before.

This plan gave the set of eleven experiments given in Table 4-1 that were all replicated three times.

Test No	Width (mm/inch)	Depth (mm/inch)	Speed (km/h)
Test 1	355/14"	175/6.5"	4.5
Test 2	457/18"	175/6.5"	4.5
Test 3	508/20"	125/5"	4.5
Test 4	508/20"	175/6.5"	4.5
Test 5	508/20"	225/8.5"	4.5
Test 6	508/20"	125/5"	7.5
Test 7	508/20"	175/6.5"	7.5
Test 8	508/20"	225/8.5"	7.5
Test 9	508/20"	125/5"	10
Test 10	508/20"	175/6.5"	10
Test 11	508/20"	225/8.5"	10

Table 4-1, Soil Bin Experiment Variables

As this was the first time that speed had been varied, it was necessary to be able to determine the speed for each test and repeat this speed for each replicate. There were two ways of measuring the speed available on the soil bin processor; one was an analogue voltage transducer, Figure 4.1 and the other was a trigger switch, Figure 4.2. The analogue voltage transducer needed calibrating and the trigger switch was an appropriate method of doing this and the two methods worked well together.

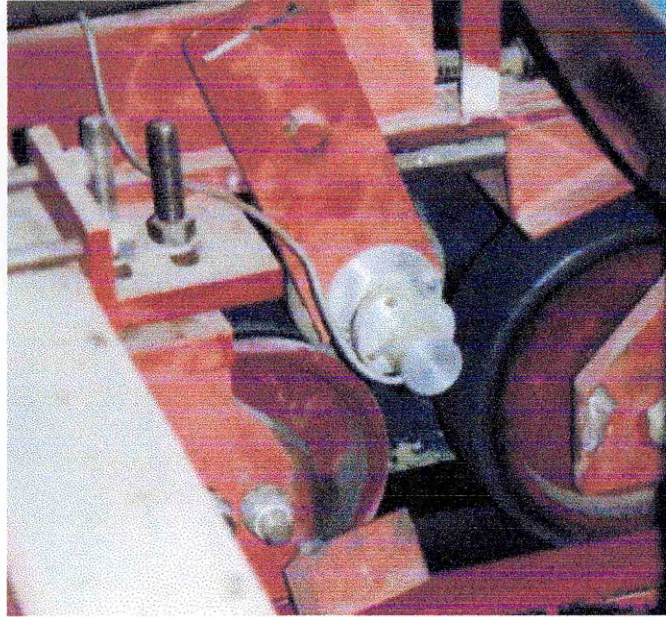


Figure 4.1, Analogue Speed Transducer

The analogue voltage transducer measured the revolution of the processor carriage wheels that were on the driven part of the processor carriage and ran along the side rails of the soil bin. This gave an analogue output that was recorded by the data logging equipment.



Figure 4.2, Pulse Input, Trigger Switch

The trigger switch was attached to the side of the processor unit and relied on two ramped bars laid beside the soil bin to provide activation of the switch. The switch produced a digital spike, which was recorded by the data logging equipment, every time it came into contact with one of the bars. Knowing the precise distance between the bars at the side of the bin provided the distance over which the processor travelled between each digital spike. To calculate the speed of the processor over this distance the time taken to cover this distance was needed, which was taken from the signal processing frequency. As all the data was being recorded at 103 Hz the time taken between the spikes could be calculated. This allowed the average time taken for the processor to cover the pre-set distance to be calculated using $\text{Speed} = \text{Distance} / \text{Time}$.

An example of the information that was recorded from both the analogue voltage transducer and the trigger switch can be seen in Figure 4.3. The analogue trace shows the calibrated speed, which corresponds to the time taken for the processor to travel the distance between the spikes.

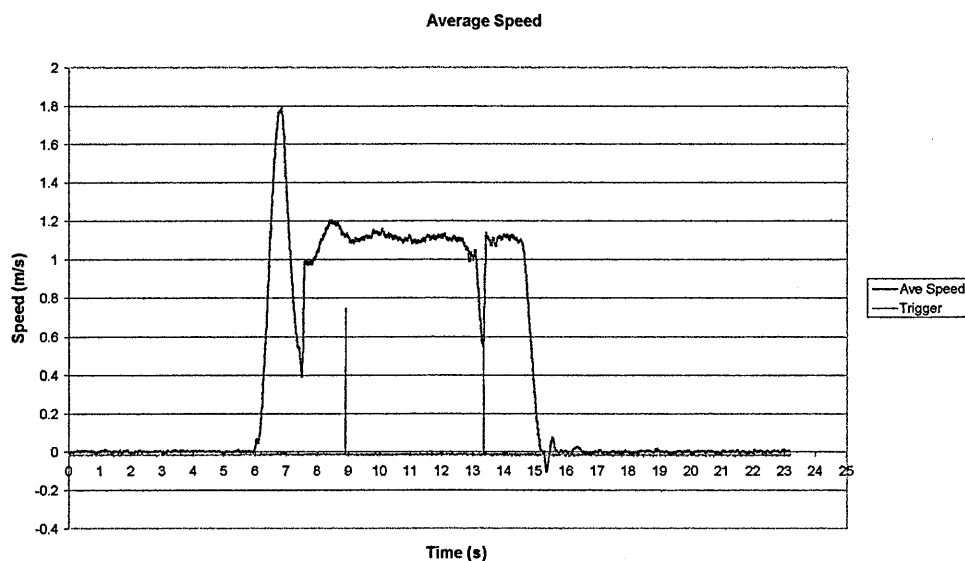


Figure 4.3, Example of Speed Trace and Trigger Spikes

The digital spikes were found to be a more accurate method of measuring the speed than the analogue wheel because the wheel tended to slip on the surface of the processor drive wheel, and provide a very periodic speed signal; this situation was

exaggerated at the higher speeds. The trigger switch always provided a clear digital spike and therefore enabled the average speed of the processor for each test to be recorded.

As the tests were to be carried out at different speeds the soil profile was to be measured for both the open furrow and the soil thrown to the open furrow side. This was to determine the effect of speed on the soil throw of the Kverneland No8 mouldboard body, as it was expected that both the furrow bottom width and the overall width of the furrow would increase with both share width and with an increase in speed as explained by Söhne (1960).

Once again the moisture content and the bulk density of the soil were measured to determine the consistency of the soil during the experiment.

4.4 Results

The following results were collated from the experiments carried out with each mouldboard configuration.

The Horizontal (draught) Forces	(kN)
The Vertical Forces	(kN)
The Moment Reactions	(kNm)
The Soil Moisture Content	(%)
The Bulk Density	(Mg/m ³)
Measured Soil Profiles from the Open Furrow.	(mm)

To monitor the soil conditions during each test the soil properties were recorded, a summary of the results can be seen in Table 4-2. A full table of the means from three replications can be seen in Appendix 2.1.

	Moisture Content (%)	Bulk Density (Mg/m ³)
Minimum	9.14	1.37
Maximum	12.36	1.63
Mean	10.86	1.53

Table 4-2, Moisture Content and Bulk Density

A table of the results showing each test with the setting that was used and the measurement of draught force, vertical force, moment reaction and the specific resistance, can be seen in Appendix 2.2.

The graphs in Figure 4.4 to Figure 4.6 show the force measurements taken at each mouldboard configuration. Figure 4.4 shows the increase in draught force, due to an increase in the share width and furrow cutting width. Figure 4.5, shows the increase in horizontal force with the increase in working depth from 125mm to 225mm; this was done at the three speeds of operation. Finally, Figure 4.6, shows the increase of horizontal force with increase of operational speed, namely 4.5 km/h, 7.5km/h and 10km/h.

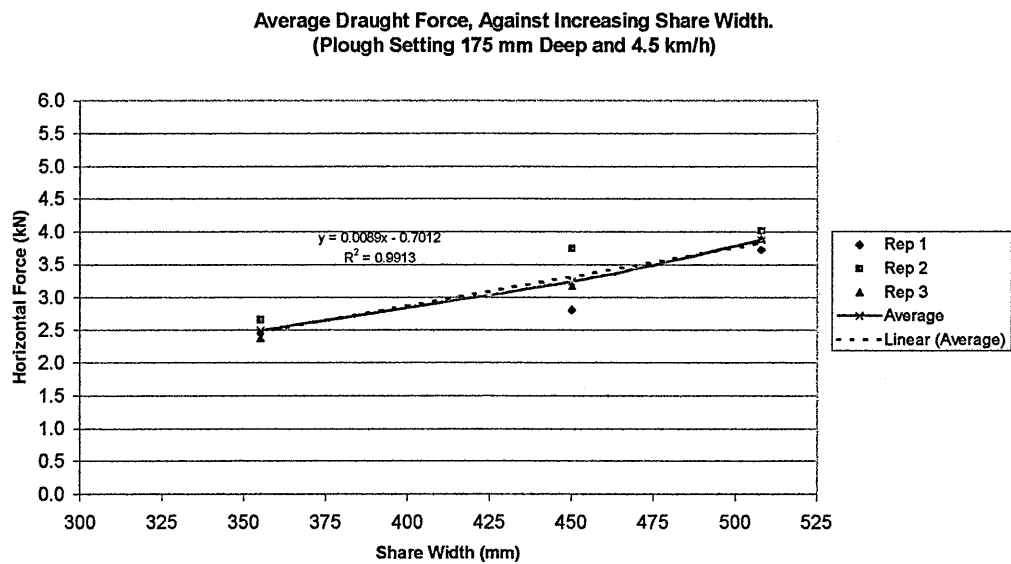


Figure 4.4, Force versus Share Width for One Depth and One Speed

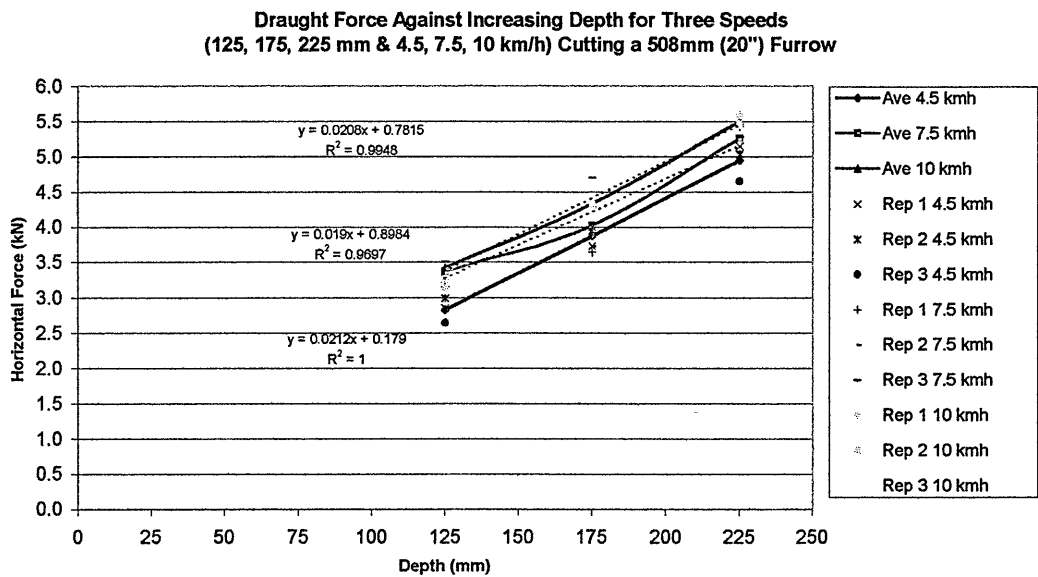


Figure 4.5, Force versus Depth for Three Speeds

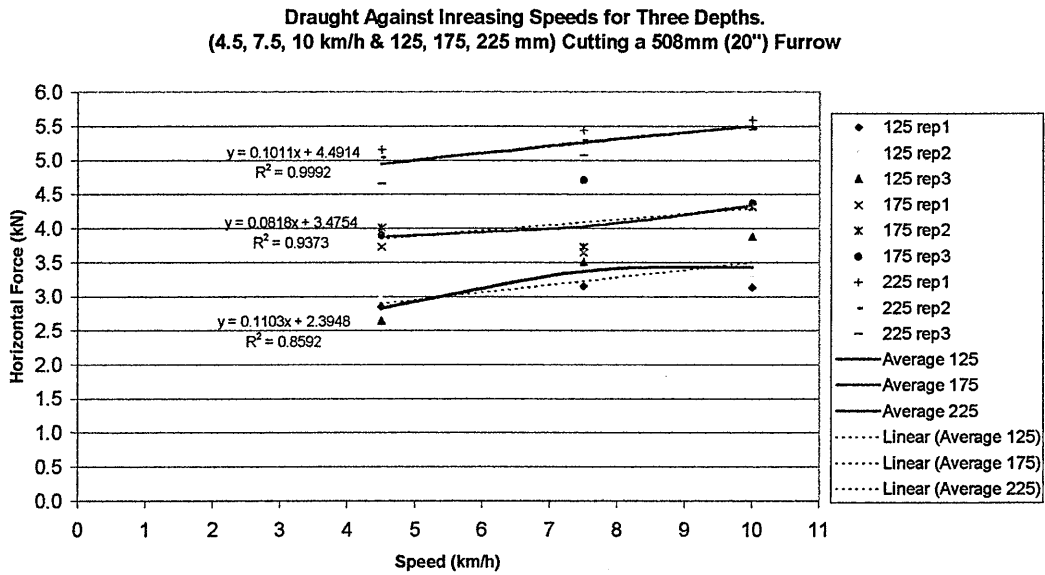


Figure 4.6, Force versus Speed for Three Depths

The measurement of the soil profiles was an important part of the experiment; this indicates the soil movement from each of the plough settings. From previous experiments it was noticed that the actual increase in furrow bottom width was not occurring as was first expected. This set of experiments allowed the opportunity to validate this point and also look at the effect of depth and speed on the furrow profile. To aid the comparison of soil profiles a datum point was set for each test to ensure it was ploughed in the same position along the soil bin so that each profile could be matched up.

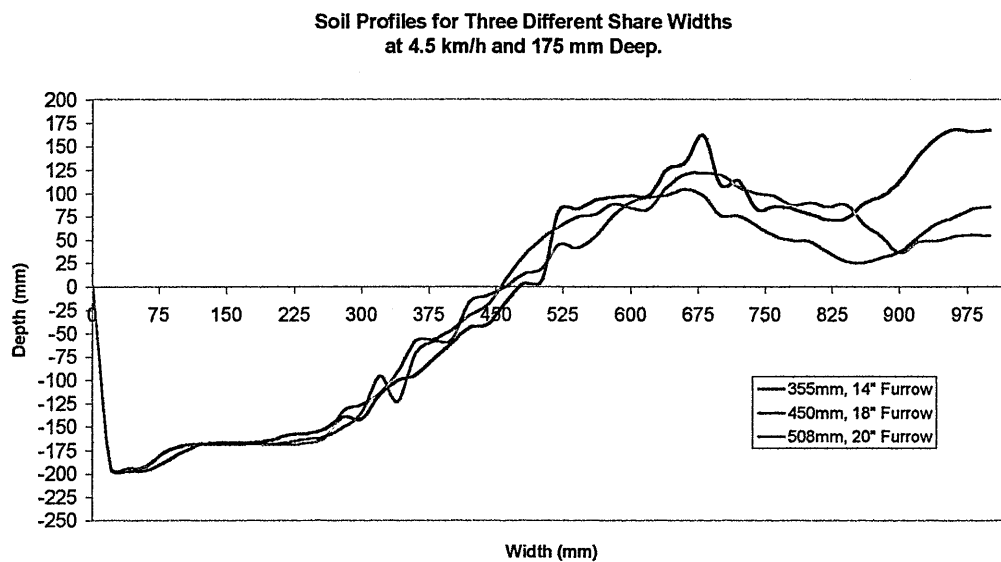


Figure 4.7, Measured Soil Profiles for Three Share Widths

Figure 4.7 shows three soil profiles taken from tests with three share widths all aligned about the furrow wall, which provides the zero datum point in the horizontal direction. This shows that there is no difference in the furrow profile for the three widths of operation used in the experiment.

This point is highlighted when the actual cutting widths that are used for each furrow width setting are overlaid onto the profile; this is shown on a larger diagram in Appendix 2.3. The first shaded box next to the furrow wall is the 355mm wide setting, the next shaded box is the 457mm furrow width and the dotted line shows the 508mm furrow width setting.

As the width of share did not increase the width of the furrow bottom, the effect of speed on the furrow profile can be considered. This can be seen for a shallow plough setting in Figure 4.8. Likewise the furrow profiles for the two other depths tested can be seen in Figure 4.9 and Figure 4.10. These show very little increase in the furrow bottom width from the slowest speed to the fastest, however, the profiles have moved further from the furrow wall at the top of the profile.

At the slower speeds, the dip between the furrow profile measured and the previous furrow produced in the soil bin is noticeable, where the profile peaks between 500 and 700mm from the furrow wall, depending on depth. As the speed is increased, the dip between furrows tends to disappear and the profiles have levelled off after one metre.

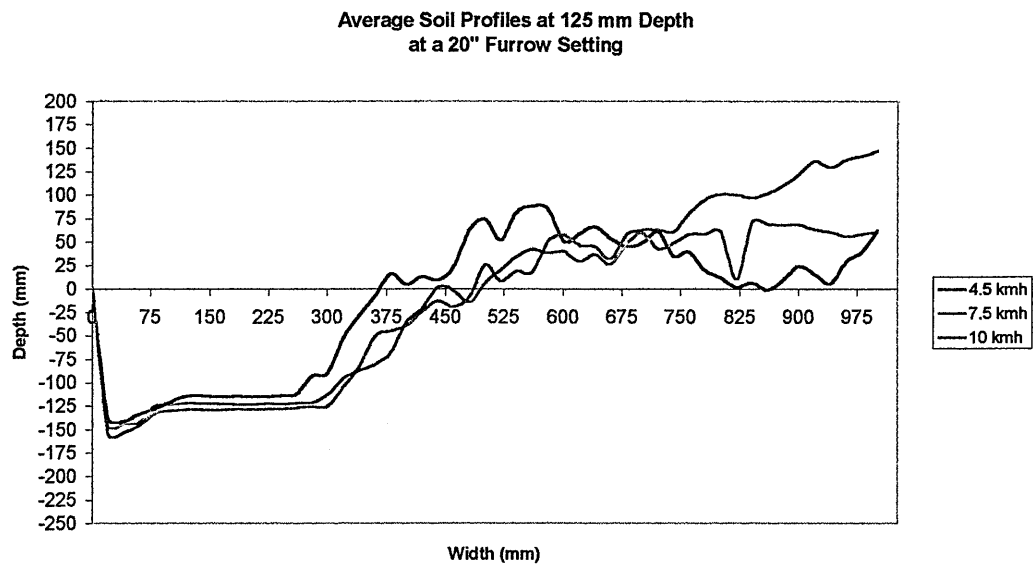


Figure 4.8, Measured Soil Profiles, 125mm Depth

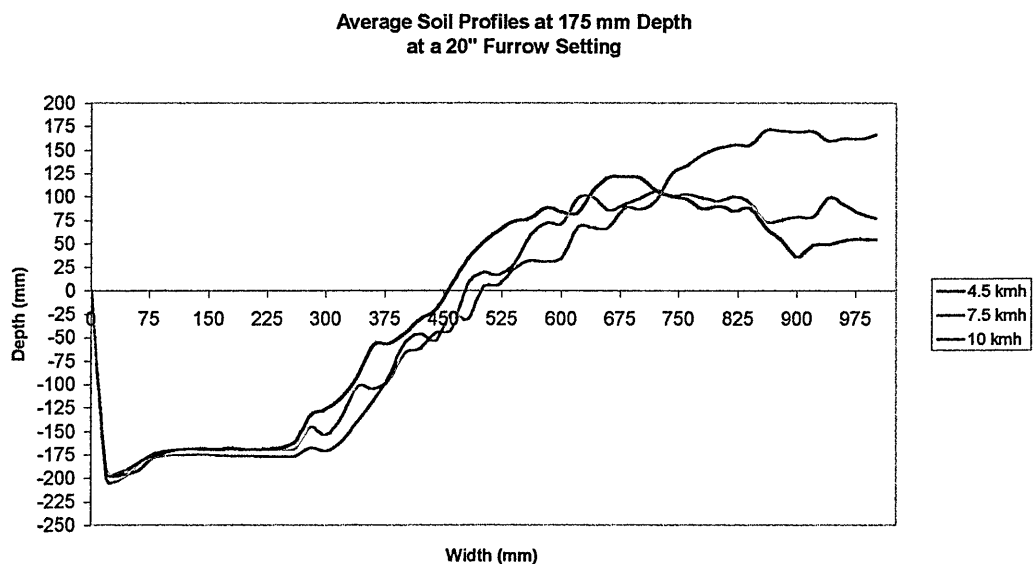
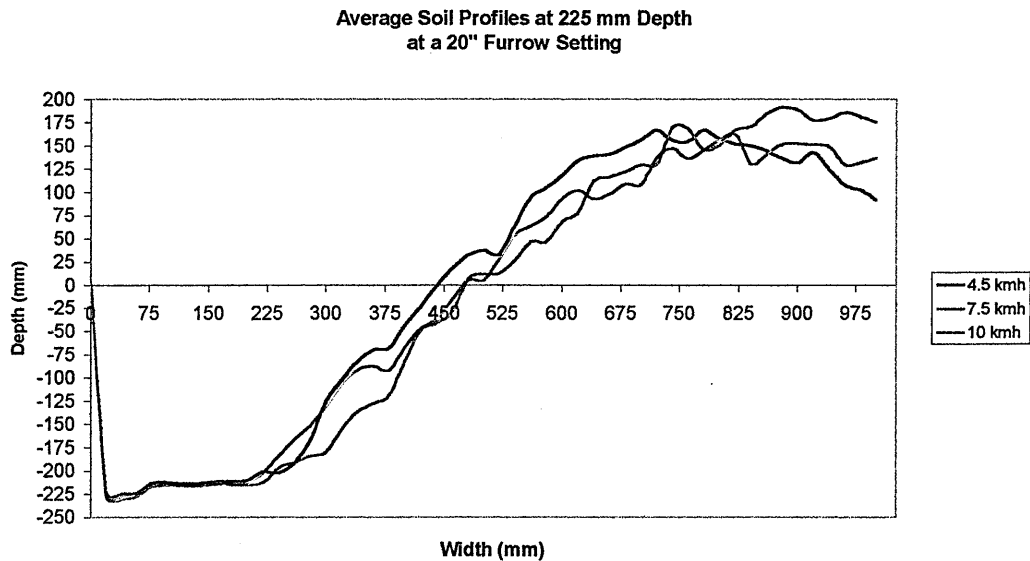


Figure 4.9, Measured Soil Profiles, 175mm Depth



4.5 Summary

As can be seen from the graphs, the draught force increased with all three of the variables width depth and speed. Previous research into plough bodies showed that horizontal force increased with the square of speed, but this was found not to be the case with the Kverneland No8 (a modern) mouldboard assembly. It can be seen that the draught force increase with speed is smaller than that with either width or depth. This means that the use of increased speed to increase the output of the mouldboard plough would be the most effective method to increase output due to the small draught force penalty. In addition to this the reduction in depth would lead to the greatest reduction in the draught force and hence provide opportunity to increase either width or speed to increase output without increasing the overall draught force required.

The soil profiles measured from the experiments show that when the effective cutting width of the mouldboard assembly was increased the actual furrow bottom width left by the mouldboard does not change. This is demonstrated by the fact that when the plough was fitted with the widest share and set to plough at the widest furrow width,

the soil profile that is produced was the same as if the plough was set to a narrow furrow setting.

The profile graphs also show that speed had very little effect on the furrow bottom width but tends to throw the soil further at the top of the profile where there is less obstruction from the furrow. There is also slightly less lateral throw at the greater depths, mainly due to the volume of soil that is being moved. When working at shallow depths the soil section being moved has less mass, and does not have to be lifted so high over the previous furrow ridge to achieve great distance in the lateral direction.

As observations in previous experiments have also suggested, when the plough is set-up at an increased furrow width setting an increase in furrow profile width was expected but never achieved. The implications of this on the scale of a plough operating in the field could be quite significant because the average size of tractors is increasing and the size of tyres fitted to these tractors is also increasing to suffice more general agricultural operations. When this tractor with its wide tyres is used for the ploughing operation its tyres are too wide to fit into the furrow bottom produced by the plough. This affects the principle around which the in-furrow plough is based, as it effectively increases the width of the furrow to be filled by re-compacting the previous furrow profile.

For this reason a method of increasing the width of the furrow bottom needs to be investigated to alleviate the problem, especially on ploughs suited to higher horsepower tractors and where the furrow width is expected to be wider as the furrow setting suggests or needs to be wider to suit tyre options.

CHAPTER 5 MOULDBOARD WIDTH STUDIES

5.1 Soil Bin Studies

5.1.1 Aim

The aim of the increased width mouldboard studies was to increase the furrow bottom width produced by the Kverneland No8 mouldboard for no significant increase in the horizontal (draught) force.

5.1.2 Introduction

In recent years the average size of tractor used on many arable farms has increased. With this increase and the need to reduce soil compaction, a trend towards wider low profile tyres has become prevalent. Due to financial, practical and time constraints modern tractors are usually fitted with one size of wheel/tyre combination from new which is very rarely changed. This has led to tillage operations such as mouldboard ploughing to be carried out with wider tyres.

This has one major implication on the principle of conventional in-furrow ploughing which is that the open furrow space that is being filled by the next furrow is always the same size. The use of tyres having greater width than that available on undisturbed soil in the furrow bottom therefore re-compacts the previously turned furrow producing an open furrow width to suit their size, which is often wider than that of the rest of the furrows.

When considering furrow width, the width at which the plough is set to cut is usually considered, which makes up the total working width of the plough. This is often not the most important furrow width to be able to produce good quality ploughing with

each bout matched. The more important width is the width of the furrow bottom, which is the space between the furrow wall and the open furrow profile left by the last furrow. This width should provide the space to accommodate the tractor tyre on the next pass of the plough. Figure 5.1 shows that the tractor tyre is wider than the space in the bottom of the furrow left by the plough and therefore the last furrow is re-compacted. This is the front wheel of the tractor and is generally of narrower section than the rear tyre that follows.



Figure 5.1, View of Front Wheel in Furrow

Figure 5.2 shows the effect of the previous furrow after the rear tyre has also been driven along. It can be seen approximately half of the tyre width is in the previous furrow that has been re-compacted.



Figure 5.2, View of Furrow after Rear Wheel Passed

Some break down of the furrow wall occurs, but as the tyres are general lined up on the inside walls the extra width of the rear tyres affects the previous furrow profile.

This problem has two implications on the quality of ploughing that can be achieved with such a tractor/plough combination. Firstly, the furrow that has to be filled on the next bout is much larger; therefore, unless some adjustment is made to the front furrow width, the amount of soil and the distance it has to move across will not match that of the previous bouts. This results in a depression in the surface where the shortage of soil has occurred to fill the open furrow.

Secondly, if adjustments are made to ensure the furrow is filled to the same level as all other furrows, the problem occurs after time. As the soil begins to settle after being ploughed, the soil that has been compacted by the tractor wheel will settle to a much lesser extent to that over which the tractor wheel has not driven; this also results in an uneven surface finish. Obviously, the frequency of these compacted furrows depends upon the number of furrows per bout.

From previous soil bin studies and some initial field tests it was found that the actual width of the furrow bottom left by the Kverneland No8 mouldboard was the same

irrespective of the plough furrow width setting. Therefore, this would lead to the problems described and shown in Figure 5.1 and Figure 5.2.

During soil bin experiments when the plough was set to plough at 355mm (14") the furrow bottom width was approximately 250 mm and at the surface it was approximately 450 mm. As the furrow setting was increased to 508mm (20") this width was expected to increase, but it did not and was found to be approximately the same for the three furrow width setting tested.

Previous attempts at solving this problem have included such features as the furrow opener, which is an attachment that fits to the last furrow of the plough. This cuts a section away from the furrow wall that allows the tractor tyre to move towards the landside and therefore not drive on so much of the ploughed furrow, Figure 5.3.

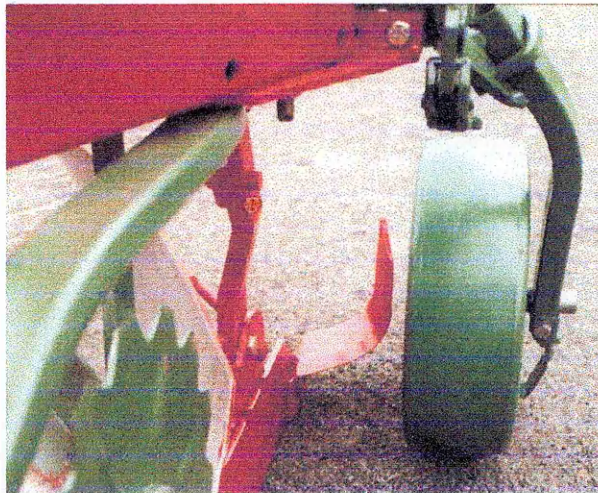


Figure 5.3, The Furrow Opener

This is not a totally satisfactory solution to the problem because of the high wear rates associated with this cutting blade, which needs replacing regularly if it is to work satisfactorily. The tractor also tends to wander more in the furrow because there is no furrow wall to hold the wheel in a straight line, which is one of the benefits of in-furrow ploughing.

An alternative solution adopted by many plough manufacturers and users, is to plough on-land; in this situation the tractor wheels do not enter the open furrow and therefore the problem is not encountered.

There are also many disadvantages associated with on-land ploughing which are considered far greater than the advantages and hence the need to increase the furrow bottom width still exists.

5.1.3 Procedure

If the furrow bottom width could be increased when the plough was set to an increased furrow width, the problem of re-compacting the previous furrow could be reduced or alleviated totally.

One of the side effects of having an increased furrow width is that the draught force is expected to increase because of the extra soil being moved. This is only true to a certain extent, because if the plough is fitted with a wide share when set to a wide furrow width the full width of soil is being cut. This means that the plough has incurred the draught force to cut the given width of soil, so to move the loose soil to an increased width equal to the furrow width setting should not result in a significant increase in force.

Previous attempts have been made to increase the furrow bottom width but these have always incurred an increase in the draught force. The most common method of increasing the furrow bottom width is to increase the angle at which the mouldboard approaches the direction of travel. This results in an increase of draught force that is not acceptable in many cases, especially on heavy land. The No8 mouldboard is a preferred body due to its lower approach angle and relative low draught force requirement.

The object of the work was to increase the width without increasing the draught force; so maintaining a low approach angle was essential. The current approach angle need not be changed because a slight modification could be done to increase the mouldboard

width. Understanding the principle of the mouldboard shape enabled a modification to be discovered that may suit the criteria. Knowing that the point on a mouldboard that determines the width of open furrow is the point at which the top and bottom edges meet on a vertical line, enabled this point to be made wider for no change in angle. If the length of the mouldboard body was increased at the same angle, due to its geometry the width would be increased automatically.

This can be seen in Figure 5.4; the addition of 152mm (6") into the throat of the mouldboard (between shin and body) moves the effective turning point of the mouldboard backwards by 120mm (4.7") but also sideways by 94mm (4") with no change in mouldboard angle.

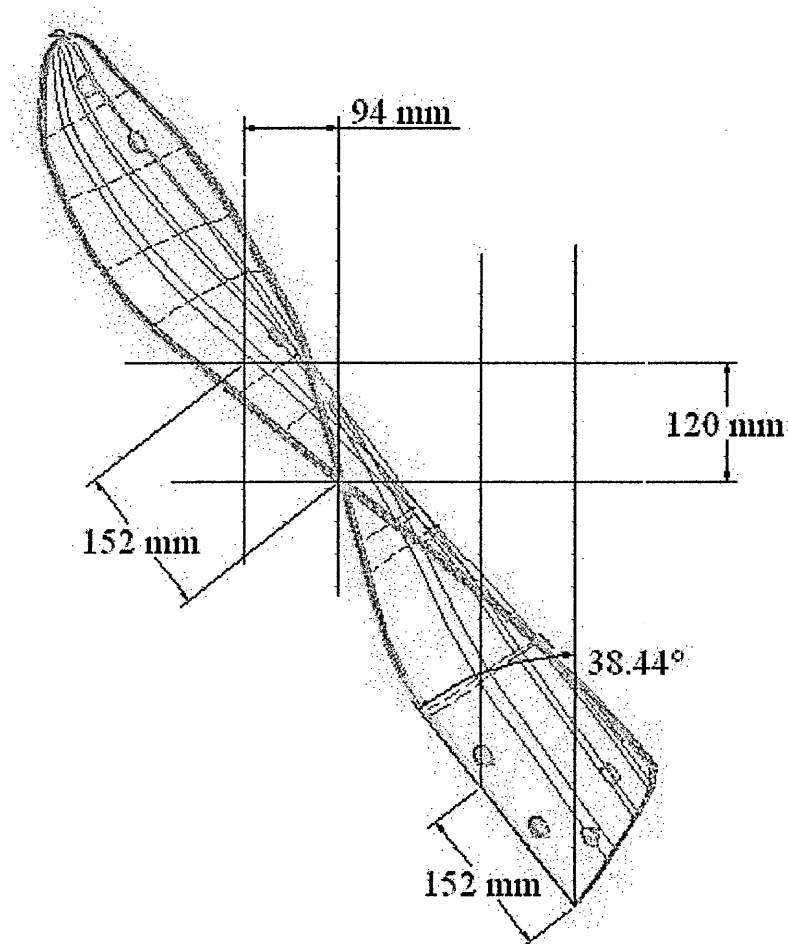


Figure 5.4, Projected Edges of a Mouldboard

This can be seen more easily on an actual mouldboard but Figure 5.4 shows the concept of adding an additional 152mm (6") into the throat of the mouldboard using an engineering drawing of the Kverneland No8 body.

Figure 5.5 shows the actual proposed placement of the extension in the mouldboard, the white section of the diagram is the area of material that is needed. This section would ensure that the angle and curvature of the mouldboard was not changed; the small curved section at the top would increase the height and stop soil flowing over the top.

The next step in the investigation was to produce this mouldboard extension along with some additional mountings at the rear to support the extended body.

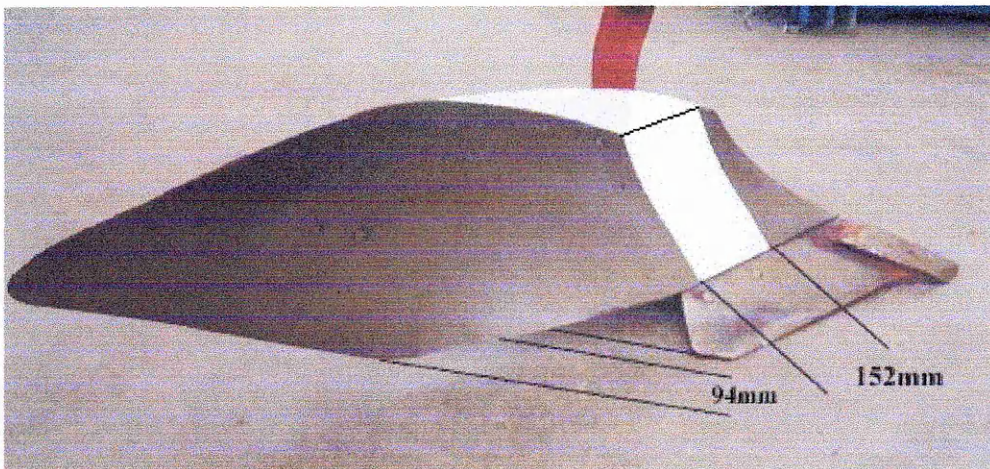


Figure 5.5, Conceptual View of Extended Mouldboard Section



Figure 5.6, Actual Mouldboard Extension Fitted to the Mouldboard

Figure 5.6, shows the fabricated extension when fitted into the throat of the Kverneland No8 mouldboard body. The increase in width of the mouldboard took the effective turning point of the mouldboard to the end of the widest share available, this being for a 508mm (20") furrow.

An experiment was set up to compare the extended mouldboard body and the regular Kverneland No8 body. This was to investigate both actual furrow width increase from the extension and any change in forces required to pull the mouldboard. One standard mouldboard was used, fitted with a 450mm (18") share and set to a furrow width of 508mm (20") and the extended mouldboard fitted with the same width share and set to the same furrow width.

The experiment variables can be seen in Table 5-1. Each test was replicated three times and the experiment carried out in a totally randomised order.

	Depth (mm)	Speed (km/h)	Mouldboard
Test 1	175	4.5	Extended
Test 2	175	7.5	Extended
Test 3	175	10	Extended
Test 4	175	4.5	Normal
Test 5	175	7.5	Normal
Test 6	175	10	Normal

Table 5-1, Extended Mouldboard Experimental Variables

The draught force, vertical force and moment reaction were measured using a 2-dimensional extended octagonal transducer, linked to signal processing and a data logger recording the measured values at 103Hz to avoid aliasing errors. As the experiments were predominantly developed to determine if furrow width could be increased without an increase in the draught force, the soil profiles of each test were also measured using the pin type soil profile meter (Figure 2.6). Other recorded variables included soil moisture content and bulk density on a dry basis.

5.1.4 Results

To monitor the soil bin conditions during the experiment, to determine a level of repeatability the soil moisture content and bulk density were recorded for each test. The maximums, minimums and means for these can be seen in Table 5-2. The full table of moisture contents and bulk densities can be seen in Appendix 3.1.

	Moisture Content (%)	Bulk Density (Mg/m ³)
Minimum	8.27	1.35
Maximum	9.55	1.58
Mean	9.02	1.47

Table 5-2, Moisture Content and Bulk Density

	Sums	Variation	Variance	Standard Deviation
Moisture Content	162.41	1.96	0.12	0.34
Bulk Density	26.41	0.01	0.00	0.02

Table 5-3, Soil Properties Analysis

The results from the experiment were tabulated and can be seen in Appendix 3.2 this shows a complete set of data from the experiment sorted into speed and mouldboard variation.

As the experiment was designed to determine if an increased furrow bottom width could be achieved for no extra horizontal (draught) force, the experiment needs to be tested statistically. In order to do this a null hypothesis was set, this being the horizontal force of the extended mouldboard will be equal to that of the normal mouldboard, for any given speed.

Therefore, μ Extended mouldboard = μ Normal mouldboard

This gives the alternative hypothesis that any pair of the horizontal forces will be different.

The results of horizontal (draught) force can be displayed in a tabular form as a percentage increase in draught force, (Table 5-4).

<u>Draught Force (kN) of each Mouldboard at 3 Speeds</u>			
<i>Speed</i>	<i>Normal</i>	<i>Extended</i>	<i>Increase</i>
	kN	kN	%
4.5 km/h	3.37	3.49	3.6
7.5 km/h	3.43	3.85	12.3
10 km/h	3.56	3.99	12.2

Table 5-4, Draught Force Increase, Normal to Extended Mouldboards

These draught force increases can be compared to the area of soil moved for each of the tests. The graphs show that the soil from the extended mouldboard is moved further than with the standard mouldboard. This can also be displayed in a tabular form and a percentage increase applied to each one.

<u>Cross Sectional Area of Soil Moved (m²) for each Mouldboard at 3 Speeds</u>			
	<i>Normal</i>	<i>Extended</i>	<i>Increase</i>
	m2	m2	%
4.5 km/h	0.055	0.063	14.5
7.5 km/h	0.058	0.066	13.8
10 km/h	0.059	0.070	18.6

Table 5-5, Percentage Increase in Cross Sectional Area of Soil Moved

From Table 5-5 the percentage increase in area of soil moved can be seen to be greater than the percentage increase in the draught force for all three speeds. For the middle speed, the percentage increase in draught and percentage increase in soil moved are

most similar. As can be seen from the table at the slowest of the tested speeds, the draught force increase from the extended mouldboard is particularly small at 3.6%. When the speed of tests is increased to 7.5 km/h, the draught force increase rises to 12.3% and stays at that level of increase for 10 km/h, which is considered a small increase.

The graphs of the soil profiles Figure 5.8 also show that the soil is moved further at the top of the profile as the speed is increased, this corresponds with the results from previous soil bin experiments.

From the analysis of variance (ANOVA) statistical test of the results from the extended mouldboard experiments there was found to be no significant effects. This means that there is insufficient evidence to reject the null hypothesis. So it is possible to say that there is no difference in the horizontal force of the extended mouldboard compared with the normal mouldboard. Table 5-6 shows the mean values of horizontal force for the experiment, with the descriptive statistics shown in Table 5-7. Appendix 3.3 shows the full table of statistical data.

Grand Mean 3.614

		<i>Mouldboard</i>	<i>Extended</i>	<i>Normal</i>
			3.775	3.452
		<i>Speed</i>	4.50	7.50
			3.430	3.638
				3.772
<i>Mouldboard</i>	<i>Speed</i>	4.50	7.50	10.00
Ext		3.485	3.850	3.989
Nor		3.375	3.427	3.556

Table 5-6, Mean Values of Experimental Results.

The LSD for the experiment was found to be 0.68 kN for 12 degrees of freedom.

Variable	Mouldboard Option	Sample No.	Mean	Median	Standard Deviation	SE of the Mean
Force	Ext	9	3.775	3.812	0.345	0.115
Force	Nor	9	3.452	3.340	0.393	0.131

Table 5-7, Descriptive Statistics of Experimental Results

The results can be plotted graphically in Figure 5.7, which shows the variables horizontal force, vertical force and resulting moments.

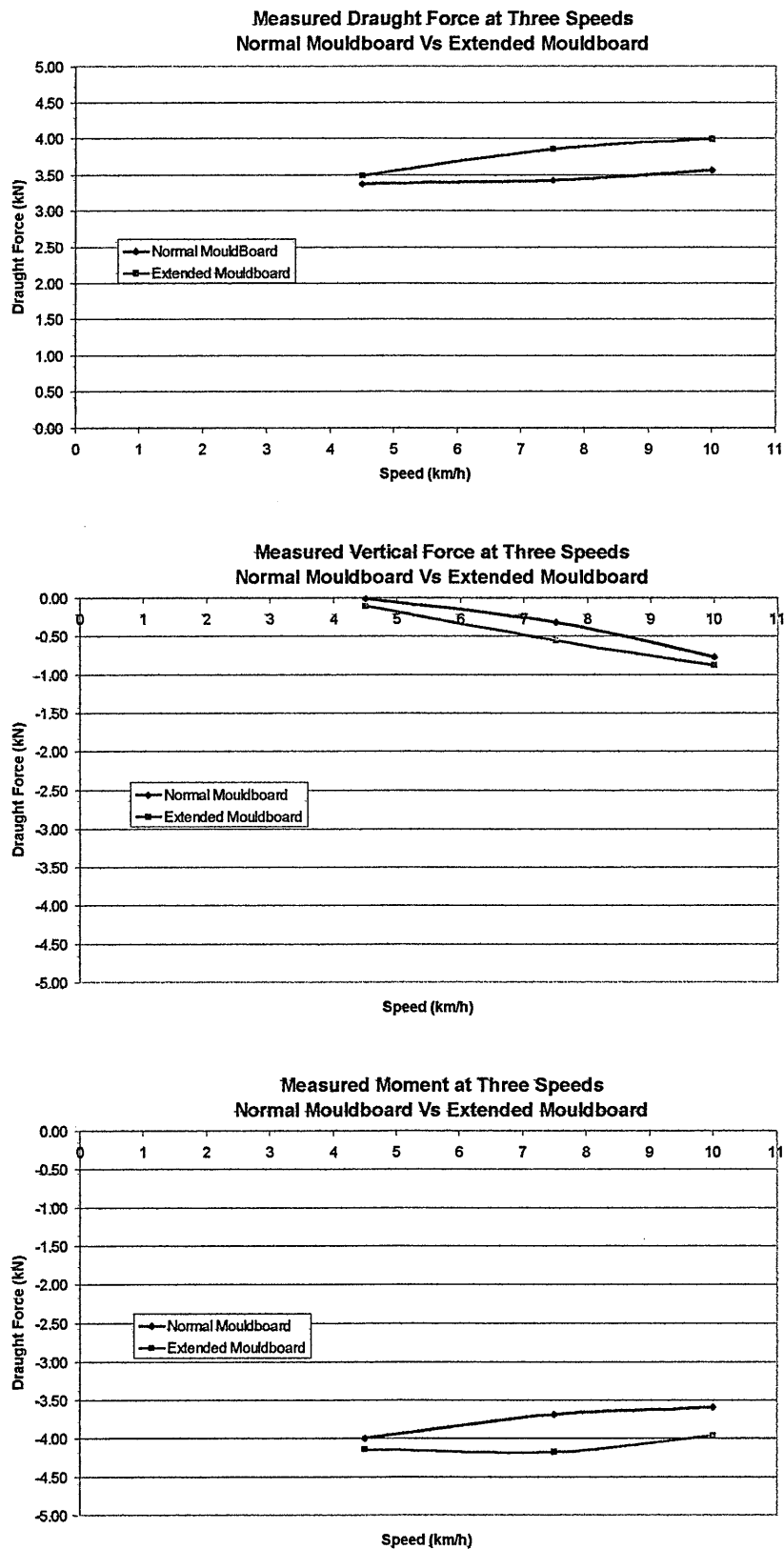


Figure 5.7, Horizontal and Vertical Forces and Moment Reactions for the Normal and Extended Mouldboard at, 4.5km/h 7.5km/h and 10km/h

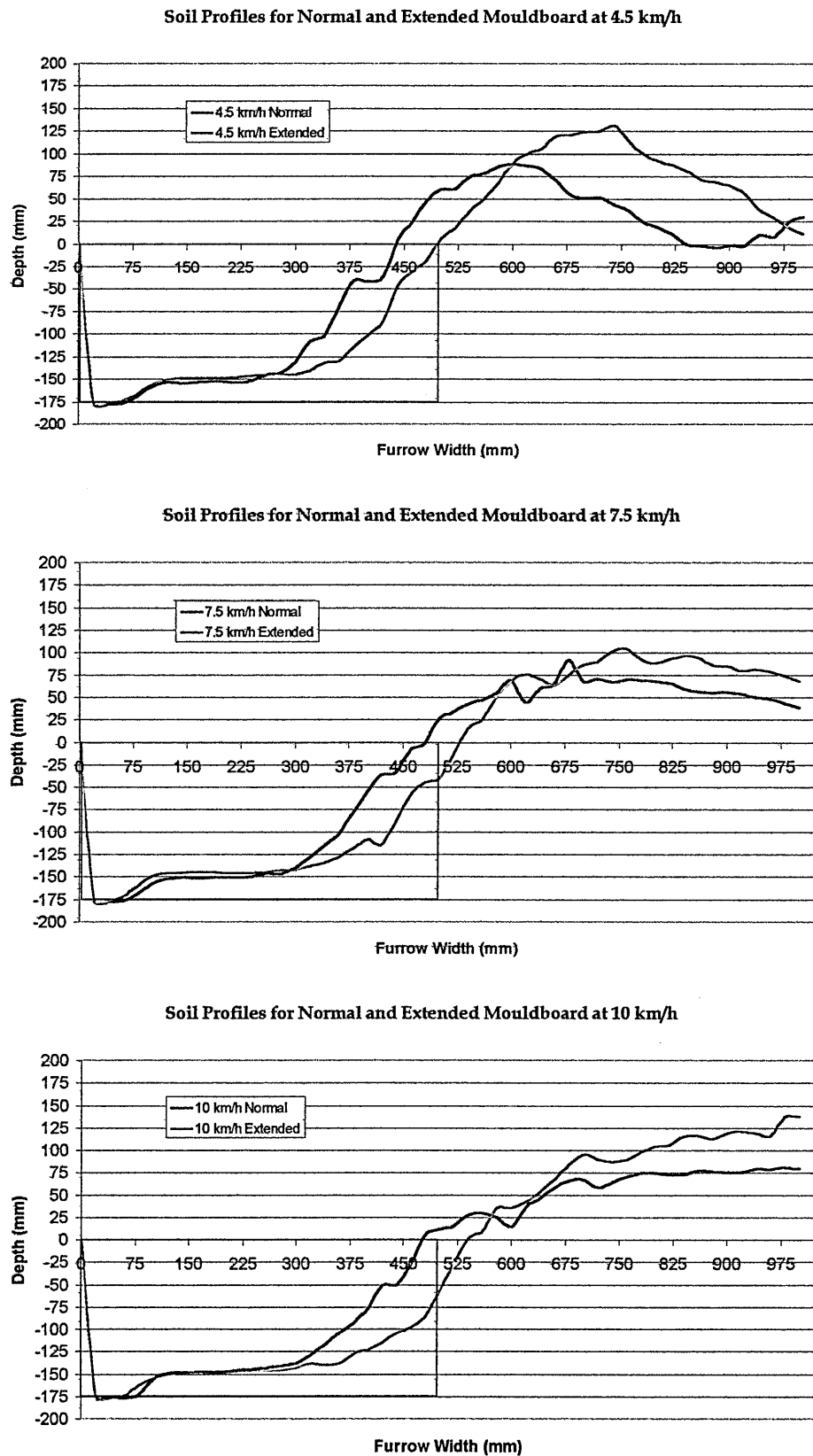


Figure 5.8, Measured Soil Profiles for Normal and Extended Mouldboards at, 4.5km/h, 7.5km/h and 10km/h

5.1.5 *Summary*

From soil bin studies using a modified Kverneland No 8 mouldboard it was possible to increase the furrow bottom width by between 60 – 90 mm for each speed tested. This gave a significant increase in the area of soil moved over that of the normal mouldboard. Although the horizontal force required for this mouldboard was increased it was shown to be a non-significant increase over that for the normal mouldboard.

This modification leads to the possibility of allowing larger tractor tyres to fit into the furrow bottom. In effect, an extended mouldboard body could be fitted to the last furrow of a plough to increase the furrow bottom width. The controversy occurs when it is considered to have produced a wider furrow bottom than a re-compacted furrow and subsequently the following furrow does not have enough soil to fill it. This leads to the argument that an extended furrow should be fitted to every body of a plough. To help determine the best use of the extended mouldboard further field testing was required

5.2 Field Studies

5.2.1 Introduction

It was shown from soil bin experiments that the extended mouldboard could be used to achieve an increased furrow bottom width under controlled conditions. This was shown both graphically and by the percentage area of soil moved by the mouldboard. This increase was achieved with the smallest increase in horizontal force, which was shown statistically to be non-significant.

In order to take the studies of the extended mouldboard further it was necessary to test its performance under field conditions. The experiments would need to determine the increase in furrow bottom width under an arable stubble condition and also whether it would incur a horizontal force penalty.

The extended body was fitted to one side (right hand) of the two-furrow plough supplied by Kverneland (UK). As only one body had been modified for the purpose of soil bin studies it was only possible to fit one extended body to the plough. It was decided that the body should be fitted to the rear so that the profile left could be measured for both increased area of soil moved and any increase in furrow bottom width (Figure 5.9). Having only one extended mouldboard body fitted to the plough would also enable the tests to determine if the work done by the extended body could be matched up to that of a normal body. The plough was fitted with the widest shares and set to a furrow width of 508 mm (20").



Figure 5.9, Front View of Extended Mouldboard in Position

During the field tests it was important to monitor several effects of the extended mouldboard; these being: -

- Furrow bottom width.
- Area of soil moved.
- How well the ploughing matches up with other furrow settings and particularly those of the conventional mouldboard.
- Effect of speed on the furrow profile and the surface condition.
- The overall draught force required to pull the extended mouldboard.

To enable all these variables to be measured many different techniques were adopted with different types of apparatus. The furrow bottom width was measured at the same time as the surface profile for the last ploughing bout. Due to the scale of the field experiment in relation to the soil bin experiments, as multiple furrows were being ploughed, it was considered insufficient to use the 1 metre steel profile meter as this only just covered one furrow and would not be able to give the resolution of profile over numerous furrows. For this reason an alternative method of measuring the soil profile was adopted. This involved placing two canes 2.5 metres apart and drawing a line tight between them to provide a horizontal line. The height to the soil surface was

then measured to the horizontal line from the furrow wall across three metres width of ploughed land. This can be seen in Figure 5.10 and the measurements were carried out twice for each furrow setting. This allowed measurement of the furrow bottom width, the area of soil moved, the effect of speed and the matching up of furrow-on-furrow for the different mouldboard and plough configurations. These profiles can be seen in the results section.

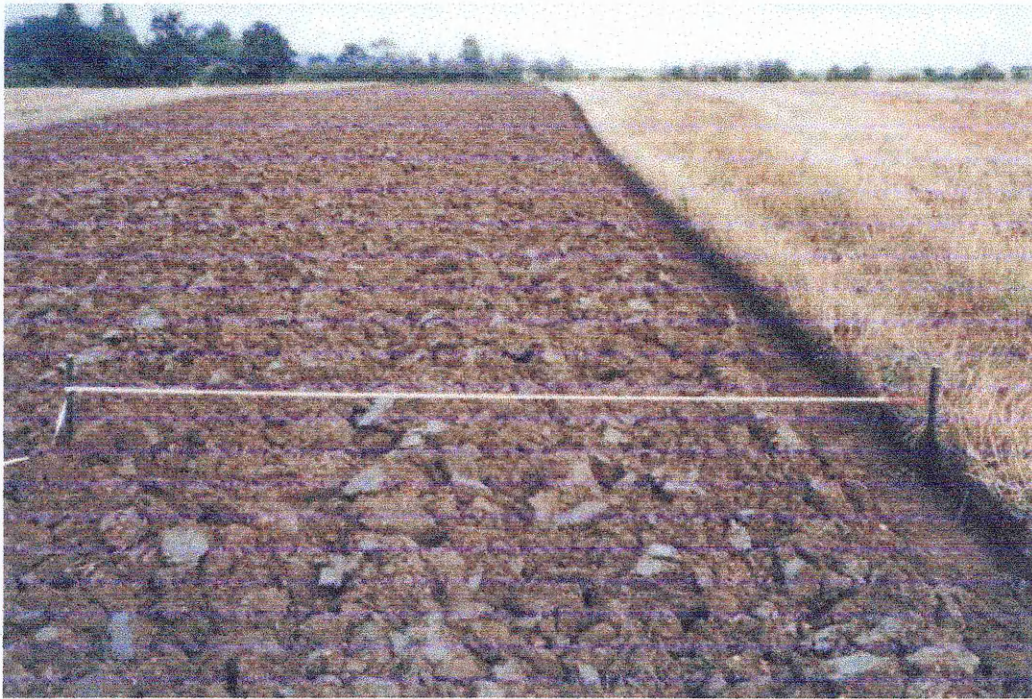


Figure 5.10, Field Scale Measurement of the Furrow Profile

In addition to these furrow measurement the horizontal forces were required to test the hypothesis that the extended mouldboard required no more force to pull than that of a conventional Kverneland No 8 mouldboard body. This was done with the use of a fully instrumented Massey Ferguson 6180, which had two small EORT's (extended octagonal Ring transducers) fitted to the lower link arms and a strain-gauged top link to give three force measurements that could be resolved to give the true horizontal force for each plough configuration. The EORT's and the gauged top link can be seen in Figure 5.11. Together with the measurement of the furrow profile and the surface condition the horizontal forces gave an additional comparison of the effect of speed.



Figure 5.11, Extended Octagonal Ring Transducer's Fitted to the MF 6180

5.2.2 Procedure

The field experiments were carried out in two sections; the first was to determine the effect of speed and mouldboard configuration on the surface finish and matching of work bouts. This was considered to have a major implication if the extended mouldboard is to be used individually on the last furrow of a plough to produce the desired wider furrow bottom, but less so if it was used for every furrow. The second section concentrated on the forces related to both mouldboard configurations and the furrow bottom profiles. From some previous fieldwork, it was seen that a depth of 225 mm (8.8") was acceptable for commercial ploughing and is close to the standard depth used in most cases. It was necessary to test the mouldboard at a shallower depth which needed to be a depth at which the standard mouldboard could be used for comparison with the extended one.

A depth of 150 mm (6") was found from previous work to be approximately the minimum depth at which the normal mouldboard could be worked. As this was the absolute minimum, it depended on the soil type and surface condition as to whether it was sustainable. Therefore a depth of, 150mm (6") was the aim but, as will be seen during the force measurement part of the experiment 175mm (6.8") was a more common depth. When considering the depths it was necessary to take into account the variation in depth that may occur from using the tractor plough set-up in nominal field conditions. This meant the depth may vary slightly from the desired value for each given test configuration due to field undulations.

The next variable was the speed of work. This is easier to vary and, providing the power available is adequate, it should be relatively constant. With the given tractor and the two-furrow plough, 10 km/h was the maximum speed that was achievable. As with previous soil bin tests, and the preliminary field tests earlier this year, the three speed of 4.5 km/h, 7.5 km/h and 10 km/h would be a satisfactory range of speeds. The intermediate speed was removed from the experiments that were designed to determine the difference in forces required by the two individual mouldboard combinations. The forces were measured in both parts, but the second experiment was carried out in more uniform field conditions and the mouldboard was interchanged, rather than the plough being turned over to change from one mouldboard to the other.

Exchanging the conventional mouldboard on the right hand side of the plough with the extended mouldboard for the appropriate test numbers throughout the experiment allowed the elimination of any errors that may be attributed to variation in the rotation of the reversible plough used. There are many adjustments on a reversible plough that may vary depending on which side the plough is facing work. Any one of these was considered a possible extra cause of variation that needed to be eliminated, hence the experiment had two sections.

When the plough was fitted to the tractor, the lower links were checked for horizontal position. To obtain the true horizontal force these are required to be horizontal whilst the tractor plough is in operation. For the depth variation of 100 mm at the plough tip

this was found to be between 2 and 3 degrees. Therefore, no horizontal correction was applied to the lower link forces because it was considered as close to horizontal as would be obtained in a field situation. In terms of the top link, this was between 18 and 24 degrees from the horizontal and would therefore have a more significant effect on the horizontal force measured through the top link, so required correcting to determine the true horizontal force. To aid this, a scaled diagram of the geometry was used to determine the angles at which the link arms and top link were operating; Figure 5.12 shows the geometry when ploughing at the shallow depth.

The force measurement part of the experiment was set up to test the conventional mouldboard as closely as possible against the extended one, reducing the possibility of field variation. A split plot experiment was used with three blocks. Due to the limited space available in the allocated field two replications of each setting were carried out in each block. Because more space was required to open up blocks one and two, block three was subsequently carried out in a different part of the field, and subsequently had to be treated separately for analysis purposes.

Figure 5.13 shows the experiment variables that had to be tested and Figure 5.14 shows the experiment layout.

Shallow Ploughing

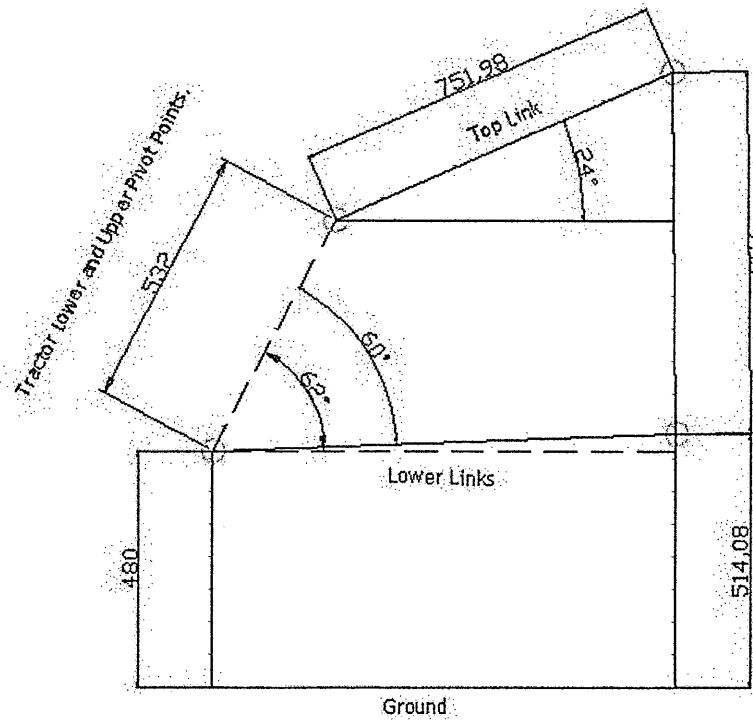


Figure 5.12, MF 6180 Linkage Geometry

1			
2			
17			1 - Ext Slow Shallow
15			
16			
24			2 - Ext Slow Deep
3			
4			
19			3 - Nor Slow Shallow
10			
11			
12			4 - Nor Slow Deep
5			
6			
21			5 - Nor Fast Shallow
11			
12			
20			6 - Nor Fast Deep
7			
8			
23			7 - Ext Fast Shallow
9			
10			
18			8 - Ext Fast Deep

Figure 5.13, Experiment Variables for Extended Mouldboard Field Tests

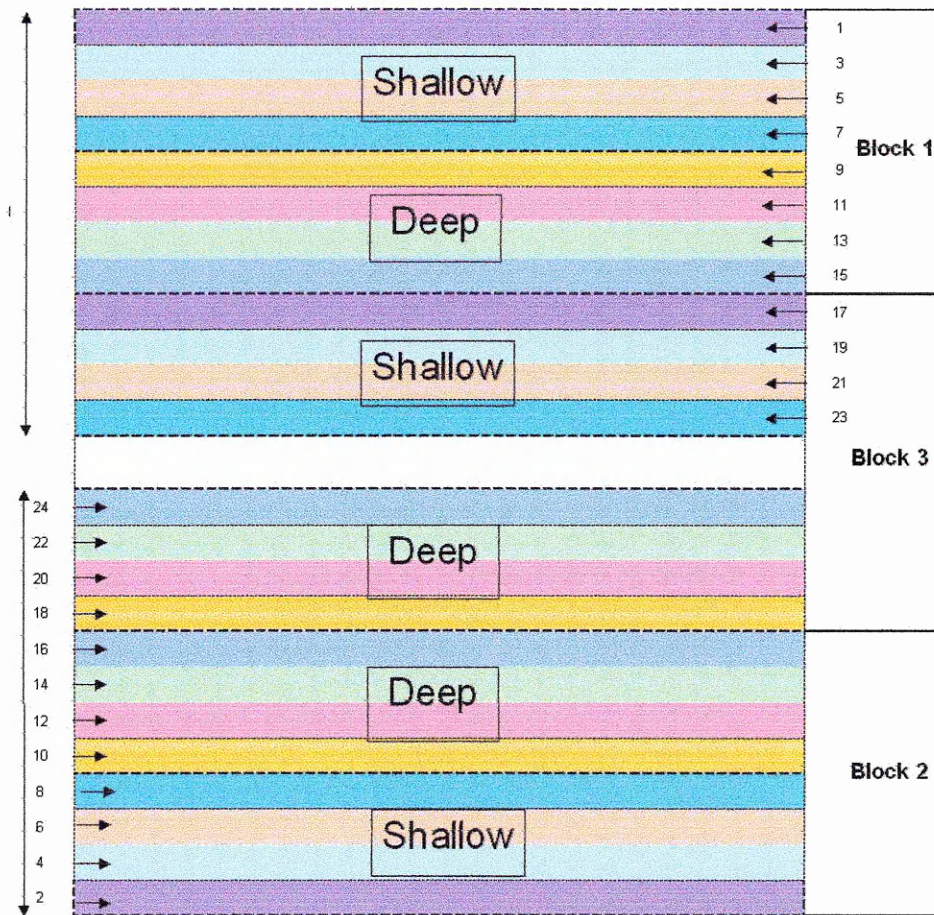


Figure 5.14, Statistical Experiment Layout, Split Plot Design

5.2.3 Results

Firstly, the effect of the three speeds is considered on the surface finish for the normal and extended mouldboards and their ability to match up the furrow with the previous. As the three speeds were carried out next to each other in the field, it was possible to produce comparative photographs to show the effect of speed (Figure 5.15).

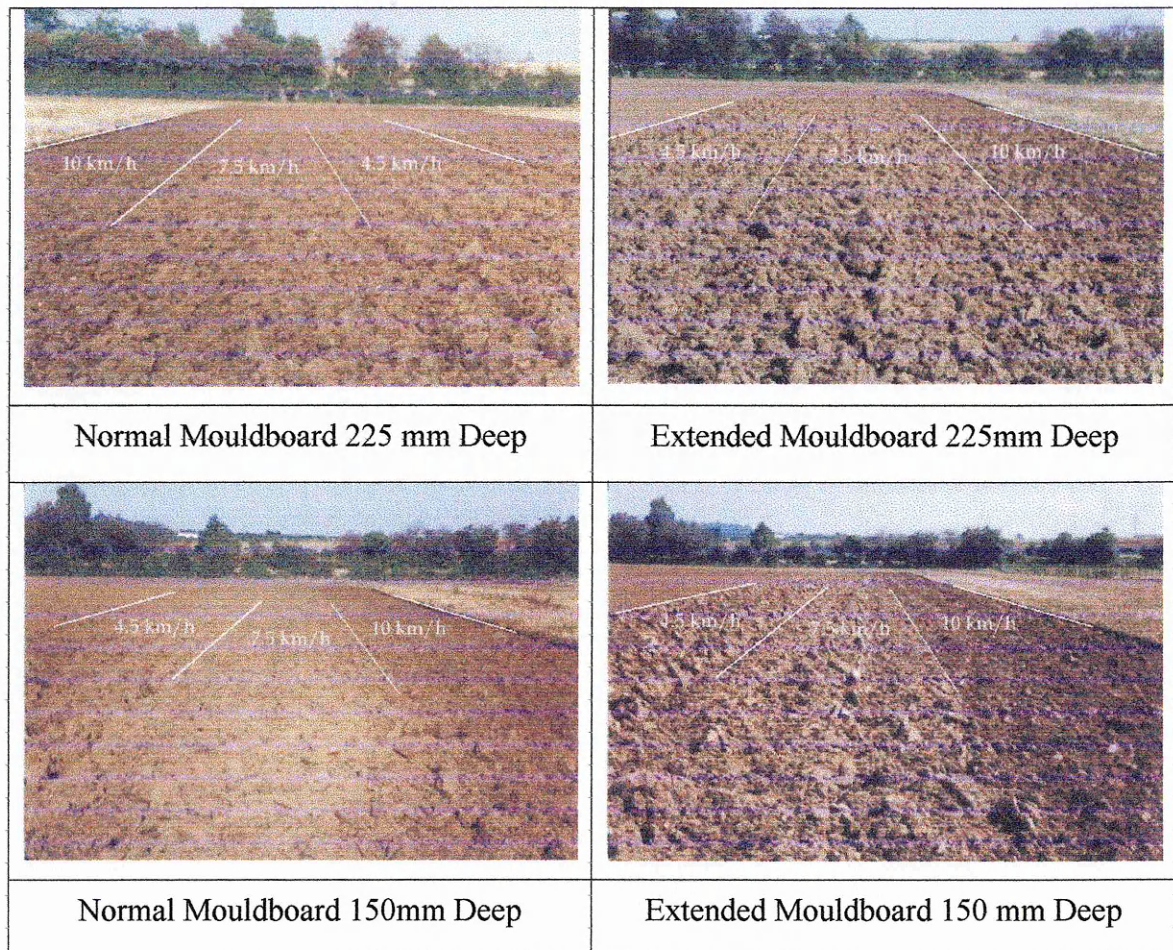


Figure 5.15, Effect of Speed on Surface Condition, Normal and Extended Mouldboard

Together with these pictures, the field scale profiles of each furrow setting and speed can be viewed for a three metre strip. Figure 5.16 shows the normal mouldboard soil profiles, for the three measured speeds. These can be seen to get flatter as the speed increases, the peaks of soil become less and the dips between get smaller. The whole soil profile has moved further away from the furrow wall. There is less variation on the profile as the speed is increased, mainly due to the size of soil particles. As speed is increased the soil becomes more fractured and broken into smaller clods, these are able to fit together more tightly and therefore do not protrude in large peaks.

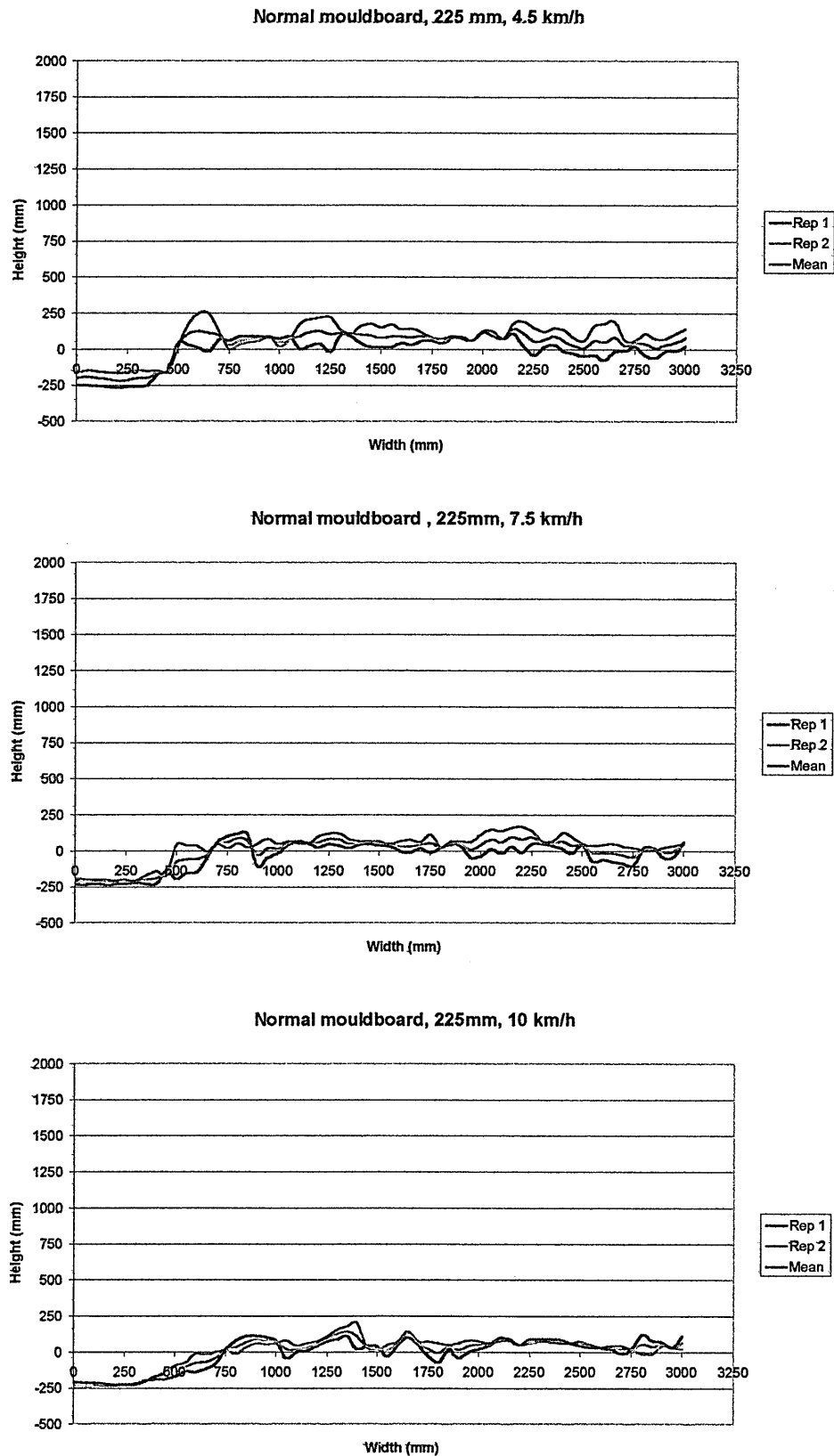


Figure 5.16, Soil Profiles for Three Speeds of the Normal Mouldboard at 225 mm Depth

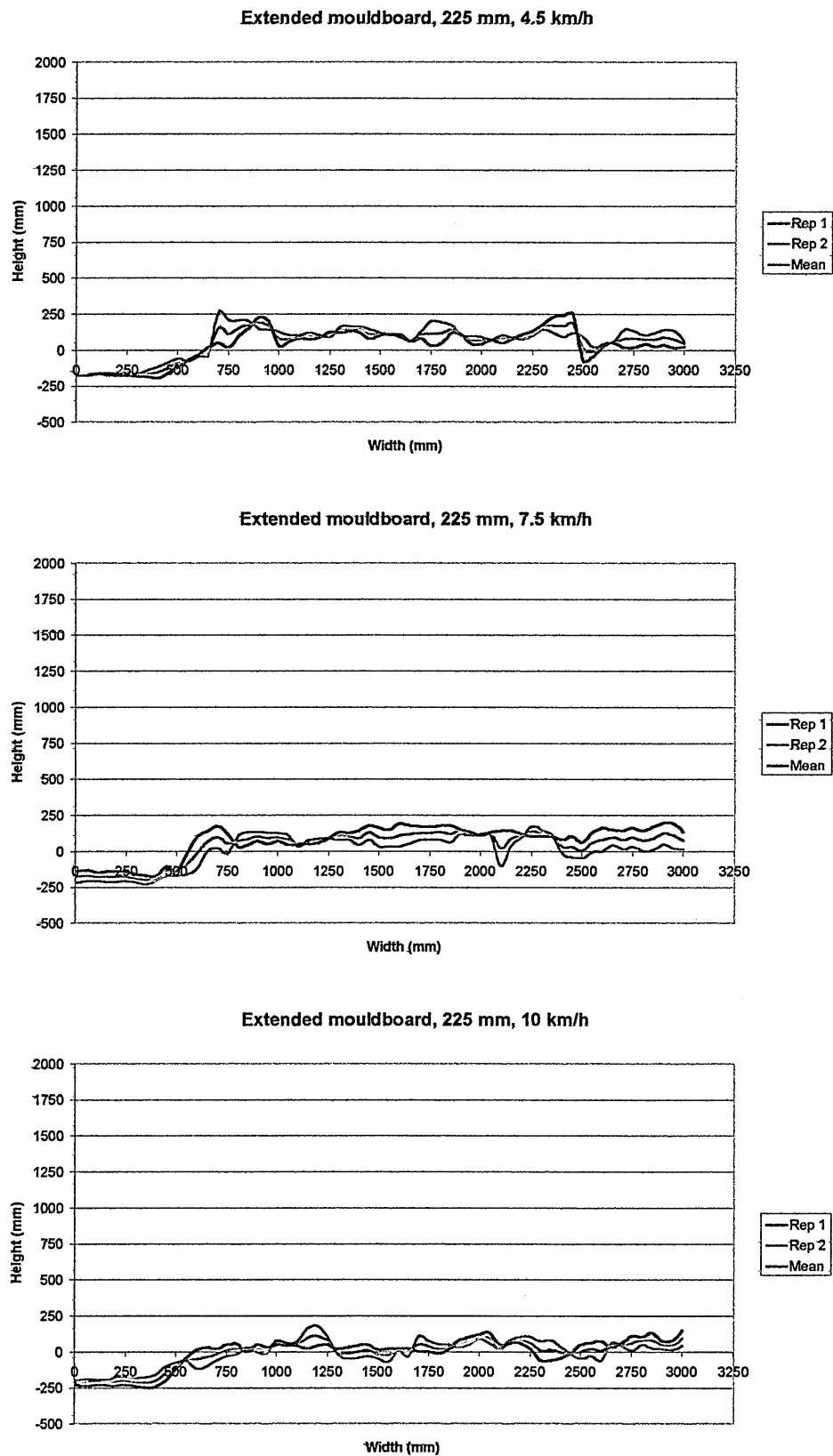


Figure 5.17, Soil Profiles for Three Speeds of the Extended Mouldboard at 225mm depth

Once again, the increase of speed reduces the deviation of the profile of the extended mouldboard shown in Figure 5.17. It can also be seen that the extended mouldboard has less effect at the increase speed as the soil tends to be thrown across which widens the furrow bottom.

The second part of the experiment dealt with the forces for the two mouldboards, Table 5-8 shows the compiled results of the horizontal forces recorded for each mouldboard.

		Conventional MB						Extended MB					
		Shallow			Deep			Shallow			Deep		
		Depth (mm)	175	Depth (mm)	225	Depth (mm)	175	Depth (mm)	225				
Speed													
km/h		Force	kN	Force	kN	Force	kN	Force	kN				
4.5	Block 1	Rep1	13.95	Rep1	17.94	Rep1	13.10	Rep1	17.20				
		Rep2	13.33	Rep2	17.56	Rep2	13.06	Rep2	18.43				
	Block 2	Rep1	14.45	Rep1	18.21	Rep1	13.27	Rep1	17.47				
		Rep2	13.52	Rep2	17.79	Rep2	13.85	Rep2	18.01				
	Block 3	Rep1	11.62	Rep1	13.16	Rep1	9.91	Rep1	12.61				
		Rep2	12.30	Rep2	13.32	Rep2	12.55	Rep2	12.09				
			Blk 1&2&3	13.2	Blk 1&2&3	16.3	Blk 1&2&3	12.6	Blk 1&2&3	16.0			
			Blk 1&2	13.8	Blk 1&2	17.9	Blk 1&2	13.3	Blk 1&2	17.8			
10	Block 1	Rep1	16.99	Rep1	22.89	Rep1	17.79	Rep1	22.45				
		Rep2	17.88	Rep2	21.56	Rep2	17.87	Rep2	23.90				
	Block 2	Rep1	17.78	Rep1	23.23	Rep1	18.17	Rep1	22.90				
		Rep2	19.59	Rep2	23.42	Rep2	18.36	Rep2	22.68				
	Block 3	Rep1	18.53	Rep1	16.73	Rep1	12.98	Rep1	15.76				
		Rep2	19.19	Rep2	17.41	Rep2	14.27	Rep2	15.85				
			Blk 1&2&3	18.3	Blk 1&2&3	20.9	Blk 1&2&3	16.6	Blk 1&2&3	20.6			
			Blk 1&2	18.1	Blk 1&2	22.8	Blk 1&2	18.0	Blk 1&2	23.0			

Table 5-8, Compiled Results from Extended Mouldboard Field Tests

It is possible to plot the data in graphical format to show the difference between the conventional mouldboard and the extended mouldboard over the speeds used in the experiment. As can be seen from the graphs Figure 5.18, Figure 5.19 there is very little difference between the draught forces required to pull two conventional bodies or one conventional and one extended body. The small variation could be due to slight undulations in the field with an associated increase or decrease in depth as a result. The maximum variation in these mean forces from the two blocks is 0.5 kN, which is in favour of the extended body and occurs at the slow shallow setting.

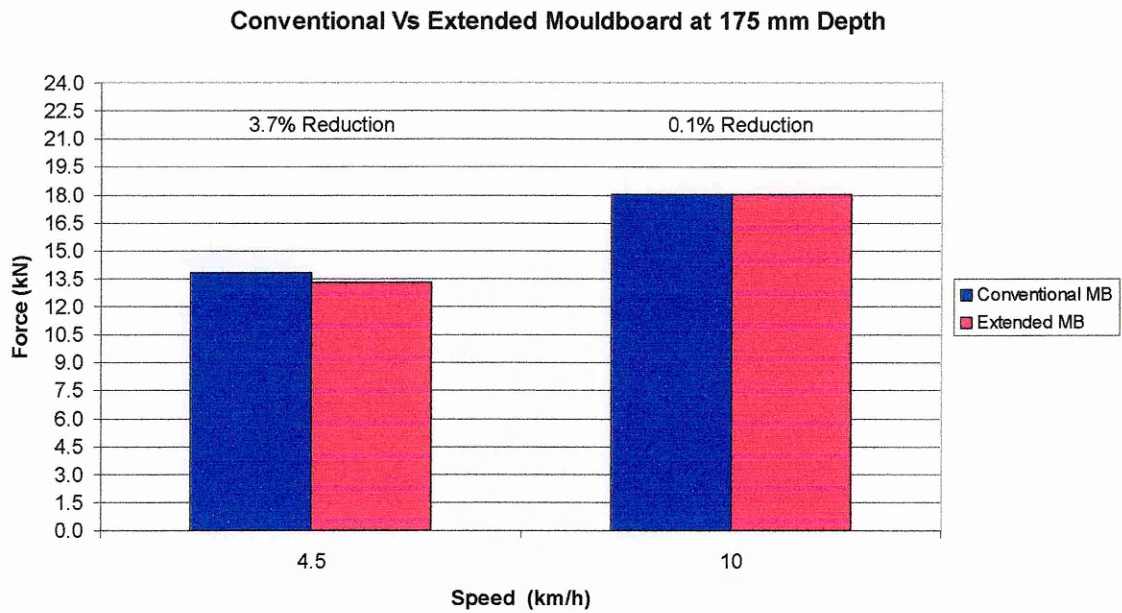


Figure 5.18, The Effect of Speed on Mouldboard Force at 175mm Depth

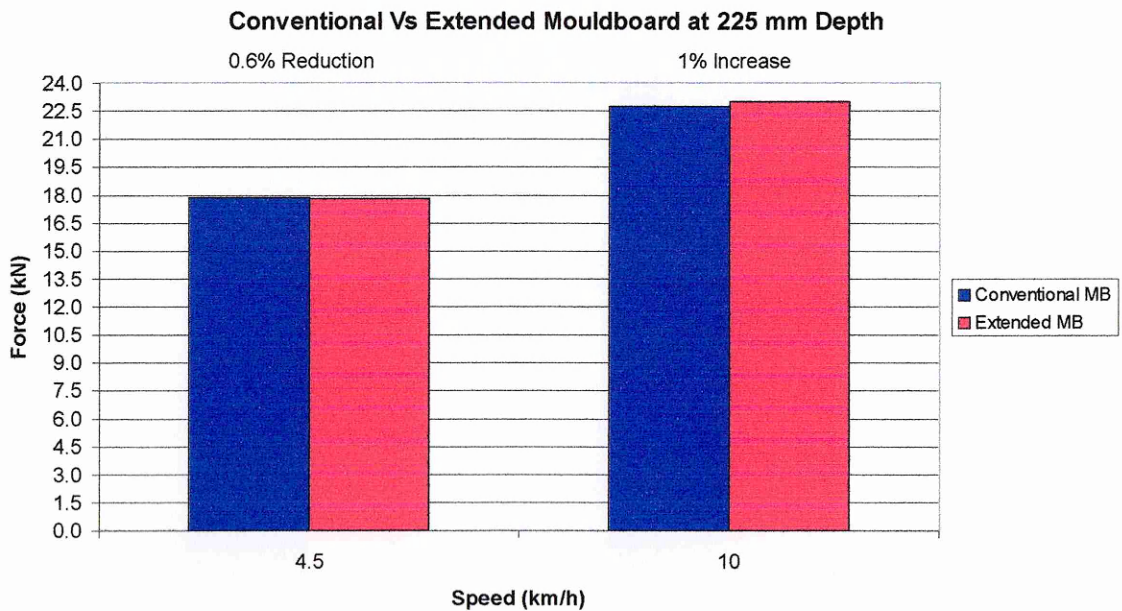


Figure 5.19, The Effect of Speed on Mouldboard Force at 225mm Depth

To validate that there is no difference in the force required from the extended body a statistical analysis was carried out for the complete experiment as a split plot ANOVA.

The analysis of the statistical data shows speed to be significant at <0.001 , using a significance level of <0.05 , therefore has an effect on the draught force, which is what is expected. The depth is shown not to be significant at 0.127 although this was expected to have an effect on the draught force, which has been shown in previous work. The reason for this is probably because the two chosen depths tend to come together nearer 200 mm than was originally planned, which can be seen from the soil profiles.

The analysis also shows the mouldboard to be just significant at 0.016 (the significance level being <0.05) over the complete set of experiments, but shows no interaction between the variables. This means that over the complete range of slowest, shallow to fastest, deep the mouldboard has an effect but at a given depth over a range of speeds there is no effect from mouldboard change, similarly for a given speed over a range of depths there is no effect from the changing the mouldboard from conventional to extended

A table of the statistical analysis in Appendix 3.4 shows the coefficient of variation for each section of the experiment, which is a measure of how well the experiment tested the selected variables. As can be seen the coefficient of variation (CV) for the BLOCKS is 13.2 %. This is relatively high and therefore the blocks have most variation in the data, which can be expected from field experiments. The CV being a test of how much the sample data deviates from the mean, the lower the value of CV the better the sample data.

This is clearly shown in the table, as the data for block three showed the greatest difference to any other; the reason for this was that it was carried out in a different part of the field. The next level of the experiment is the WPLOTS, which are the depth changes within the blocks. These have a CV of 9.4% which means the sample data is better, but the most closely tested are the SPLOTS which are the split plots of different mouldboard and speed, these have a CV of 2.6%.

With the results from the force measurement and the area of soil moved it is possible to compare the normal mouldboard with the extended mouldboard in terms of the specific resistance. To do this the area of soil moved by each mouldboard when the force measurements were taken was measured. This allowed direct comparison of the force taken to pull the mouldboard with the area of soil moved.

The area of soil moved was calculated for mouldboard type, depth and speed combinations and compared to the force required for each setting. The results can be seen in Table 5-9.

Shortened descriptive terms are used in the table to identify the different plough configurations; these can be outlined in Figure 5.20.

Abbreviation		Description
Norm	=	Normal Mouldboard
Extd	=	Extended Mouldboard
Slow	=	4.5 km/h
Fast	=	10 km/h
Shallow	=	175 mm
Deep	=	225 mm

Figure 5.20, Descriptive terms for Mouldboard Variables

Mouldboard Configuration	Theoretical Area Moved <i>m2</i>	Measured Area Moved <i>m2</i>	Measured Horizontal Force <i>kN</i>	Measured Specific Resistance <i>kN/m2</i>	Reduction Specific Resistance %
Norm Slow/Deep	0.1143	0.0898	16.33	181.83	
Extd Slow/Deep	0.1143	0.1193	15.97	133.89	26%
Area Increase		33%			
Norm Slow/Shallow	0.0889	0.0833	13.19	158.48	
Extd Slow/Shallow	0.0889	0.1168	12.62	108.13	32%
Area Increase		40%			
Norm Fast/Deep	0.1143	0.0885	20.88	235.88	
Extd Fast/Deep	0.1143	0.1133	20.59	181.82	23%
Area Increase		28%			
Norm Fast/Shallow	0.0889	0.0826	18.33	222.00	
Extd Fast/Shallow	0.0889	0.1046	16.57	158.53	29%
Area Increase		27%			

Table 5-9, Measured Area and Specific Resistance Table

It can be seen that the measured area moved by the normal mouldboard is lower than the theoretical area that should be moved by the mouldboard at these settings. The measured area of the extended mouldboard matched the theoretical area more closely than the normal mouldboard.

It can be seen that the extended mouldboard creates between 27 and 40 % increase in area of soil moved, which leads to a reduction in the specific resistance of between 26 and 32 %. This is an additional benefit occurring from the fitting of the extended mouldboard.

A closer look at the furrow profiles just around the area of the furrow bottom highlights the increased furrow bottom width. This follows the same trend as the area

of soil moved, with the shallow/slow setting having the most increase in furrow bottom width. This can be seen from Figure 5.21 to be approximately 150mm. This reduces for the deep/slow setting to just over 100mm as shown in Figure 5.22.

Furrow Profile Comparison for 4.5 km/h at 175 mm

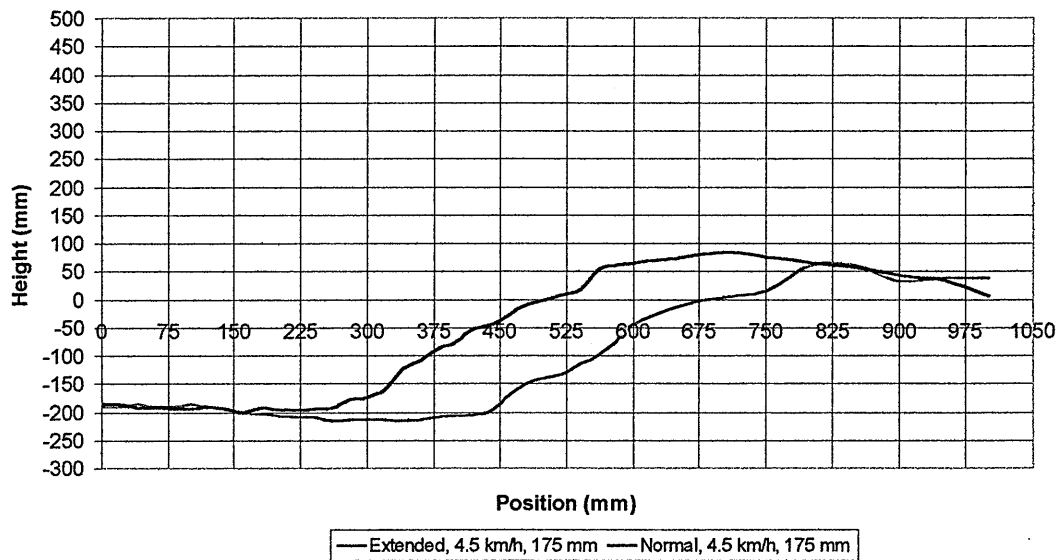


Figure 5.21, Furrow Bottom Width Profiles, 4.5 km/h at 175 mm

Furrow Profile Comparison for 4.5km/h at 225mm

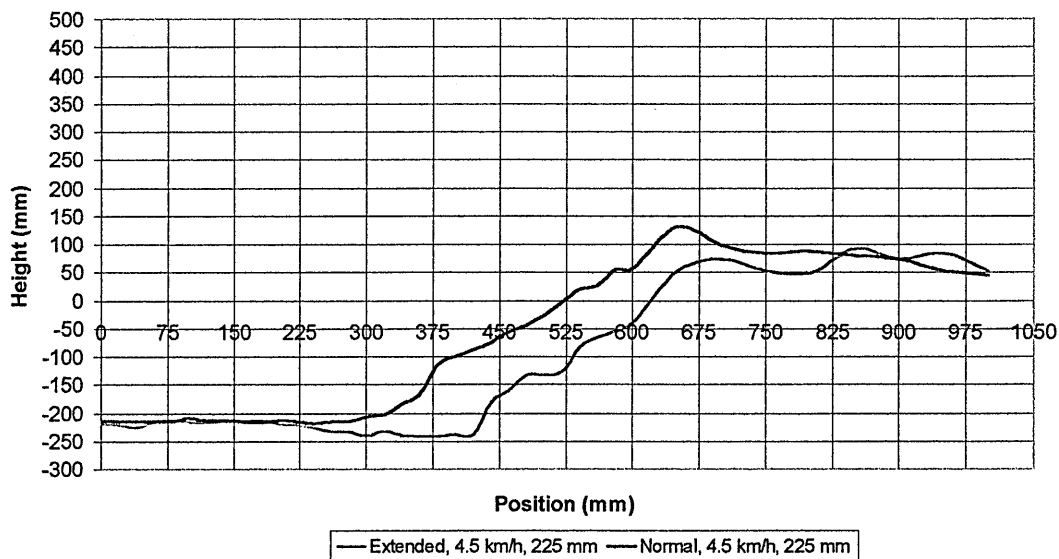


Figure 5.22, Furrow Bottom Width Profiles, 4.5 km/h at 225 mm

The increase in furrow width is less evident at the increased plough speed of 10 km/h ranging between 100mm and 140mm for the shallow and deep mouldboard comparisons, respectively. The profiles can be seen in Figure 5.23 and Figure 5.24. The reason for this is that the soil is thrown further at the increased speed with the normal body.

Furrow Profile Comparison for 10 km/h at 175mm

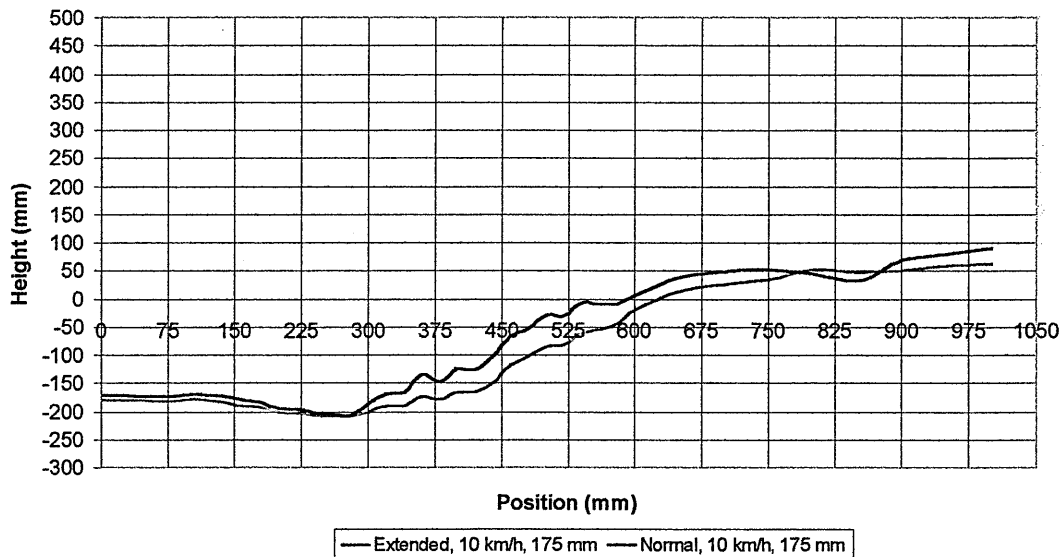


Figure 5.23, Furrow Bottom Width Profiles, 10 km/h at 175 mm

Furrow Profile Comparison for 10 km/h at 225 mm

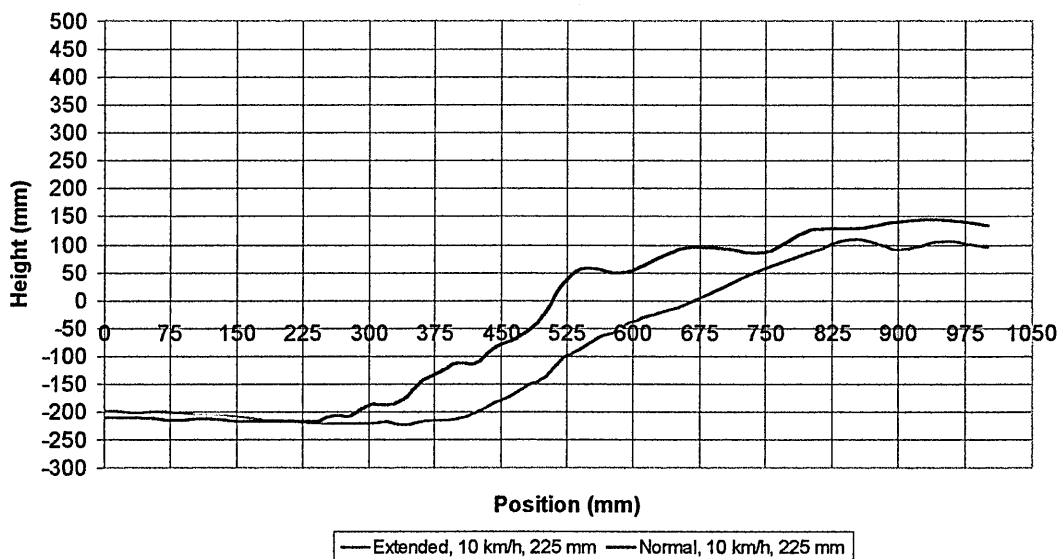


Figure 5.24, Furrow Bottom Width Profiles, 10 km/h at 225 mm

5.2.4 *Summary*

The results from the soil bin tests show that the extended mouldboard could lead to the possibility of increasing the furrow bottom for very little draught force increase, allowing the furrow bottom to accept wider tyres and not re-compact the previously ploughed furrow. This approach was then taken to a field situation and similar results found.

Increasing the furrow bottom width with minimal or no increase in the horizontal force could have many implications on the use of standard mouldboard ploughs that are operated with the tractor working in the furrow bottom. It would enable larger tractors with wider and possibly low ground pressure tyres, to be used for the ploughing operation with no adverse effects on the previous furrow. These tyres have the potential to alleviate in-furrow compaction commonly associated with this tillage operation.

Previous research carried out at the National Tillage Machinery Laboratory (NTML) found that the forces contributing to the total horizontal force on a mouldboard assembly are generated approximately from 80% for the cutting and failing of the soil and the remaining 20% from that generated by the mouldboard. Similar results to those were found whilst testing the mouldboard individually in the soil bin. This would explain the very small differences between the normal mouldboard body and the extended mouldboard in terms of horizontal force, because the plough was set to the same cutting width the same length soil failure planes are created. The open furrow is empty and able to take the furrow slice so that the force to invert and move the soil across into it is minimal.

The extended furrow was only fitted to the last furrow of the plough, which gave the desired effect in terms of increasing the furrow bottom width for the accommodation of the tractor tyre since it is only the last furrow of each plough bout that has to be driven in. This meant that any increase due to the extended mouldboard was only

affecting 50% of the force to pull the plough because it was a two-furrow plough. This would obviously become a smaller percentage as the number of furrows is increased.

Further study of the soil profiles and surface levels from the first part of the experiment showed that at slower speeds the soil from the extended mouldboard was left more proud because it had been pushed across into the previous furrow more than the leading furrow. The extended mouldboard therefore leaves a similar furrow profile and soil consolidation for the 508mm (20") furrow as the standard mouldboard at a furrow width of 355mm (14"). This can be seen from Figure 5.25, where a comparison of the furrow left by a normal mouldboard at two furrow widths can be made against that left by the extended mouldboard.

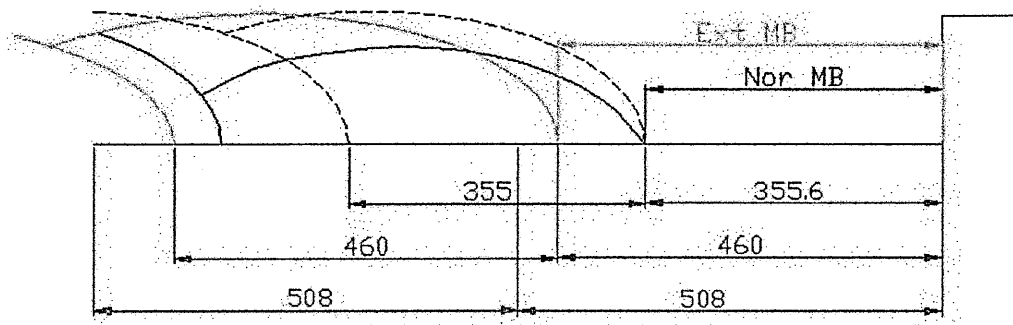


Figure 5.25, Diagram of Furrow Width Principal

The normal mouldboard does not push the furrow slice far enough over to the side when operating at 508mm (20") (see the blue profile in Figure 5.25) and, therefore, the furrow profile is lower than when ploughing at narrower widths. This highlights the limitation of a current plough set to 508mm (20"), the furrow profile is more laid over and less consolidated against the previous furrow, this makes the inverted slice more susceptible to sinkage after time.

Because the extended mouldboard pushes the soil across, leaving a wider furrow bottom, it also produces a more acceptable soil profile. These variations in soil profile left by the different mouldboards at different operating widths highlight the need for the same mouldboard to be fitted to each furrow of a plough to eliminate variation. The more consolidated a furrow is when inverted the less likely it is to sink after time. If all furrows are consolidated to the same amount the whole field profile will settle evenly.

As the extended furrow leaves an increased open furrow area, there is the concern that the front furrow of a standard mouldboard will not be able to fill the open furrow. This would lead to a shortage of soil in the front furrow and, therefore, prone to depression. Again the fitting of extended mouldboards to all furrows of a given plough, so that the soil from each body is moved to the side equally would overcome this problem.

One aspect of the extended mouldboard was that with the increase in width there was also an increase in the length of the mouldboard assembly, by slightly more than the increase in width. This was not a problem with a two-furrow plough with only the rear furrow changed. This could cause a problem on ploughs with many furrows especially if all furrows were fitted with an extended body because it takes the weight further away from the hitching point of the plough, and, with the increased section of metal, could possibly make large mounted plough more difficult to handle.

Some consideration was given, and an example considered. If the centre of gravity of a extended mouldboard was taken backwards by the same amount as the total increase in length of each plough body. For a 4-furrow plough, the increased moment on a tractor would be 0.8187 kNm and on a tractor 3m long the extra counter balance on the front would have to be 27.8 kg. Therefore, this is not a problem in practice.

CHAPTER 6 SKIMMER STUDIES

6.1 Introduction

Together with the mouldboard there are many other soil engaging parts of a mouldboard plough that can affect its performance in terms of soil inversion, trash burial and horizontal forces. One of the most Important parts is the skimmer, which is a smaller, and usually mouldboard-shaped attachment, located slightly forward and slightly above the tip of the mouldboard assembly. These come in a variety of shapes and sizes with differing cutting angles and soil contact areas.

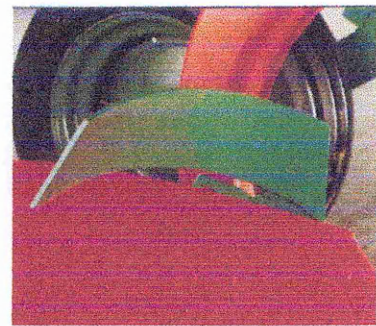
Figure 6.1 shows a full range of possible skimmers available from Kverneland.



Manure Skimmer



Maize Skimmer



Trash Board

Figure 6.1, A Range of Different Skimmers Available for Kverneland Ploughs

6.2 Initial Soil Bin Investigations

6.2.1 Aim

To determine the horizontal soil forces and disturbance patterns of the conventional Kverneland skimmer under soil bin conditions, using three rake angles, three approach angles and three speeds. This work will help to determine whether an improved shape or design can be used to improve the soil handling capabilities at higher speeds. It will also allow evaluation of force predictions for the skimmer carried out in Chapter 7.

6.2.2 *Introduction*

From the beginning of the research soil engaging parts of the plough have been of interest and have been discussed. It was decided to use the conventional Kverneland skimmer in the soil bin and determine operating forces and soil disturbance profiles. This should give a better understanding of the skimmer as currently used and highlight any areas in which it could be improved to operate better at higher speeds.

The skimmer is thought to be one of the plough components which limits the ability to operate at increased forward speeds. If this could be overcome the plough could be operated at increased speeds and, therefore, increased work rates could be achieved.

Initially the skimmer was examined in terms of depth of work and speed of operation and then by varying approach and rake angles. From these experiments the most likely operating parameters which would give increased or improved performance were used in a true working position in front of the mouldboard assembly.

Chalk dust was used on the surface of the soil to give an indication of the coverage and amount of soil moved by the skimmer for each configuration. This gives some similarity to having a surface residue although largely applicable to two dimensions.

6.2.3 *Procedure*

6.2.3.1 *Skimmer Approach Angle and Rake Angle Tests*

The optimum skimmer operating depth was considered to be approximately 50 mm (2") so this was used for the first set of experiments. To enable the skimmers approach and rake angles to be varied, a bracket was produced so that the appropriate angles could be selected for the individual experiments. The bracket allowed three angles of approach and three rake angles of the skimmer to be used in the soil bin. These were

the normal skimmer operating position, with a vertical skimmer leg and normal approach angle, which gave an approach angle of approximately 50-55 degrees and a rake angle of approximately 35-40 degrees. The angles could be increased or decreased by 30 degrees. This arrangement gave large variations in the angle of work for a normal skimmer which were thought to be the extremes of any modified angles at which the skimmer would be used. The bracket was fitted to a small Extended Octagonal Ring Transducer (EORT) to enable the skimmer forces to be measured separately from the main plough forces when tested together. Figure 6.2 and Figure 6.3 show the skimmer bracket that was attached to the small EORT for the soil bin experiments.

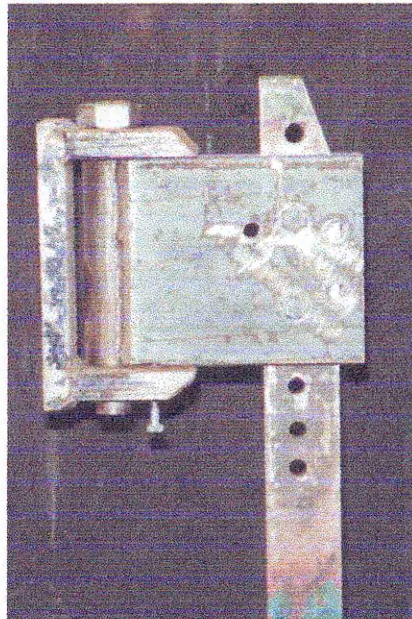


Figure 6.2, Side View of Soil Bin Skimmer Mounting



Figure 6.3, Front View of Soil Bin Skimmer Mounting

The bracket consists of a vertical axis hinge which attaches to the small EORT via the flat plate shown in Figure 6.2. The position of the vertical hinge or pivot is determined by a locating bolt at the top and bottom, which gives the skimmer its variable approach angles. From this vertical hinge there are two plates between which the skimmer leg fits. These plates have a series of holes that allow the leg to be attached at different rake angles; this in-turn results in different skimmer rake angles.

The holes in the leg of the skimmer allowed the height to be adjusted as the skimmer rake angles was increased or decreased. With the addition of three speeds the experiment consisted of 27 different random combinations and with three replications there was a total of 81 experiments.

Table 6-1 shows the different configurations at which the skimmer was set for the experiments. These are arranged into the three speeds for each skimmer configuration, but, for the experiment, each replication was carried out randomly in the soil bin.

<i>Speed</i>	<i>Rake Angle</i>	<i>Approach Angle</i>	<i>Speed</i>	<i>Rake Angle</i>	<i>Approach Angle</i>
4.5	Normal	Normal	4.5	Reduced	Normal
7.5	Normal	Normal	7.5	Reduced	Normal
10	Normal	Normal	10	Reduced	Normal
4.5	Normal	Decreased	4.5	Reduced	Decreased
7.5	Normal	Decreased	7.5	Reduced	Decreased
10	Normal	Decreased	10	Reduced	Decreased
4.5	Normal	Increased	4.5	Reduced	Increased
7.5	Normal	Increased	7.5	Reduced	Increased
10	Normal	Increased	10	Reduced	Increased
4.5	Increased	Decreased	4.5	Increased	Normal
7.5	Increased	Decreased	7.5	Increased	Normal
10	Increased	Decreased	10	Increased	Normal
4.5	Increased	Increased			
7.5	Increased	Increased			
10	Increased	Increased			

Table 6-1, Skimmer Experiment Variation

The normal-normal configuration applied to the skimmer in its unmodified position as it would be used on the Kverneland plough. The reduced rake angle setting brought the skimmer leg forward by 30 degrees at the soil surface. This made the skimmer have a similar rake angle to the plough point, causing the skimmer to lift the soil.

The increased rake angle moved the bottom of the skimmer leg backwards by 30 degrees and caused the leading edge of the skimmer to be almost vertical which caused the soil to be kept down and forced around the sides of the skimmer.

Decreasing the approach angle of the skimmer moved its cutting edge backwards by 30 degrees, making the skimmer have a smaller approach angle than the ploughshare. This caused very little soil disturbance and it flowed past the skimmer very easily.

Increasing the approach angle of the skimmer pushed the cutting edge of the skimmer forward at the heel by 30 degrees and caused the skimmer to be almost square-on (ie. at 90 degrees) to the direction of travel, as for a flat blade. This caused a greater amount of soil movement as the soil flowed around the ends of the skimmer.

The other combinations of the skimmer gave variations on these positions and soil flows, which are given in the results.

The moisture content and bulk densities were measured for all the tests and are given in the results section.

6.2.4 Skimmer Depth Variation Tests

After the initial experiment to examine approach angle, rake angle and speed, the effect of depth was considered. This was done because when the skimmer is working in a field situation the depth of work, although set to a constant value relative to that of the ploughing depth, would not normally be constant due to field variations, undulations and unevenness of the surface. This may affect the effectiveness of the skimmer and the quality of work achieved.

The skimmer was tested at two forward speeds and at four depths for each speed. The speeds were 4.5 km/h and 10 km/h and depths of 25mm, 50mm, 75mm and 100mm were used. The forces acting and soil movement of the skimmer at each setting were determined. All configurations are given in Table 6-2.

Chalk was used on the surface to help determine the soil movement. The moisture contents and bulk densities were measured to check that the soil conditions remained the same throughout the experiments. These are given in the results.

In addition to the measurements, all the skimmer experiments were videoed to enable closer inspection of the soil flow for the different skimmer configurations

<i>Skimmer</i>	<i>Depth (mm)</i>	<i>Speed (km/h)</i>
Skimmer 1	25	4.5
Skimmer 2	50	4.5
Skimmer 3	75	4.5
Skimmer 4	100	4.5
Skimmer 5	25	10
Skimmer 6	50	10
Skimmer 7	75	10
Skimmer 8	100	10

Table 6-2, Skimmer Depth Variations

6.3 Results

It is appropriate to view the results from the skimmer depth variation experiments initially, as the angle variations of the skimmer were all carried out at one depth. Once again the moisture content and bulk density were monitored for consistency. Unlike mouldboard experiments more than one test could be carried out in the soil bin between preparations. The mean moisture content and bulk density can be seen in a table in Appendix 4.1

Although the skimmer is set at one depth relevant to the depth of ploughing when used in a field situation, it was thought that the variation on the surface of a given field could cause a variation in the ability of the skimmer to handle soil. This is in addition

to any effect of speed that causes a change in the soil handling capabilities. Therefore, the change in soil throw was of most interest for this part of the experiment. Also of interest was the force change due to the depth of work.

Figure 6.4 shows the effect of speed on mean draught force for two different skimmer speeds. The horizontal force of the skimmer tested at 4.5 km/h increases by a factor of 6.38 over the depth range of 25mm to 100mm, and by a factor of 12.62 when tested at 10 km/h. The horizontal force increases with depth of work due to the area of soil being cut, as the tip of the skimmer is triangular. Increasing the depth introduces more soil onto the skimmer body increasing the force, this combined with the increase in speed results in the greater than linear increase in force.

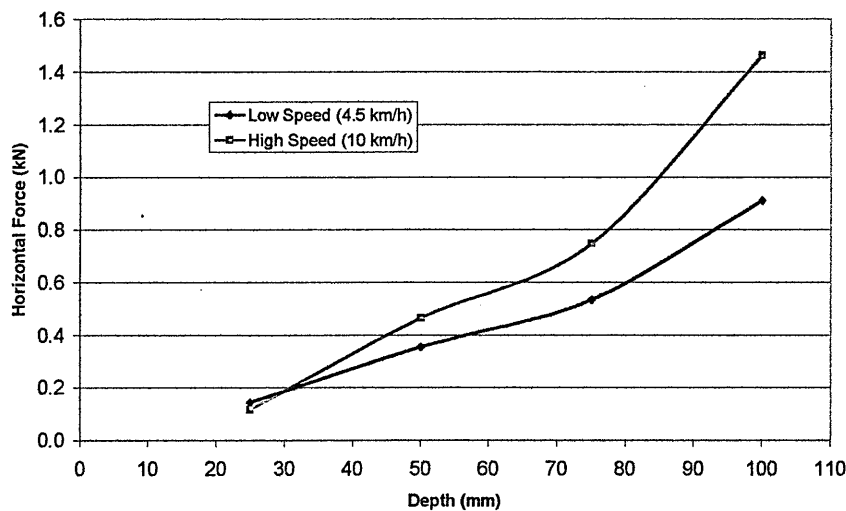


Figure 6.4, Skimmer Horizontal Force Increase with Depth

The increase in force would be incurred either if the skimmer encountered an increase in plough depth under a field situation, or if the skimmer was set to the wrong depth initially. This increase in horizontal force is greater when the plough is operated at higher speeds.

Figure 6.5 shows the effect of speed on mean draught force for a range of skimmer depths. This shows that the shallower the skimmer can be set the less effect the plough

operating speed has on the horizontal force. This means that at shallower operating depths the speed of operation can be increased without an adverse increase in the horizontal force.

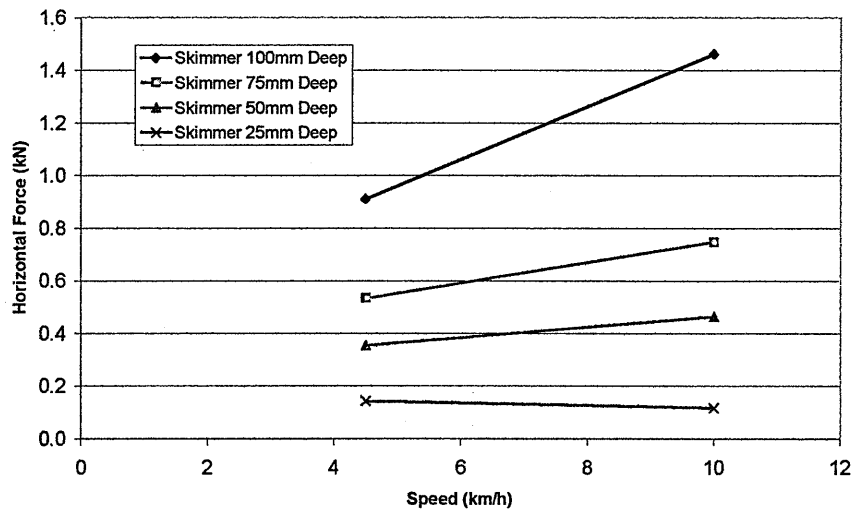
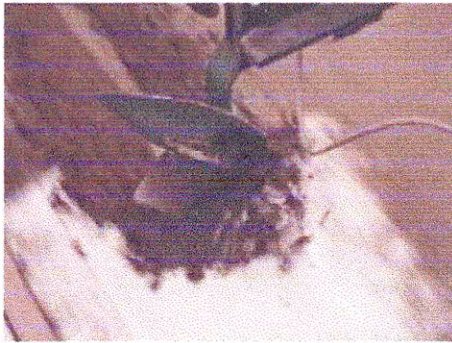


Figure 6.5, Skimmer Horizontal Force Increase with Speed

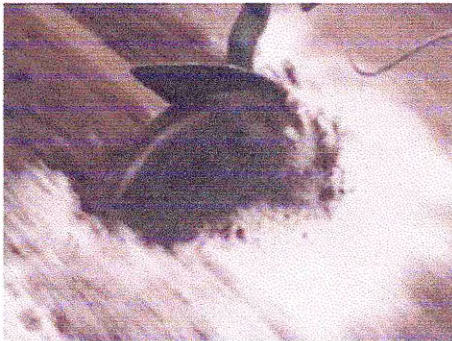
Both the draught forces and the soil throw were affected greatly by the depth, which had a greater effect than the speed. The skimmer forces follow a similar trend to that of the mouldboard when tested under controlled conditions. As was found with the mouldboard assembly, the increase in horizontal force due to depth is greater than that due to speed. More experimental variations would be needed to determine a trend between the increase in horizontal force with speed, but the effect of depth is near to exponential on the horizontal force.



Skimmer 25 mm Deep, 4.5 km/h



Skimmer 25mm deep, 10 km/h



Skimmer 50 mm Deep, 4.5 km/h



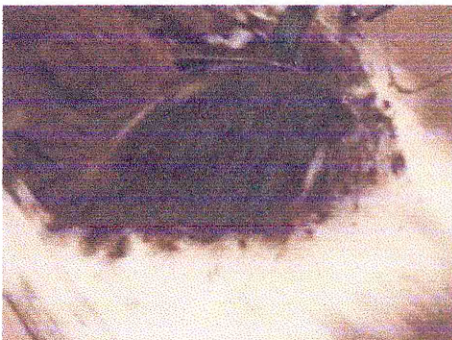
Skimmer 50mm deep, 10 km/h



Skimmer 75 mm Deep, 4.5 km/h



Skimmer 75mm Deep, 10 km/h



Skimmer 100mm Deep, 4.5 km/h



Skimmer 100mm Deep, 10 km/h

Figure 6.6, Soil Throw for a Variation of Depths at Two Speeds

It can be seen from the photographs in Figure 6.6, that the depth of the skimmer has a major effect on the amount of soil that flows from it, which, in turn, increases the distance from the tip of the skimmer the soil travels. This distance is again increased by speed, which increases the lift height of soil and its trajectory. At 10 km/h the soil flow that leaves the skimmer at the 25, 50 and 75mm depths actually leaves a gap on the soil surface before impacting. This is mainly due with the approach angle of the skimmer not being suited to speeds of 10 km/h. This could lead to the problem of the soil landing on the back of the mouldboard of the furrow in front. The problems is eased slightly at the 100mm depth due to the volume of soil flowing over the skimmer, but the overall distance travelled is similar.

The variation in skimmer angles needs to be considered with the view of improving the current skimmer configuration both in terms of horizontal force and the soil flow and placement.

The complete table of the measured mean forces in Appendix 4.2 shows the variation in the skimmer horizontal and vertical forces for the different configurations.

Firstly, the horizontal forces of the skimmer at the various settings were considered. Figure 6.7, shows the variation in horizontal force for the various skimmer rake and approach angles. As with previous skimmer experiments the trend in horizontal forces is to increase with speed. The magnitude of the forces is small, but all the skimmers follow a similar relationship. The reduced rake / increase approach angle and the increased rake / increase approach angle settings have the most varied results, which are the two settings that produce the most soil movement and are subject to most turbulence from the soil.

The reduced rake/increased approach requires considerably more horizontal force than all the other skimmer configurations, approximately 0.6 kN. This would be a factor to consider when choosing an improved skimmer because even though horizontal force is a small part of the total horizontal force of the plough an improved skimmer, ideally, would not have an increased requirement.

It is also useful to examine the vertical force of the skimmer because this could affect the penetration of the plough if vertical forces become excessive. Figure 6.8, shows the variation in vertical force for the skimmer at different rake and approach angles.

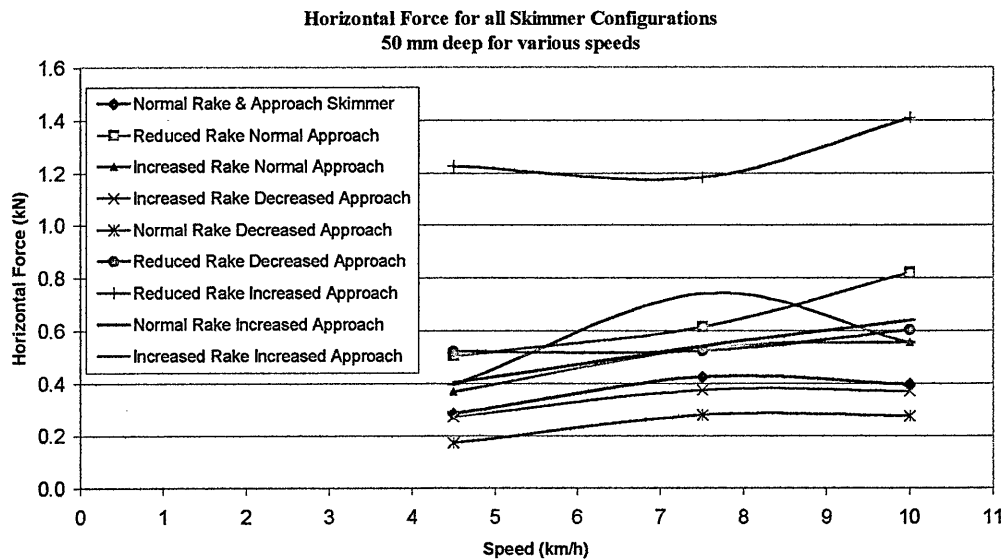


Figure 6.7, Skimmer Horizontal Force for Various Angles

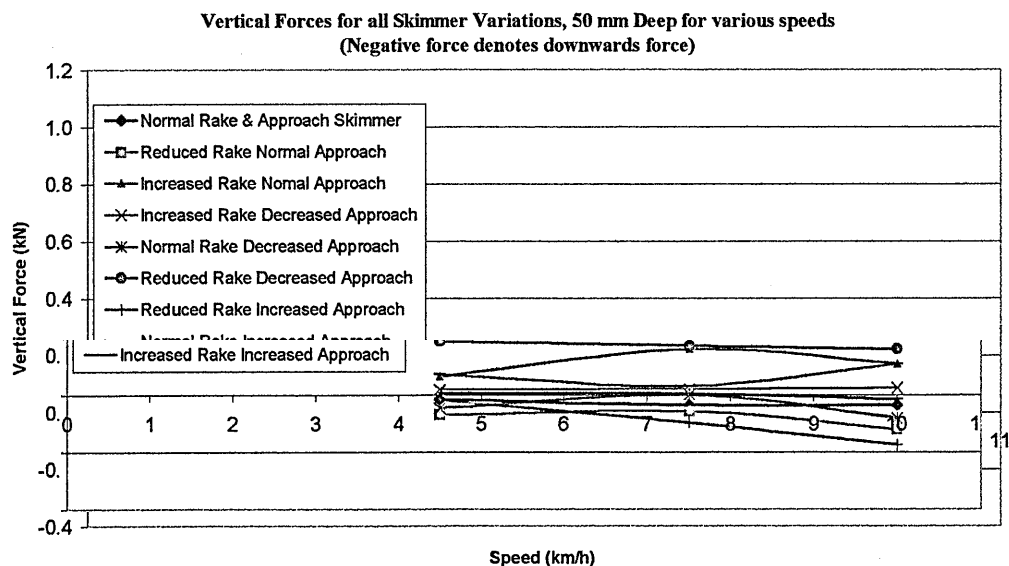


Figure 6.8, Skimmer Vertical Force for Various Angles

It can be seen from the measured values of forces on the graph that the reduction in rake angle and the increase in approach angle together increase the horizontal forces, they also tend to increase the vertical (downwards) force. In contrast an increase in rake angle and a decrease in approach angle together reduce the horizontal force; this also results in a change in the vertical force direction from downward to upwards. A downward vertical force denotes a penetration force and an upward vertical force denotes a scrubbing force.

Finally, viewing the soil disturbance and profiles produced by each skimmer allows an additional comparison of the various configurations. Figure 6.9, shows the soil profile of the normal skimmer configuration over the range of speeds tested.

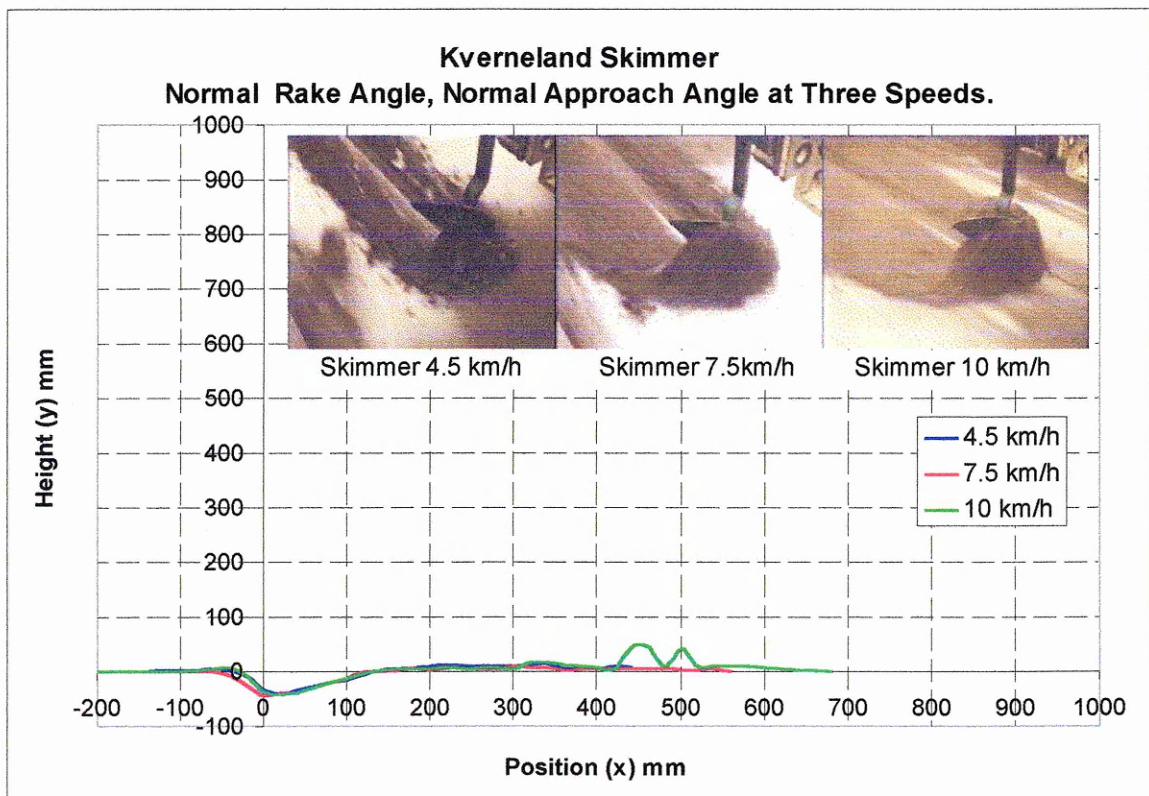


Figure 6.9, Normal Skimmer Configuration Soil Profiles.

As was noticed with the varying depth studies, an increase in speed produced an increase in the amount of soil thrown. This soil profile can then be compared to that of the various skimmer configurations tested.

The soil flow from an improved skimmer configuration should be better than that of the normal skimmer at increased speed, so that it throws the soil into the correct position, entering the furrow bottom with an undisturbed path. The conclusions from the study were as follows:

- a) A reduction in the rake angle causes an increase in the width of soil cut by the skimmer but also causes much more soil disturbance. At high speeds the soil is thrown further across in the open furrow direction.
- b) Increasing the rake angle results in a very small v-shaped section of soil being disturbed. The amount and distance of soil flow is controlled well over the speed range but slightly more soil flows to the on-land side of the furrow. See Figure 6.10.
- c) Reducing the approach angle causes a very small disturbance and the soil flow is similar at high speed to that at low speed. The clearance at the back of the skimmer is reduced and may be prone to scrubbing. See Figure 6.11.
- d) Reducing the approach angle and reducing the rake angle tended to lift the soil with similar soil disturbance profiles as with the original skimmer configuration. The final position of the soil tends to be further back than for the original skimmer, and it may not reach the furrow bottom in time for the mouldboard to cover it.
- e) Reducing the approach angle and increasing the rake angle keeps the soil flow very low and close to the surface but has a very small soil disturbance profile. The high-speed soil flow is well controlled and not thrown too far to the side. See Figure 6.12
- f) Increasing the approach angle and increasing the rake angle produces a very small disturbance profile and tends to send the soil more to the on-land side than towards the open furrow side, which is not a desirable result.

- g) Increasing the approach angle and reducing the rake angle produces a very wide disturbance profile but lifts the soil very high and it is inconsistent; this occurs at all the speeds examined.
- h) Increasing the approach angle with a normal rake angle causes the soil flow to go towards the on-land side rather than to the open furrow side but leaves a similar disturbance profile to that of the normal skimmer configuration.

From the experimental variations the most favourable combinations for an improved skimmer configuration can be seen in Figure 6.10, Figure 6.11 and Figure 6.12. Those were the increased rake angle and reduced approach angle combinations.

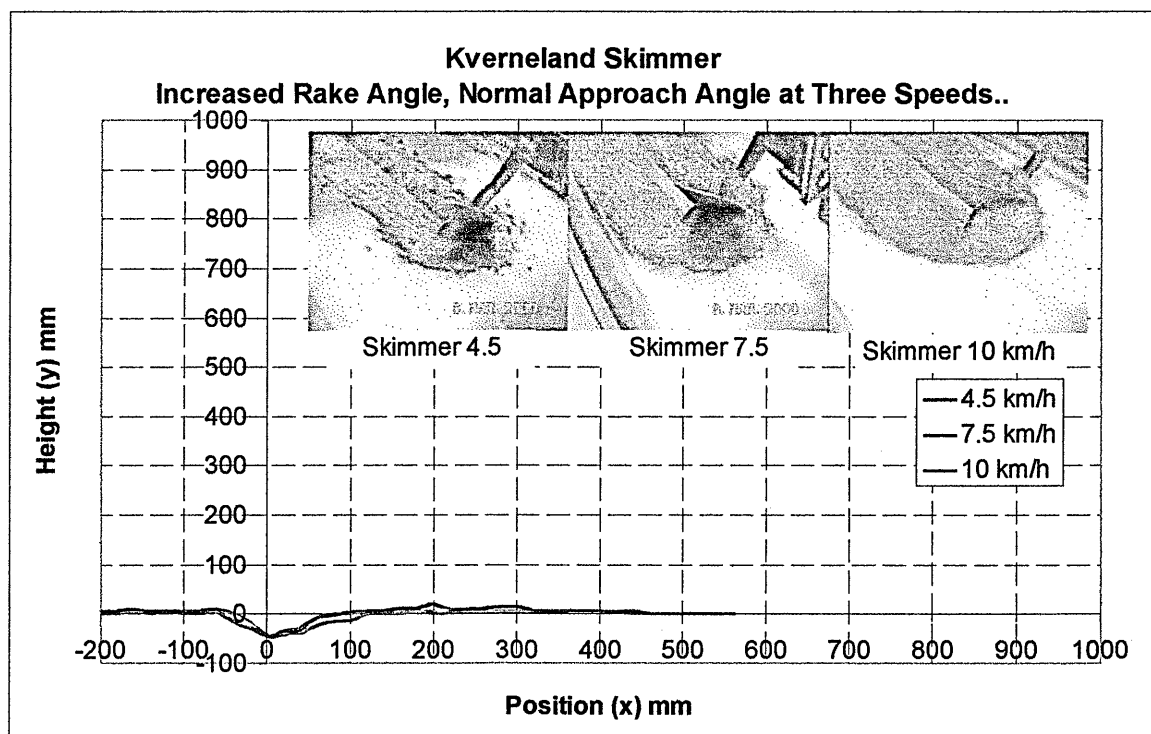


Figure 6.10, Normal Approach Increased Rake

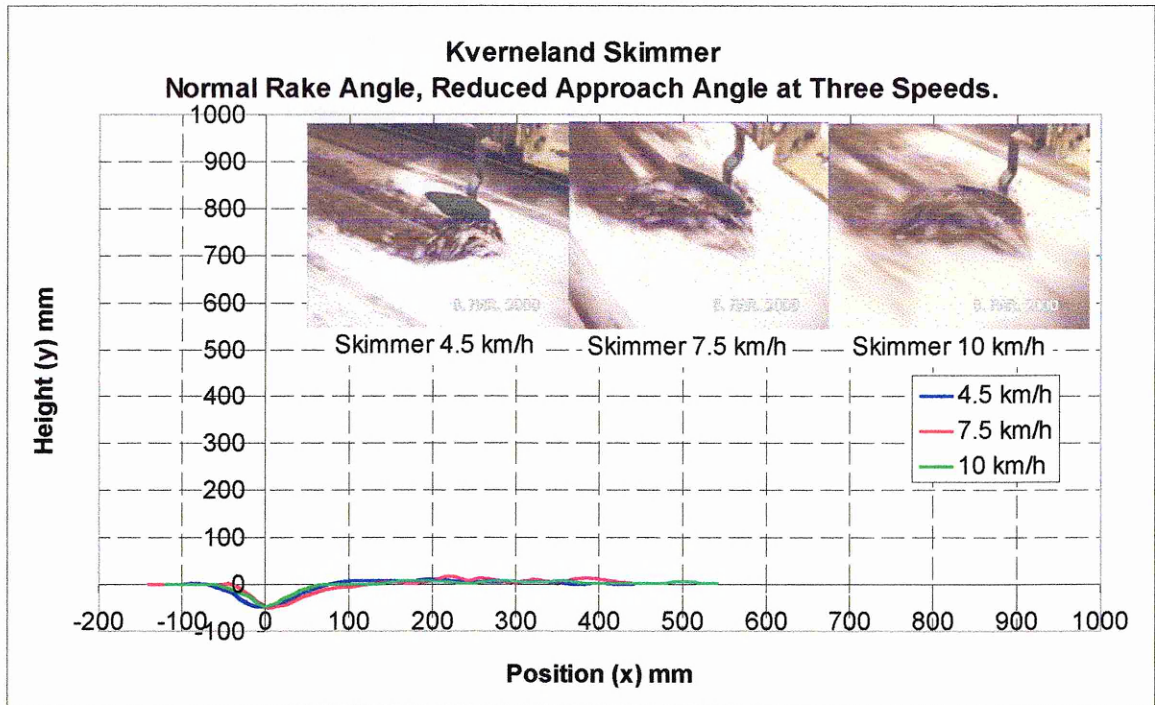


Figure 6.11, Reduced Approach, Normal Rake

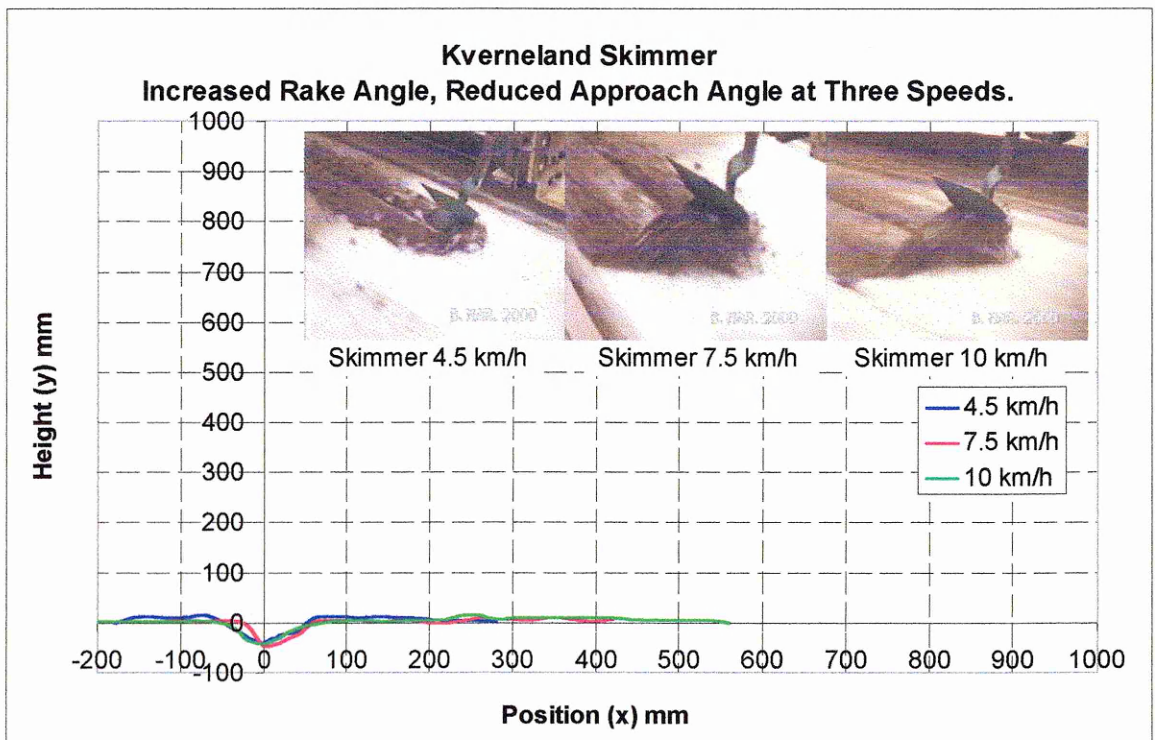


Figure 6.12, Reduced Approach, Increased Rake

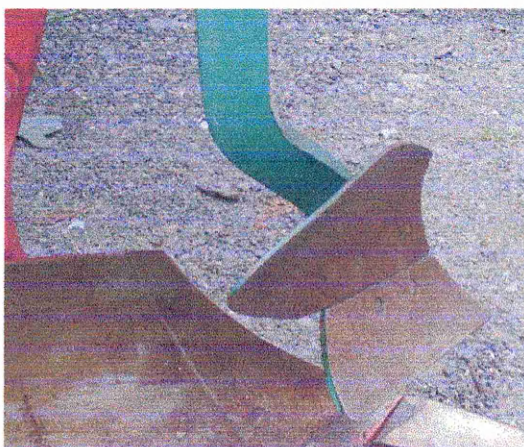
6.4 Field Studies

6.4.1 Aim

To determine if the conventional Kverneland skimmer could be improved in terms of its trash handling performance over a range of operating speeds under field conditions. This was to be done with a modified Kverneland skimmer fitted to a five furrow Kverneland plough.

6.4.2 Introduction

Following controlled soil bin experiments a slightly modified and adjustable skimmer was produced to fit on to a conventional Kverneland plough. The skimmer was adjustable in two planes, (a) to vary the approach angle to that of the direction of travel and (b) to vary the rake angle. The skimmer used also had a slightly increased curvature to that of a standard skimmer. This means that the radius of curvature was reduced for the upper part of the skimmer to increase the skimmers ability to throw the soil over more quickly and place it in the bottom of the previous furrow.



Normal Skimmer



Reduced Radius Skimmer

Figure 6.13, Skimmer Shapes Used for Field Experiments

Figure 6.13, shows the standard Kverneland skimmer and the reduced radius skimmer used in the field experiments. The reduced radius skimmer can be seen attached to an adjustable skimmer leg, for adjustment of the rake and approach angles.

The skimmer had to be slightly modified from the one used in the soil bin due to the limited space available when fitted to the plough in the normal working position. The skimmer used in the soil bin was adjusted for rake angle and approach angle by moving the entire skimmer leg; this was not possible when fitted to the plough so the skimmer body itself had to be made adjustable at the bottom of the skimmer leg.

Figure 6.14, shows a view of the skimmer adjustment that was produced to enable the required movement of the skimmer head when fitted to the plough.

The rake angle adjustment was controlled by moving two notched circular clamps which were tightened by a clamping bolt located through the centres of the clamps.

The approach angle of the skimmer was adjusted by turning the its body on a shaft fitted to the back of the skimmer; this was bolted to the rake angle adjustment. This shaft was in turn clamped, using two large bolts inside a hollow pipe to the bottom of the skimmer leg. The angle of the skimmer head was adjustable and there was a certain amount of height adjustment.



Figure 6.14, Strengthened Skimmer Adjustment

With these two adjustments and the ability to lift and lower the skimmer leg in the plough beam clamp, the skimmer tip could be placed in the correct position for a variety of rake angles and approach angles. The most important factor was the operating depth of the point of the skimmer for a given ploughing depth, which needed to be 50mm (2").

The rake angle adjustment of the skimmer was done with a notched clamp, which was located between the skimmer leg and the skimmer body. There were 24 steps in the clamp, which meant that each notch gave a change in angle of 15 degrees. The clamp provided a positive step between each notch, holding the skimmer at the selected rake angle. By rotating the skimmer in the series of notches it was possible to increase or decrease the rake angle in increments of 15 degrees.

The adjustment of the skimmer for the approach angle was less specific because the clamping method allowed infinitely variable angles to be chosen, and it was the clamping force that located the skimmer at its set approach angle. As the approach angle was less controllable and more difficult to repeat, only one change of angle was chosen which was a reduced angle of 20 degrees from the normal skimmer approach angle. The angles that the skimmer were moved through in the soil bin were 30 in

each plane so this gave the ability to test two notches for rake angle and one for approach angle, whilst remaining within the limits of the soil bin experiment.

When the skimmer was fitted to the plough a digital video camera was attached to the plough beam (Figure 6.15). The camera was mounted in an appropriate position to view the soil flow from the modified skimmer and study the effect of the changes of rake angle and approach angle caused by the different settings Figure 6.16.

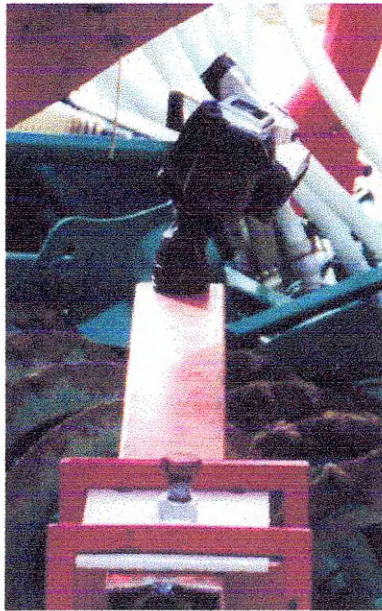


Figure 6.15, Digital Camera Mount

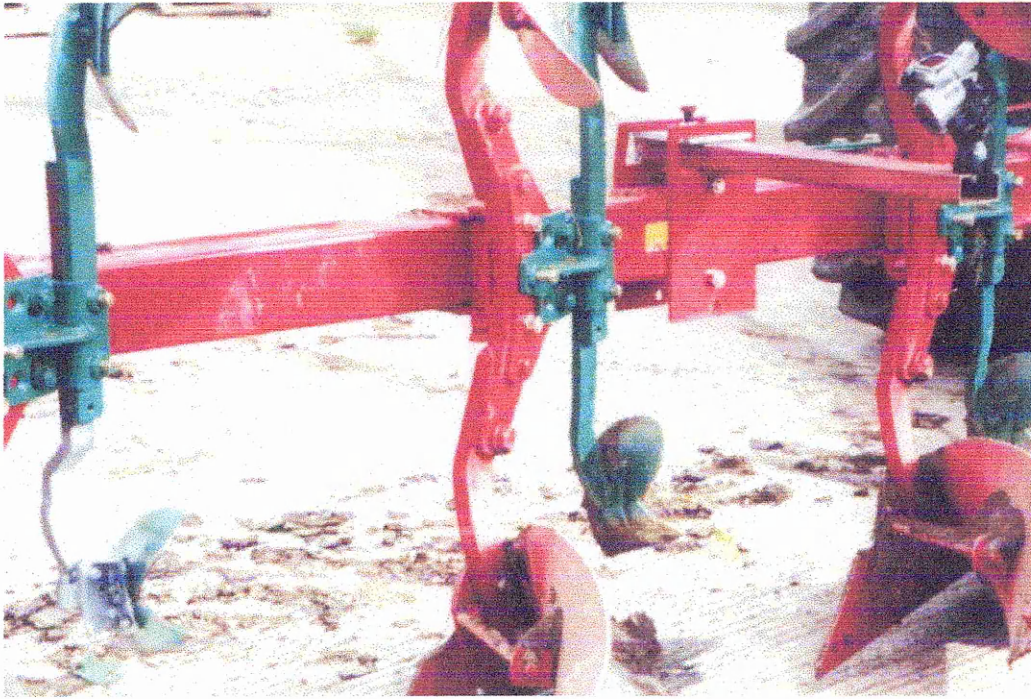


Figure 6.16, Digital Camera Positioned on Plough Beam

6.4.3 Procedure

As a complete variation of skimmer rake angles and approach angles were tested in the soil bin, only those which would give beneficial and/or improved operation from that of the conventional skimmer were of interest for the field studies. The skimmer settings thought to improve the operation and soil handling ability of the skimmer from that of the conventional skimmer include,

- A small increase in the rake angle of the skimmer cutting edge (up to 30°). This included an increase in curvature of the upper part of the skimmer body.
- A decrease in the approach angle of the skimmer in the direction of travel.
- A combination of both of these variables.

These changes were determined from earlier soil bin experiments, both testing the skimmer independently and with the skimmer in its working position in front of the mouldboard assembly. Initial tests showed that a reduction in the rake angle of the skimmer produced greater soil disturbance than the standard skimmer, which was

uncontrollable and loosened soil from the skimmer was lifted high above the original soil surface. This would be of little use for an improved skimmer setting. Likewise the increase in approach angle moved more soil and it tended to be to the landside rather than to the open furrow side which is undesirable. Along with the increase in approach angle came an increase in horizontal force, which was also not acceptable.

In terms of finding a skimmer setting that was an improvement from the standard skimmer, a configuration with any combination of increased approach or reduced rake angle would be rejected. This left a choice of increased rake angles and reduced approach angles, or some combination of the two. It was shown from soil bin experiments that the combinations of reduced approach angle, and increased rake / reduced approach angle also gave lower horizontal forces than the standard skimmer which would be beneficial. The configuration of increased rake and normal approach angle gave slightly higher horizontal forces than the normal skimmer setting, but was the closest.

These options gave the basis for the chosen setting used in the field, shown in Table 6-3.

Skimmer	Rake Angle	Approach Angle
Setting 1	Increased 1 Notch (15)	Normal Approach
Setting 2	Increased 1 Notch (15)	Reduced Approach (20)
Setting 3	Increased 2 Notches (30)	Normal Approach

Table 6-3, Skimmer Field Variations

These settings could then be compared to the conventional skimmer configuration under normal field trash conditions. As the modified skimmer described earlier was fitted to a five furrow plough, the operation of a conventional skimmer and the modified one could be viewed simultaneously and compared whilst in work. The ploughing was carried out on regular wheat stubble where the straw had been chopped behind the combine and the chaff spread. There were some areas of the field where the

crop had been laid and hence missed by the harvester; this resulted in a greater mass than would normally be expected. The ploughing was carried out at a depth between 175mm (7") and 200mm (8") and the skimmer was set to approximately 50mm (2") below the surface as recommended.

6.4.4 Results

Field tests were carried out with the objective of getting a better soil flow from the modified and adjustable skimmer than from the standard Kverneland skimmer. This meant operating the tractor plough combination at different forward speeds and viewing the modified skimmer together with the standard one to see any differences in operation. The video camera attached to the plough allowed the modified skimmer to be viewed simultaneously with the standard skimmer fitted to the furrow either in front or behind, depending upon camera angle.

Video was taken from both the camera mount attached to the plough beam and from the side of the plough so as to be able to see the soil flow into the furrow bottom.

The first skimmer variation was to increase the rake angle by one notch (15°) when ploughing at 10 km/h, as can be seen from Figure 6.17 this had a visible effect on the soil throw under field conditions. The front skimmer in the photograph is the standard one, which can be seen to be throwing the soil much higher and towards the back of the mouldboard in front. The rear skimmer in the photograph is the modified one that has a much lower and controlled soil flow.



Figure 6.17, Increased Rake Angle1 Notch, Normal Approach Angle

When the same skimmer configuration is viewed from the front (Figure 6.18) the soil flow can be seen more clearly, and can be seen turning down from the top edge of the skimmer body and being directed towards the furrow bottom.



Figure 6.18, Increase Rake Angle 1 Notch Front View

The rake angle of the skimmer was then increased 2 notches and the ploughing carried out at 10 km/h. Firstly, from the side (Figure 6.19) the soil flow from the modified skimmer can be seen to be much closer to the soil surface and, therefore, has less distance to travel to the furrow bottom where it is aimed.



Figure 6.19, Increased Rake Angle 2 Notches, Normal Approach Angle

When viewed from the front (Figure 6.20) the soil flow is rapidly directed downwards but comes closer to the back of the mouldboard body in front. This necessitated reducing the approach angle of the skimmer to try and alleviate the problem.



Figure 6.20, Increased Rake Angle 2 Notches, Front View

To reduce the approach angle of the skimmer the rake angle was returned to a 1-notch increase, which reduced the scrubbing on the back of the skimmer which caused straw and trash to accumulate.

As can be seen from Figure 6.21, the soil flow from the skimmer at the increased rake and reduced approach angle is directed much better towards the open space between the mouldboard body in front and the turning furrow slice of the following mouldboard. If this is compared to the standard skimmer configuration, seen at the front of Figure 6.21, at a speed of 10 km/h the soil is thrown directly at the back of the mouldboard body in front and is required to drop into the furrow bottom under its own weight.



Figure 6.21, Increased Rake Angle 1 Notch, Reduced Approach Angle

This soil flow can be highlighted on the photograph with the use of added lines; Figure 6.22 shows the difference between the soil flow from the standard skimmer (right hand line) and the modified skimmer (left hand line) at an increased rake angle and reduced approach angle.

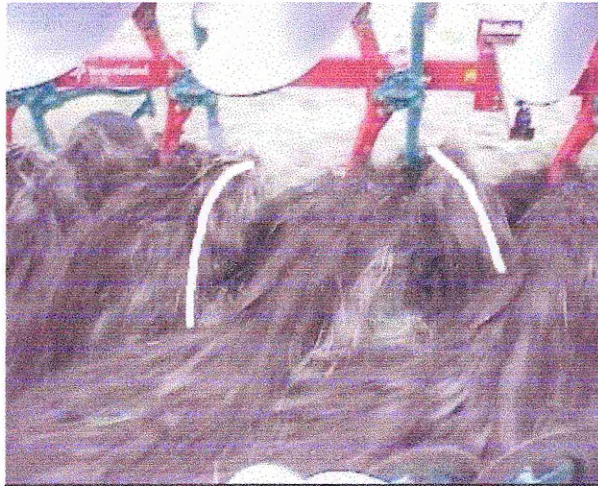


Figure 6.22, Increased Rake Angle 1 Notch, Reduced Approach Angle, Highlighted Soil Flow

When the increased rake angle and reduced approach angle skimmer was viewed from the front it was possible to determine the path of the soil to its correct and final position in the furrow bottom, Figure 6.23. The reduced approach angle skimmer worked well at high speeds because it allowed the soil to flow on a similar flow path to the soil leaving the mouldboard, without changing the angle greatly. This was found to reduce the interference between the soil flow paths and, therefore, reduce the disturbance of the soil being turned, leading to a cleaner inversion process.

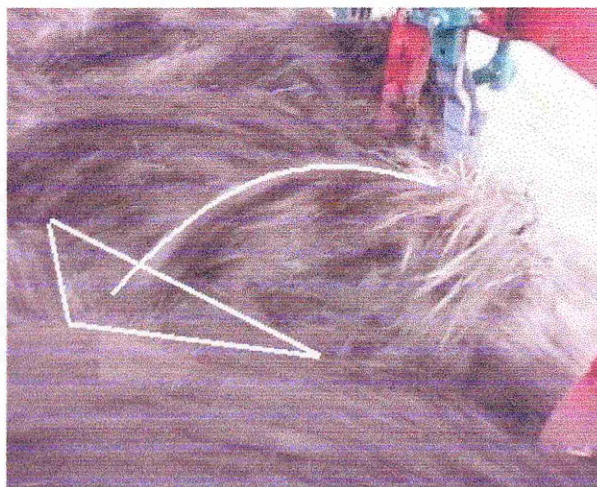


Figure 6.23, Soil Flow Path from Modified Skimmer

It was noted that increasing the rake angle of the skimmer by 1 notch (15 degrees) worked well over a speed range of 4.5km/h to 10km/h. The reduced approach angle gave less of an improvement at lower speeds, with a tendency for the straw to wrap around the leading edge of the skimmer body. This was mainly due to the vertical edge facing the direction of travel. However the reduction in approach angle was less important at the lower speeds as the soil was not thrown across at such high velocities.

6.5 *Summary*

It was found from controlled experiments that in addition to the speed of operation, the working depth of the skimmer had an effect on the amount of soil moved and the distance it was thrown. The variation in depth was considered an uncontrollable factor in a field situation due to undulations in the surface profile. The skimmer is set to the correct depth (50mm) when the plough is set to its desired depth at the beginning of work, and is very rarely adjusted by the operator. Depending on the previous crop, the amount of trafficking, and the weather conditions at times of trafficking, the surface variation could be much greater than 50mm, which is recommended as the optimum depth for a skimmer to operate. This means that the skimmer working depth could vary from zero to 100 mm in the worst case, which would also depend on the number of furrows and the tractor linkage reaction times.

From soil bin experiments, the difference in soil movement from 50 to 100 mm could explain why the skimmer has difficulty burying trash in some situations especially at increased speeds. The effect of speed makes the situation worse but the depth of work could be a significant contribution to the problem. As the depth of skimmer work is increased there is a greater volume of soil for the skimmer to handle and move across into the open furrow. If this situation occurs when large amounts of surface residue are present, the likelihood of some of the trash not being buried increases. This may lead to a possible way of improving the depth control and consistency of skimmers fitted to mouldboard ploughs if their ability to work at increased speeds is to be improved.

After looking at a range of rake and approach angles of a skimmer during soil bin experiments the best combinations for improved operation were highlighted as

- An increase in the rake angle of the skimmer, so enabling the turning of soil into the furrow bottom more quickly.

- A decrease in the approach angle, which reduces the amount of lateral throw of the soil, so reducing the chance of it hitting the mouldboard in front.
- A combination of these two angles to improve the skimmer operation.

Under field conditions, a modified skimmer was used and it was shown that a more controlled soil flow can be achieved by changing the angles of the skimmer body and increasing the curvature of the upper part of the skimmer.

An increase in the rake angle of the skimmer gave faster soil turning, keeping the soil moved by the skimmer closer to the soil surface with more opportunity to enter the open furrow bottom and be buried in the correct way by soil leaving the following mouldboard.

Reducing the approach angle meant that at increased speeds the soil was not thrown across the furrow profile at high velocities and the flow of soil corresponded with that of the mouldboard. The reduced angle skimmer was not found to be as effective at lower speeds where the trash in the top layer of the soil profile had a chance to collect around the leading edge of the skimmer body.

Overall, it was considered that it is possible to improve the ability of the standard Kverneland skimmer to work at increased speeds under field conditions. To increase the ability of the skimmer to operate at optimum performance factors such as variable angle skimmers should be investigated, so that the angle of the skimmer matches the speed of work and/or the prevailing trash conditions. An ability to control the depth of each skimmer independently on the move, according to the field undulations, would also remove the adverse effects that occur from varying depths of work. This could be done with a skimmer that followed the contours of the land independently of the mouldboard and the rest of the plough.

CHAPTER 7 DRAUGHT FORCE PREDICTION MODELS

The following chapter describes the methods and processes of predicting the forces acting upon two components of a commercially available mouldboard plough. The first component is the mouldboard assembly (based upon the Kverneland No8 mouldboard) and the second is the standard manure skimmer assembly. These predictions are both based upon general soil dynamics equations using Mohr-Coulomb soil properties.

7.1 Mouldboard Force Prediction

7.1.1 Aim

To develop a relatively straight forward, but accurate method of predicting the horizontal forces acting upon a conventional, commercially available mouldboard plough assembly. The prediction model makes use of previously developed soil mechanics equations modified to suit the shape, size and configuration of the components involved in the soil movement of a mouldboard plough body, and the known Mohr-Coulomb soil properties.

7.1.2 Introduction

The mouldboard plough is one of the oldest primary tillage implements and remains the only tillage operation with the advantage of total soil inversion, leaving a trash free surface and the burial of any weed seeds. Ploughing accounts for more traction energy than any other field operation Kepner *et al.*, (1978); for this reason understanding the forces involved with the cutting and the moving of soil by mouldboard ploughs has always been important. Under the current state of the agricultural economy, tillage implements have to be efficient and highly productive.

Understanding the forces, which act upon a mouldboard plough when working at different settings, can assist in enabling the correct configuration of width, depth, speed and number of furrows to be selected to optimise productivity. The objective was to develop and evaluate a mathematical model to predict the effects of those variables on the draught force of mouldboard ploughs using basic Mohr-Coulomb soil mechanics properties.

Much work has been conducted on measuring the draught forces of ploughs of different shapes and different settings Rogers *et al.*, (1956). There have also been several different methods of predicting the forces acting on mouldboard ploughs. Prediction models from O'Callaghan *et al.*, (1965) and Gyachev, (1985) used mathematical approach to determine the force of the soil slice on the mouldboard plough, with the former reliant upon a computer algorithm to handle the large number of calculations.

The draught force of mouldboard ploughs was predicted by Seig (1982), adopting the general soil mechanics equations modified by Hettiaratchi *et al.*, (1966) for blades and by Godwin and Spoor (1977) for tines. The method adopted two equations for the prediction, using three dimensional tine theory for the tip and two dimensional blade theory for the rest of the share.

Goryachkin (1968) pioneered studies on the forces acting on the body of a plough; and derived the general formula of resistance to traction and a concept of its components. Oskoui and Witney (1982) adapted the equation by Goryachkin (1968), using cone index data as a measure of soil strength and the effect of the mouldboard tail angle to predict the forces. A rapid method of predicting forces was adopted by Desbiolles *et al.*, (1999) that used either cone penetrometer data or a simple narrow tine to predict the draught of tillage implements, including mouldboard ploughs. All these prediction models are compared with varying amounts of experimental data.

The two equations used by Seig (1982), that is three dimensional crescent failure for the tip and two dimensional passive failure for the share, was considered a good place to start a prediction model that would suffice for the needs of the objectives of the research. In its original form Seig's prediction neglected any velocity effects but these effects are considered to be important for a complete and powerful prediction model.

The work of Wheeler and Godwin (1995) was considered which involved the prediction of tine forces at speeds up to 20 km/h, using the theory of McKyes to include an inertial term for soil cutting on a wide tine or blade. In addition to these general soil dynamics equations, the theory of inertia and momentum Gyachev, (1985) and suggested mouldboard shapes and acceleration forces [Sohne, 1959 #7] for soil flowing over the mouldboard body were added to the prediction model, refining it further to improve the accuracy of the predicted force acting on the mouldboard assembly compared to those of measured values.

7.1.3 Procedure

As stated in the introduction, the method of Seig (1982) was considered a suitable starting place for developing a force prediction model further. As the tip protrudes in front of the share by a significant amount the dual approach to prediction was considered the more appropriate, this being 3-dimensional crescent failure for the tip and 2-dimensional passive failure for the share.

In order to improve the force prediction model it was considered necessary to highlight the components that go together to make up the total horizontal force acting upon a mouldboard assembly. This can be done with the use of a schematic diagram to show the parts of the mouldboard plough assembly and where the forces act upon these parts.

Figure 7.1 shows a mouldboard assembly and the parts that are considered to have an effect on the total horizontal force of such an assembly. Where w_w is the “Width of the wing” or share and w_T is the “Width of the tip” or point, (β) is the angle of the share to the direction of travel and (θ) is the angle of the mouldboard to the direction of travel assuming the angle is constant along an imaginary horizontal line on the mouldboard.

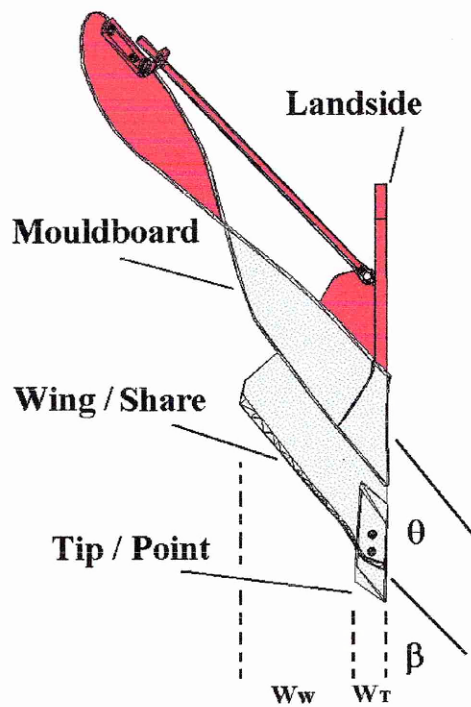


Figure 7.1, Mouldboard Plough Assembly

Figure 7.2, shows the three major components of horizontal force considered to make up the total horizontal force of a mouldboard plough assembly.

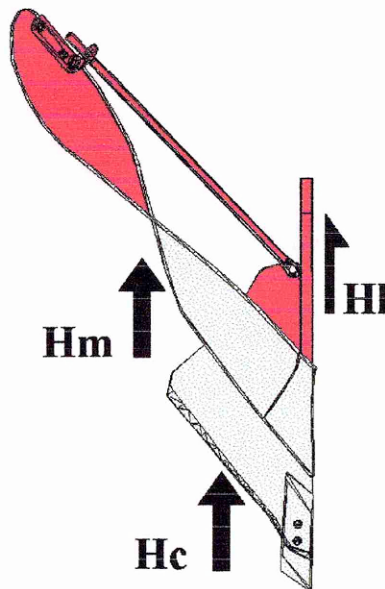


Figure 7.2, Horizontal Force Components

H_c is the horizontal cutting force produced by the tip and the share when cutting the soil slice. H_m is considered as the horizontal mouldboard force produced by the lifting and turning of the soil slice. H_l is the horizontal force component of the landside drag force which results from the friction effects of the lateral forces generated by H_c and H_m .

These three major components considered to produce the total horizontal force have to be broken down further in order to understand and apply the theory to calculate the forces. The breakdown of H_c and H_m can be seen in Figure 7.3. H_c the cutting force is divided into the 3-dimensional soil failure component H_p occurring about the tip/point and the 2-dimensional soil failure component H_s resulting from the share. Likewise H_m includes both the momentum change of the soil moving over the mouldboard H_{mc} and the potential energy required to lift the soil H_e .

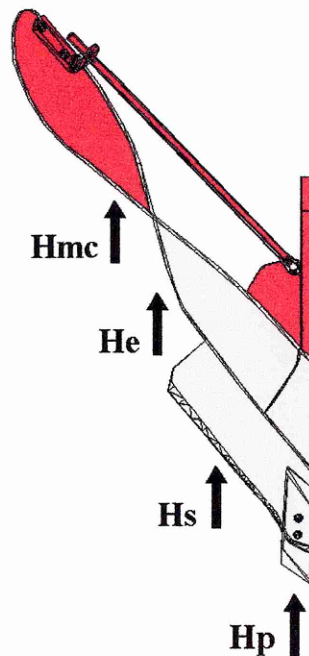


Figure 7.3, Break Down of Horizontal Force Components

The components of side force can be seen in Figure 7.4, once again one from the soil cutting effect (H_{cs}) and one from the soil moving/turning effect (H_{ms}). These add up

to make the total side force that acts at the angle of friction, δ (δ) and produces the resistance in the horizontal direction.

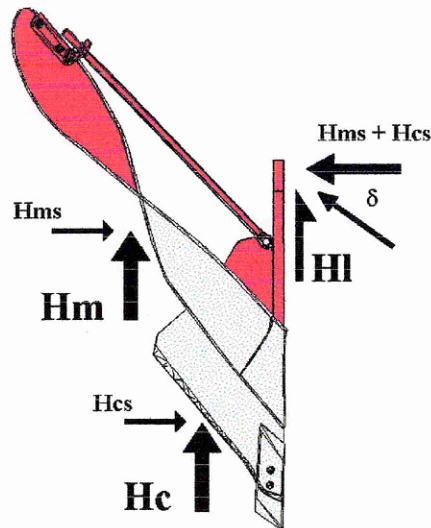


Figure 7.4, Side Components of Force and Resulting Frictional Angle

To aid the understanding of forces that contribute to the three major components considered to produce the horizontal force acting on a mouldboard assembly a hierarchical flow diagram can be used, Figure 7.5. This shows the three major components and the sub-components that are considered. This method of structuring the forces allows the individual equations to be associated with each sub-part, of which the summations make up the three major components.

A flow diagram showing the components that make up (H_t) the total horizontal force on a mouldboard plough body

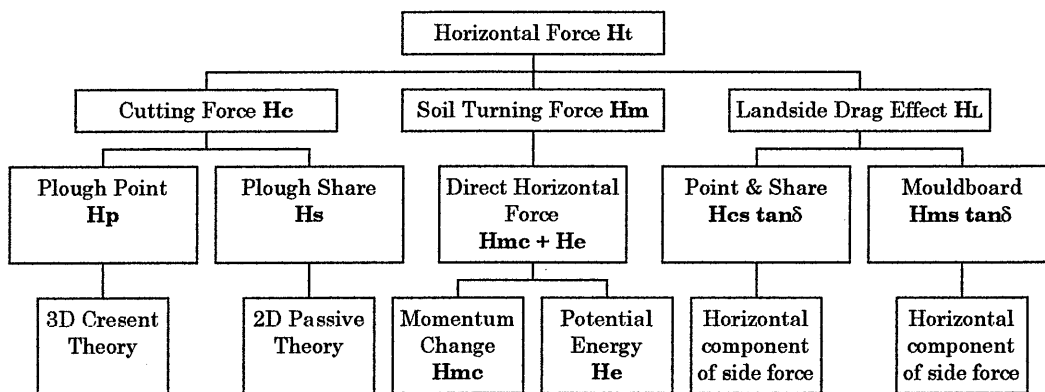


Figure 7.5, Hierarchal Flow Diagram of Plough Forces

Sub components of these three major sections can be identified and explained. For the cutting force (H_c), there is that of the tip and that of the share. These are both predicted using a modified version of the split general soil mechanics equation, using the 3-dimensional crescent and 2-dimensional passive failure theories.

The sub sections of the soil moving can be considered as the horizontal and the lateral. These are both created by an inertial velocity effect that the soil is given, and the energy exchange of accelerating the soil in a given direction. Finally, the landside drag effect that is made up from all the side forces produced by the other two sections (H_c and H_m) applied tangentially to the landside causing a frictional resistance to horizontal movement.

The notation used in the conceptual build up of the forces and the actual prediction model can be seen in Table 7-1.

<u>Force Components</u>		<u>Soil Properties</u>	
Ht	= Total Horizontal Force	γ	= Bulk Unit Weight
Hp	= Horizontal Point Force	c	= Cohesion
Hs	= Horizontal Share Force	δ	= Angle of Soil/Metal Friction
Hm	= Horizontal Mouldboard Force	ϕ	= Angle of Internal
He	= Force due to Potential Energy		Shearing Resistance
Hcs	= Horizontal Cutting Side Force	m	= Rupture distance ratio
Hms	= Horizontal Mouldboard Side Force		
HI	= Horizontal Landside Force	N	= <u>Dimensionless Number</u>
<u>Plough Geometry</u>		<u>Suffixes</u>	
d_T	= Depth of Tip/Point	γ	= Gravitational
w_T	= Width of Tip/Point	ca	= Cohesive and Adhesive
d_w	= Depth of Wing	a	= Inertial
w_w	= Width of Wing	q	= Surcharge
α	= Rake Angle	<u>Constants</u>	
β	= Share Approach Angle	Ko	= Reduction in Crescent Failure
θ	= Mouldboard Angle	kl	= Reduction in Share Width
v	= Velocity	n	= Velocity Increase, Power Term
		m	= Potential Energy Soil Lift

Table 7-1, Notation and Constants

Where the constants used for the mouldboard prediction are as follows. A value of 0.5 was used for Ko the reduction in crescent failure, as crescent failure was not thought to occur on both sides of the tip. A value 0.25 was used for kl as some of the share width was thought to be accounted for already by the tip failure. A value of 1.7 was used as the power term for the velocity effect, this would normally be 2 or a squared term for inertia but as the soil may not all be travelling at the same speed across the mouldboard body 1.7 gave a better empirical fit. A value of 2 was used for m, the height at which the soil was lifted for the potential energy term.

7.1.3.1 Prediction Equations

Having broken the horizontal force components of the mouldboard plough assembly down into these small and localised parts it is possible to apply an equation to each section.

7.1.3.2 Cutting Forces of the Tip and Share

The prediction methodology for the cutting section was based on the theoretical force prediction models of Godwin *et al.*, (1984) divided into the point and the share. This assumes a force generated by a 3-dimensional crescent failure about the point and a force from a 2-dimensional passive failure occurring from the share as used by Seig, (1982).

The dual equation used by Seig follows the form shown below Equation 7.1, where D is the total horizontal (draught) force of the plough cutting force, tip and wing. The constants in Table 7-1 do not apply to Seig's equation.

$$\begin{aligned}
 D = & \left[(\gamma d_T^2 N_{\gamma T} + c d_T N_{c a T}) \times W_T \left(\frac{m d_T \sin \rho}{2} \right) \times \sin(\alpha_T + \delta) \right. \\
 & + c_a W_T d_T \times (N_{a T} \sin(\alpha_T + \delta) + \cos \alpha_T) \left. \right] \sin \omega + \\
 & \left[(\gamma d_W^2 N_{\gamma W} + c d_W N_{c a W}) \times (K W_W) \times (\cos(90 - \alpha_W - \delta) \times \sin \beta) \right]
 \end{aligned}$$

Equation 7.1

A velocity factor was added to this initial equation based upon the work of McKyes, (1985) as used by Wheeler and Godwin, (1996). This was added separately to the tip and the wing so as to apply the correct dimensions to the variable depth (d). The top

line of the velocity factor in Equation 7.2, is divided through by the acceleration due to gravity, (g) to get the correct units.

$$\left(\frac{\gamma^2 N_a d}{g} \right)$$

Equation 7.2

Therefore, the formula used to predict the soil cutting effect of the plough point takes the form, Equation 7.3.

$$Hp = \left\{ \left[\left(\gamma d_T^2 N_{\gamma T} + c d_T N_{cT} \right) \left(w_T + Ko^* d_T \left(m - \frac{1}{3}(m-1) \right) \right) \right] + \left[\left(\frac{\gamma^2 N_a d_T}{g} \right) \left(w_T + Ko^* 0.6 d_T \right) \right] \right\} \sin(a_T + \delta)$$

Equation 7.3

As can be seen the $\frac{m d_T \sin \rho}{2}$ in Equation 7.1 has been replaced by $\left(m - \frac{1}{3}(m-1) \right)$ in Equation 7.3. This simplifies the crescent effect calculation but gives a sufficiently accurate prediction.

The formula used to predict the share force is added to complete the cutting section. Equation 7.4.

$$Hs = \left\{ \left[\left(\gamma d_W^2 N_{\gamma W} + c d_W N_{cW} \right) + \left[\frac{\gamma^2 N_a d_W}{g} \right] \right] \cdot (W_W - kl^* d_W) \right\} \cdot \sin(a_W + \delta)$$

Equation 7.4

Where N_a in both Equation 7.3 and Equation 7.4 above is calculated using the following Equation 7.5

$$N_a = \frac{\tan \beta + \cot(\beta + \phi)}{(\cos(\alpha + \delta) + \sin(\alpha + \delta) \cot(\beta + \phi)) \cdot (1 + \tan \beta \cot \alpha)}$$

Equation 7.5

$$\text{Where } \beta = \arctan\left(\frac{1}{m - \cot \alpha}\right)$$

Equation 7.6

7.1.3.3 Turning and Lifting Force

The soil turning can be separated into the energy required to lift, accelerate and move the soil over the shape of the mouldboard, changing its rate of momentum. This can be expressed as potential energy, which is independent of velocity. In addition, the momentum change effect of the soil flowing over the mouldboard is dependent on the velocity; there is also the frictional and adhesive effect of the soil moving over the mouldboard. The angle of the mouldboard θ was considered constant at an angle equivalent to the angle along an imaginary horizontal line on the mouldboard, as shown in Figure 7.1. The formula for the momentum component of horizontal force acting on the mouldboard is given by Equation 7.7

$$Hmc = \left(\frac{\gamma}{g}\right) \cdot (W_T d_T + W_W d_W) V^n (1 - (1 - \sin \theta \cdot \tan \delta) \cos \theta)$$

Equation 7.7

For the purpose of potential energy it was found that a soil lift height of twice the depth of the soil slice gave the best relationship to the measured values. This constant then links the relationship between depth of work of the mouldboard assembly and the lift height of the soil slice.

$$He = \gamma.(d_T w_T + d_w w_W).(md_W)$$

Equation 7.8

7.1.3.4 Landside Drag Force

This can be separated into point/share and mouldboard, considering the horizontal force occurring from the frictional component of the side force applied by each of these parts of the plough. The point and the share produce a side force during the cutting of the soil slice, which is transmitted as force through the landside. Additionally, as the mouldboard is turning the soil slice there is a side force involved due to the approach angle of the mouldboard, which is also transmitted to the landside. The combination of these forces creates a frictional resistance due to the interface friction between the plough landside and the soil.

The horizontal force resulting from the landside drag is due to the side force generated by the cutting action of the wing given by Equation 7.9.

$$Hcs = \left[\left\{ \left(\gamma d_W^2 N_{\gamma W} + c d_W N_{cW} \right) + \left[\frac{\gamma'' N_a d_W}{g} \right] \right\} \cdot (W_W - k l d_W) \right\} \cdot \sin(a_W + \delta) \cdot (\cos \beta) \cdot \tan \delta$$

Equation 7.9

Likewise, the horizontal landside force is also contributed to by the side force generated from the soil flowing over the mouldboard is given by Equation 7.10.

$$Hms = \left(\frac{\gamma}{g} \right) \cdot ((W_T d_T + W_W d_W) \cdot V'' \cdot \sin \theta (1 - \sin \theta \tan \delta) \cdot \tan \delta$$

Equation 7.10

These forces act upon the landside, from which the resistance to direction of travel is generated as a result of the soil/metal friction coefficient ($\tan \delta$), which produces the horizontal landside force.

$$Hl = (Hcs + Hms) \tan \delta$$

Equation 7.11

7.1.3.5 Total Draught Force

The total predicted horizontal force (H_t) is the vector sum of all the individual components as given in Equation 7.3 to Equation 7.11.

$$H_t = H_p + H_s + H_{mc} + H_e + H_l$$

Equation 7.12

7.2 Experimental Procedure & Equipment

The predicted forces from the model were compared to the results of preliminary laboratory studies where the effect of width, depth and speed on the horizontal (draught) forces of a general purpose mouldboard assembly (Kverneland No 8) were recorded in controlled soil conditions of known Mohr-Coulomb properties.

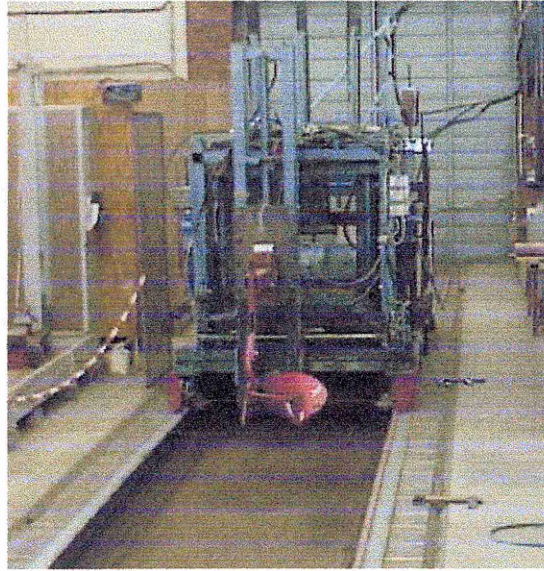


Figure 7.6, Indoor Soil Bin Facility

Soil bin studies were conducted to determine the forces acting on a modern general-purpose/semi-digger mouldboard assembly for the width depth and speed combinations shown in Table 7-2. The assembly consisted of the plough point, a share, a landside and the mouldboard. The experiments were carried out under controlled laboratory conditions, in a sandy loam soil of known properties, using the indoor soil bin facility at Cranfield University, Silsoe similar to that reported by Godwin, *et al.*, 1984. Figure 7.6, shows the indoor soil bin.

A soil particle analysis gave 68.1% sand, 22.1% silt and 9.8% clay; this soil can be prepared to a controlled moisture and density to give a repeatable test environment. The plough assembly was fitted to the processor unit via a 2-dimensional extended octagonal ring transducer Godwin, (1975) used to measure the horizontal force, the vertical force and the resulting moment of the total mouldboard assembly.

Width (mm)	Depth (mm)	Speed (km/h)
508	125	4.5
508	225	4.5
508	125	10
508	225	10
355	125	4.5
355	225	4.5
355	125	10
355	225	10

Table 7-2. Width, Depth and Speed Combinations used in the Laboratory Study

A second and smaller 2-dimensional extended octagonal ring transducer was attached to the back of the mouldboard to measure the horizontal and lateral forces, Figure 7.7. The lateral mouldboard force was selected because it was expected to have a more significant effect on the landside force as the depth of work increased Girma, (1989). The mouldboard was held slightly above its normal mounting position so that all its forces were transmitted through the octagonal ring.

To enable this to be achieved a mounting bracket was made up to hold the small octagonal ring transducer independently on the plough leg and enable the mouldboard to be located in the correct position. Spacers were added to the other components of the assembly to ensure that all sections lined up and the soil flow was not disturbed. The force transducers were linked to a signal conditioning and data logging unit via strain gauge amplifiers and the forces were recorded at 103 Hz to avoid aliasing errors.



Figure 7.7, Small EORT for Mouldboard Measurement

The dry base soil moisture content and bulk unit weight were measured for each laboratory test and the Mohr-Coulomb properties were measured using triaxial apparatus to determine the angle of soil internal shearing resistance (ϕ) and cohesion (c). A sliding frictional plate was used to determine the angle of soil/metal friction (δ) and adhesion (c_a). The results of the laboratory test can be found in Appendix 5.1 and 5.3, but are summarised in Table 7-3.

Measured Property	Value
Moisture Content (mc)	9.25 %
Bulk Unit Weight (γ)	1.56 kN/m ³
Cohesion (c)	10.54 kN/m ²
Soil internal shearing resistance (ϕ)	30.75°
Soil/metal friction (δ)	24°
Adhesion (c_a)	Negligible (Assumed Zero)

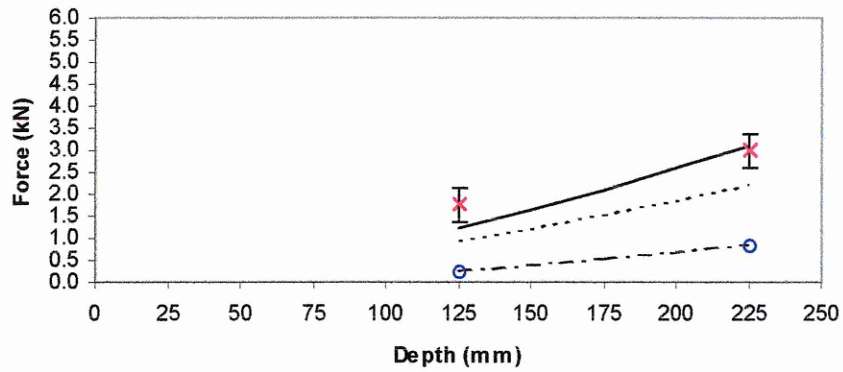
Table 7-3. Soil Physical Properties

7.2.1 *Results*

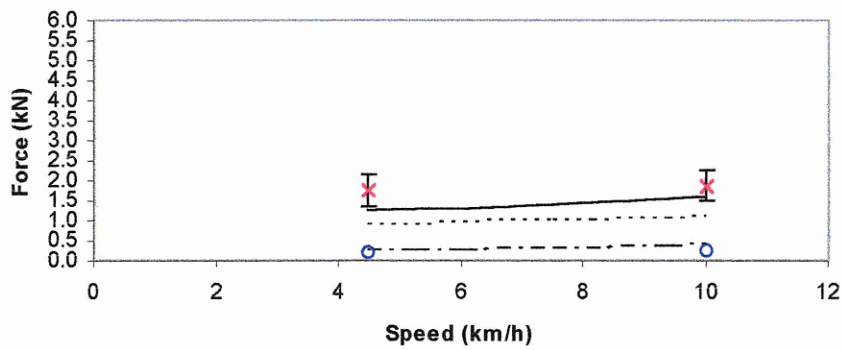
Once the measured values for horizontal force had been obtained, it was possible to compare the experimental values with those of the prediction model.

The first three graphs in Figure 7.8 show the measured and predicted horizontal forces for both the complete mouldboard assembly and the mouldboard independently. These are for mouldboard configurations shallow (125mm), slow (4.5km/h) and narrow (355mm). All the other combinations of the mouldboard variables can be seen compared with the predicted values of horizontal force in Figure 7.9 to Figure 7.11.

355 mm (14 ") Furrow at 4.5 km/h
Three Main Predicted Sections Vs Measured



355 mm (14 ") Furrow, 125 mm Deep
Three Main Predicted Sections Vs Measured



125mm Depth at 4.5 km/h over Two Furrow Widths

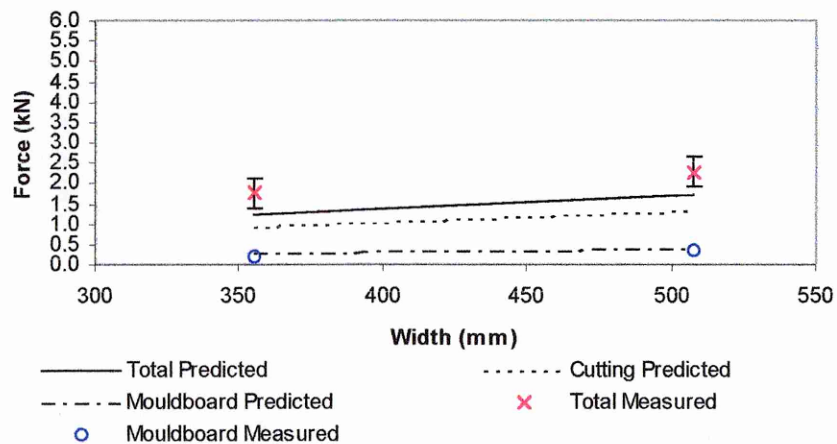
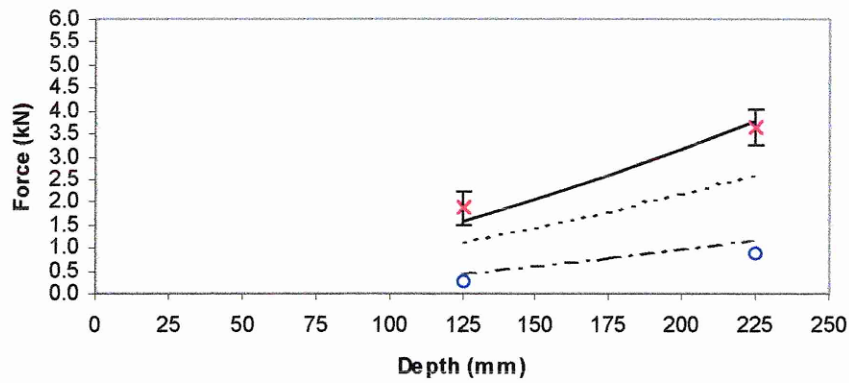
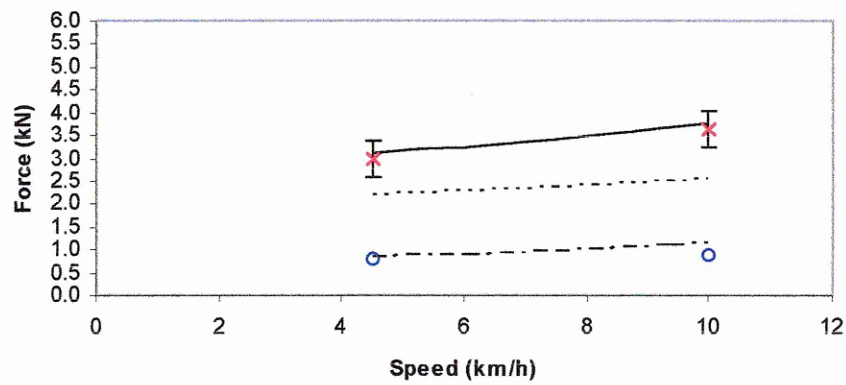


Figure 7.8, Depth, Width and Speed Relationships

**355 (mm) 14" Furrow at 10 km/h
Three Main Predicted Sections Vs Measured**



**355 mm (14") Furrow, 225 mm Deep
Three Main Predicted Sections Vs Measured**



225mm Depth at 4.5 km/h over Two Furrow Widths

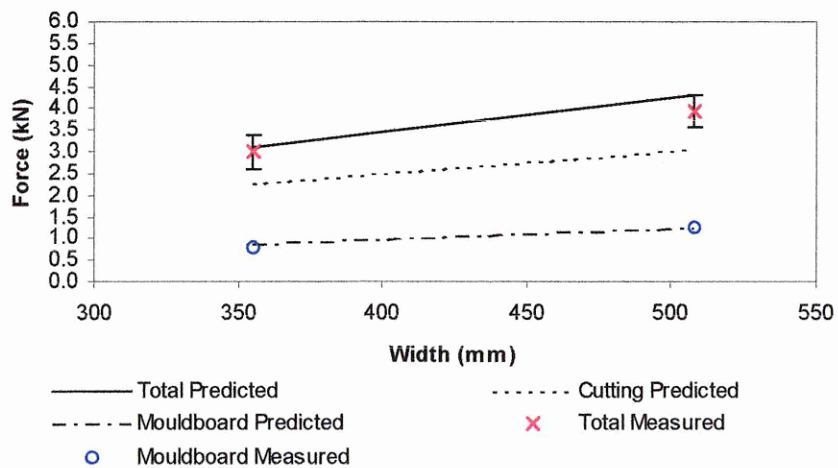
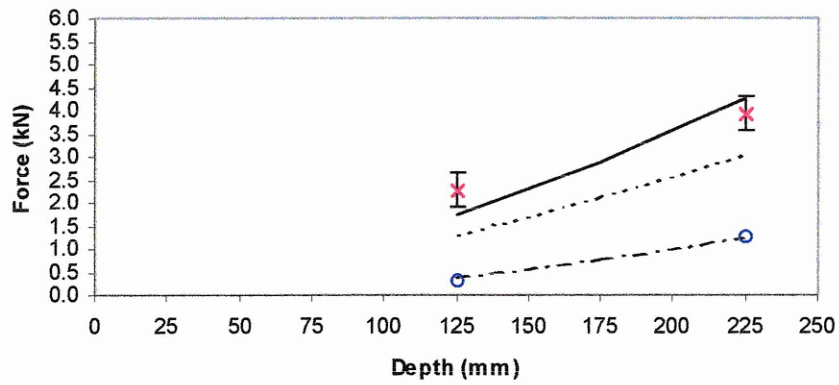
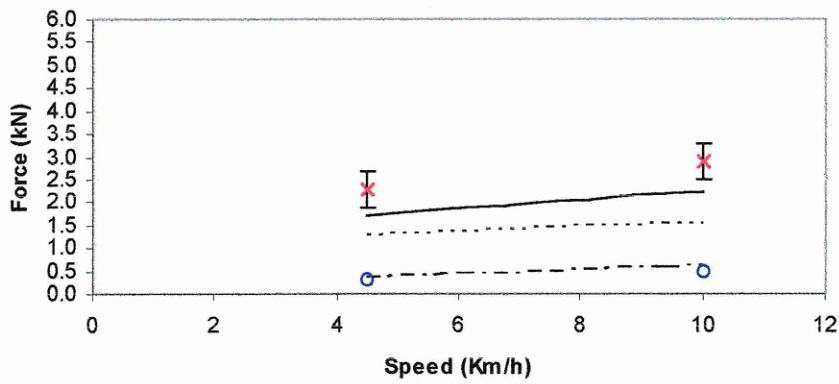


Figure 7.9, Depth, Width and Speed Relationships

**508 mm (20 ") Furrow at 4.5 km/h
Three Main Predicted Sections Vs Measured**



**508 mm (20") Furrow, 125 mm Deep
Three Main Predicted Sections Vs Measured**



125mm Depth at 10 km/h over Two Furrow Width

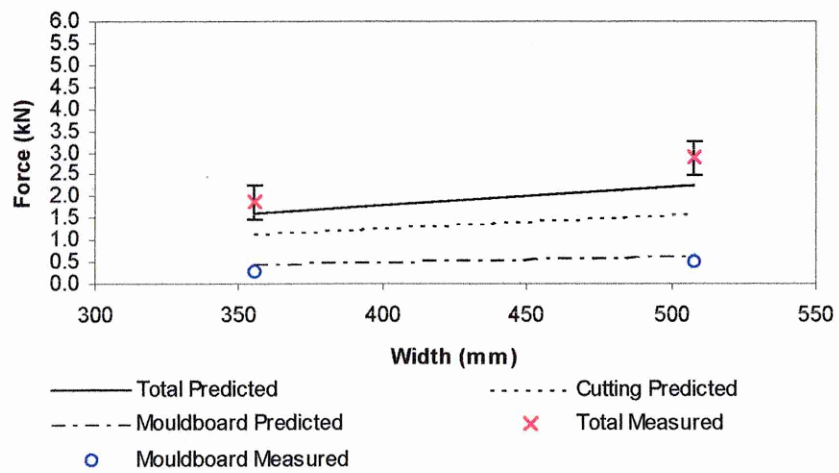
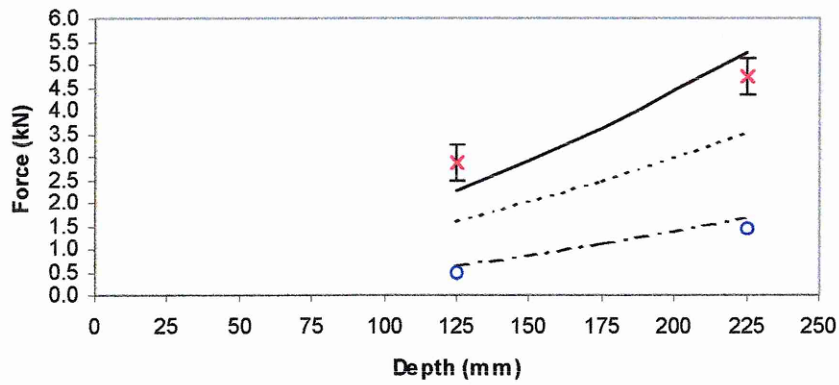
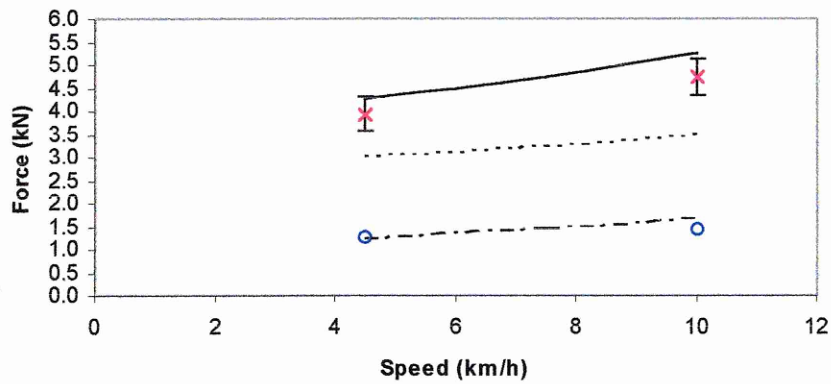


Figure 7.10, Depth, Speed and Width Relationships

508 mm (20 ") Furrow at 10 km/h
Three Main Predicted Sections Vs Measured



508 mm (20") Furrow, 225 mm Deep
Three Main Predicted Sections Vs Measured



225mm Depth at 10 km/h over Two Furrow Widths

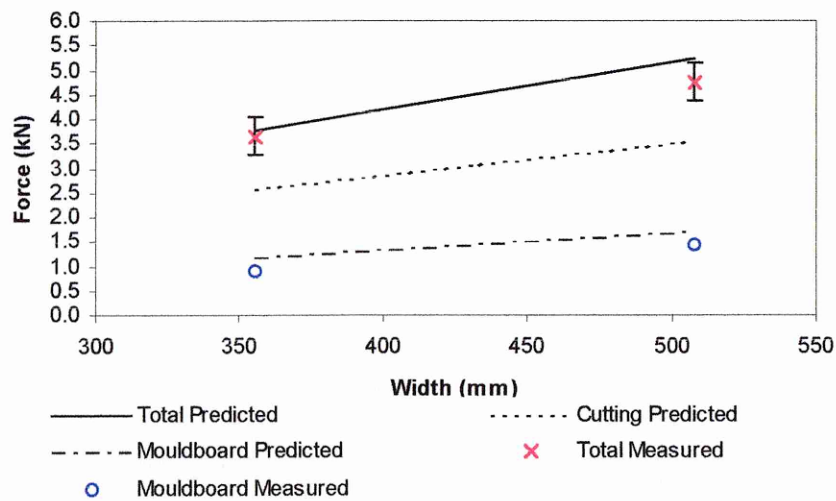


Figure 7.11, Depth, Speed and Width Relationships

An alternative method of displaying this data that shows up some valuable points is to look at the main effect on draught, this can be done for all three variables, width, depth and speed, see Figure 7.12

Effect of different variables on draught force change

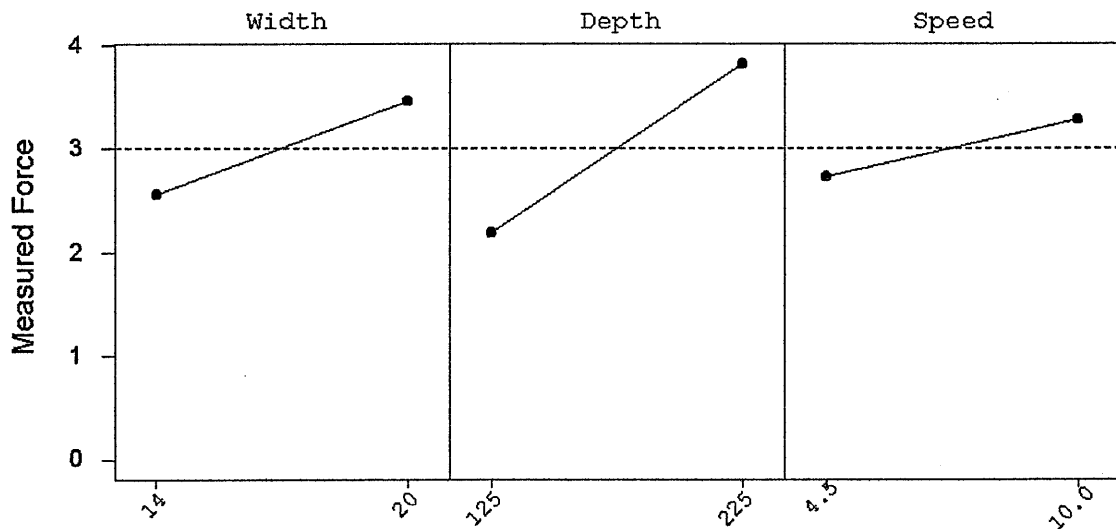


Figure 7.12, Main Effect Graphs for Total Mouldboard Assembly

These three graphs show the difference between the two values of each variable, and it can be seen that the depth of operation has the greatest effect on the measured draught force. Width has less effect and speed has the least effect on the horizontal force of the complete mouldboard assembly. The effects of the variables can then be looked at for the horizontal mouldboard forces individually and displayed in the same way.

Main Effects Plot - Data Means for Mouldboard Measured Forces

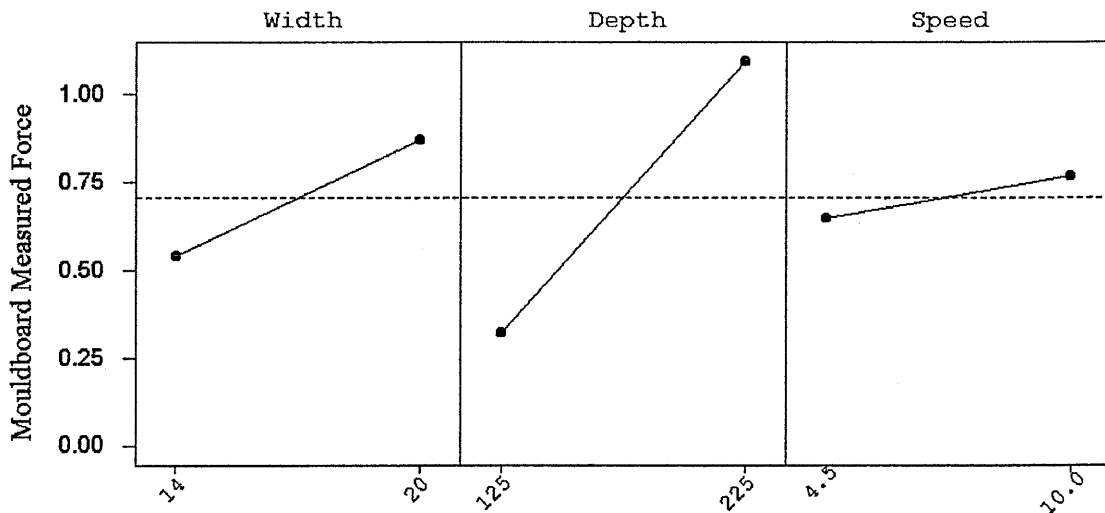


Figure 7.13, Main Effects Graphs for the Mouldboard Individually

These again show that the depth of work has the greatest effect on the horizontal force.

Regression plots can be used for the whole tip, share and mouldboard assembly, and the mouldboard assembly individually, to determine how well the predicted data fits that of the measured values. Figure 7.14 shows the regression plot for the total measured and predicted forces, whereas Figure 7.15 highlights the mouldboard forces independently. In both cases the agreement is excellent with values of the coefficient of variation (R^2) of 0.967 for the whole assembly and 0.950 for the mouldboard.

Analysis of variance statistical tests were carried out on the measured soil bin results and the summary tables can be seen in Appendix 5.6.

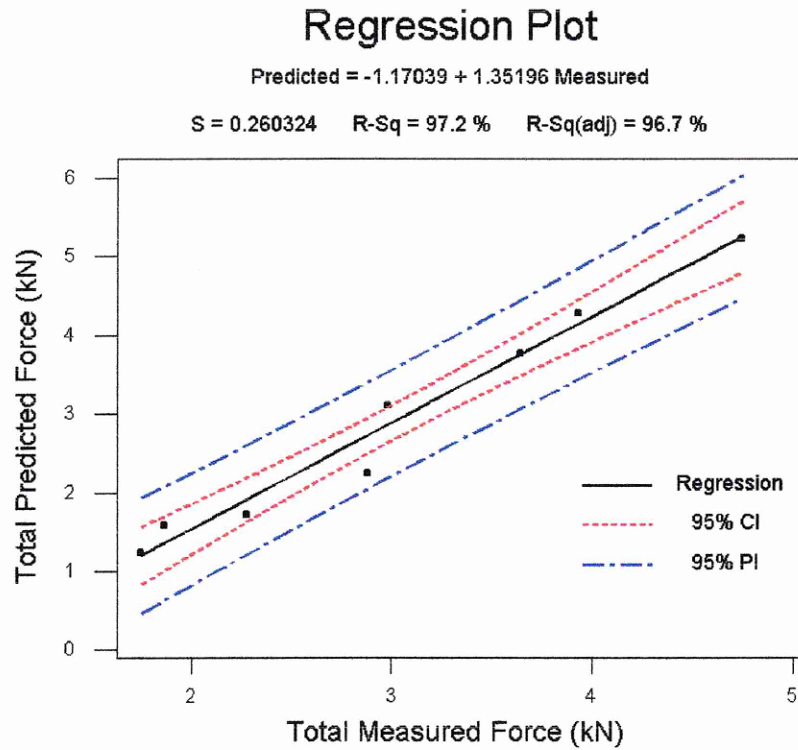


Figure 7.14, Regression Plot of Total Tip, Share and Mouldboard Forces, Measured Vs Predicted

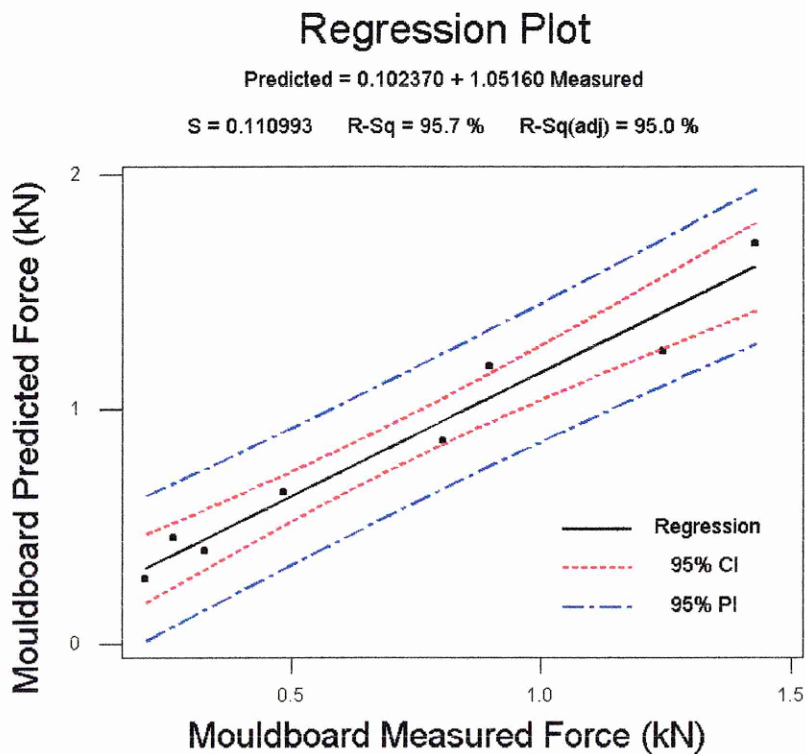


Figure 7.15, Independent Mouldboard Forces, Measured Vs Predicted

7.2.2 Summary

The combinations of width, depth and speed used in the experiments are given in Table 7-2; the results of the work are presented in Figure 7.8 through Figure 7.11, together with the predicted values. The least significant difference (l.s.d) at 95% confidence level is also shown for the complete measured data set (0.38kN) for which the coefficient of variation was 7.4%.

Figure 7.8 to Figure 7.11, show the increase in draught force for the total assembly and for the mouldboard individually with the increase in working depth. As was expected the draught force increased with the depth of work. This was true for both the measured and the predicted values.

These Figures also show the effect of speed on the draught force of the mouldboard assembly; the draught force increase due to speed had the smallest effect with as little as 7% increase for the narrow-shallow setting, and 26% increase for the wide-shallow configuration.

1. The force prediction based upon Mohr-Coulomb soil theory and inertia effects was developed from the three principal fundamental aspects of cutting, turning and drag; in order to predict both the total and the mouldboard force acting upon a general-purpose mouldboard assembly.
2. When compared to experimental measurements for a range of working widths, depths and speeds the model predicts total draught force within the range 29.6 % (under prediction) to 10.4 % (over prediction) with an average error of 7.4 %. The model over-predicted values of horizontal force at higher speeds and larger depths, but under-predicted at lower speeds and shallower depths.
3. Depth had the greatest overall effect on the measured total draught force, increasing by 65% to 95% over the range used. The increase due to width was the next largest effect ranging from 23% to 30% over the depth range. The draught force increase due to speed was the least with only a 7% increase over the speed range.

7.3 Skimmer Force Prediction

7.3.1 Aim

To develop a method of predicting the forces on the plough skimmer, based on the prediction used for the mouldboard assembly. With the addition of experimental studies this would result in information on the direction and magnitude of the forces acting upon a relatively unstudied part of the plough.

7.3.2 Introduction

The modern skimmer as fitted to the mouldboard plough has taken shape as much by accident as by design. There has been very little if any research into the forces required by the skimmer for its current shape and design. Together with experimental work carried out under the controlled conditions of the soil bin, it was considered that the previously developed mouldboard prediction model could be used to model the forces required by the skimmer. It can be looked at as a scaled-down mouldboard and, therefore, the soil handling and resulting forces were thought to be generated in a similar way to those of a full-sized mouldboard.

The prediction model used for the mouldboard assembly was thought to be expandable and flexible enough that the variables of the skimmer could be accommodated without the ingress of significant error.

Predicting and understanding the forces acting upon the skimmer would help to determine if its current location and configuration is the best and whether optimum performance is being achieved. This can be examined over the full working range of the skimmer, which is the same as that for the plough to which it is fitted.

7.3.3 Procedure

As for the mouldboard an understanding of how the skimmer interacts with the soil was needed to be able to predict the forces involved. Due to the shape of the skimmer at its mounting position in relation to the mouldboard, the widths and angles of cutting change when the approach angle is changed. Likewise the rake angle changes with a change in approach angle, as well as any change in rake angle introduced for experimental purposes.

As the skimmer was set on the soil bin processor to be rotated through 30 degrees in each plane there were quite large changes in the section of skimmer that was interacting with the soil. The depth of the skimmer was kept constant through the experimental procedure so that the changes in soil cutting due to rake and approach angles had to be considered for prediction purposes.

To help understand at what angles the skimmer would be interacting with the soil in the experiments, a 3-dimensional wire frame model was constructed using a computer drawing package. This enables the skimmer to be rotated in the planes of rake and approach as it was in the practical experiments. The skimmer could then be viewed from the front and the side, enabling the width of cut and the rake angle to be determined for each configuration.

Figure 7.16, shows the whole set of various skimmer configurations. The skimmer in the centre of the diagram is set to normal rake and approach angles. All skimmers to the right have a decreased approach angle and skimmers to the left have an increased approach angle. The skimmers above the centre have increased rake angles and the ones below the centre have reduced rake angles. From these drawings a table of depths, widths and angles could be produced, which was then used for the purpose of calculation. These can be seen in Table 7-4.

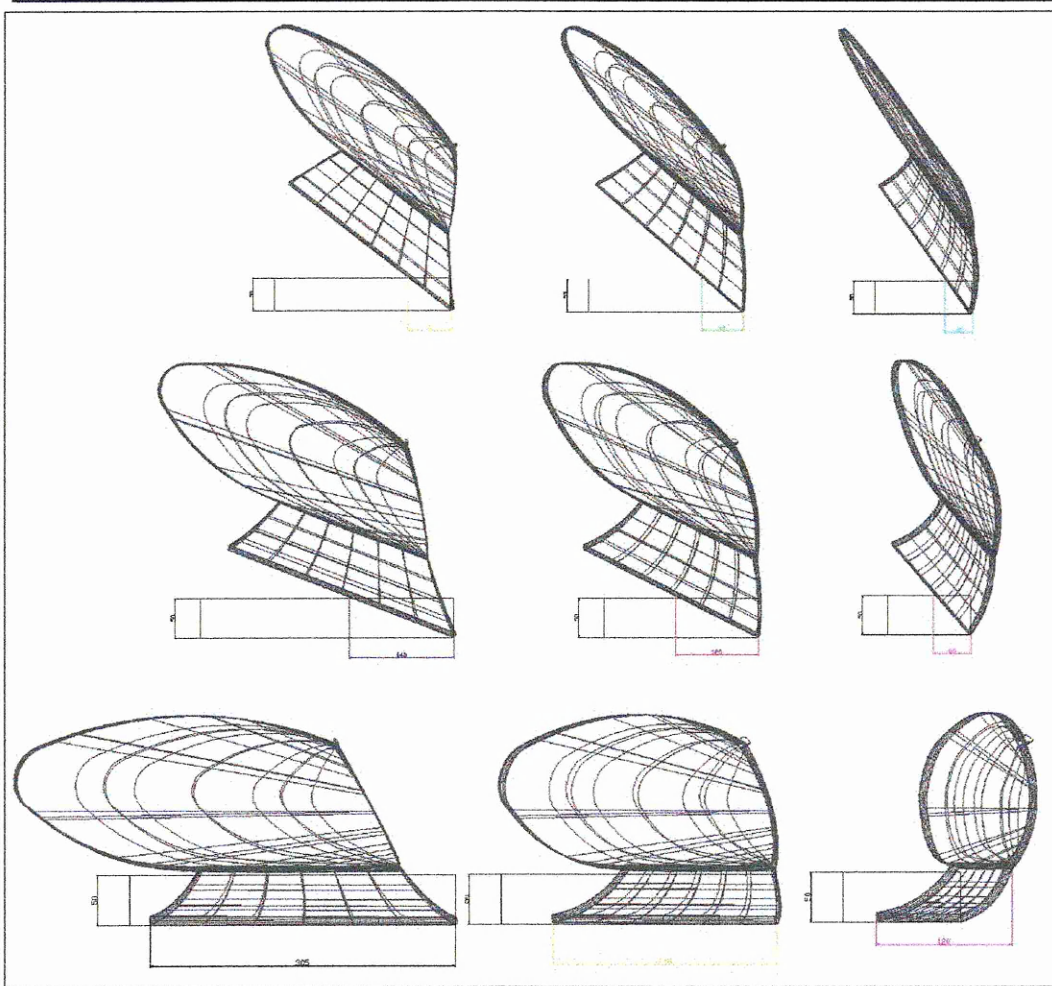


Figure 7.16, All Skimmer Variations used for Experimental Tests

<u>Skimmer Rake Angle and Approach Angle</u>					
Depth (mm)	Rake Angle α	Calculation Value (Degree's)	Approach Angle θ	Calculation Value (Degree's)	Width of cut (mm)
50	Normal	45	Normal	50	120
50	Reduced	15	Normal	45	240
50	Increased	75	Normal	67	65
50	Normal	51	Decreased	20	60
50	Normal	51	Increased	80	140
50	Increased	75	Decreased	38	45
50	Increased	80	Increased	90	70
50	Reduced	18	Decreased	15	120
50	Reduced	25	Increased	75	305

Table 7-4, Skimmer Rake and Approach Angles Used for Calculation Purposes

7.3.3.1 Skimmer Calculations

As with the mouldboard prediction there was considered to be both soil cutting and soil throwing forces. Unlike the mouldboard prediction, the cutting was considered as a single component just using the 3-dimensional cutting section of the horizontal force equation and the soil throw was taken as the soil moving along the skimmer body and included some potential energy.

The equations for the skimmer prediction are as follows:

Soil Cutting

$$Hc = \left\{ \left(\left[d_T^2 N_{\mathcal{T}} + c d_T N_{cT} \right] \left[w_T + Ko^* d_T \left(m - \frac{1}{3} (m-1) \right) \right] \right) + \left(\left[\frac{w^n N_a d_T}{g} \right] \left[w_T + Ko^* 0.6 d_T \right] \right) \right\} \sin(a_T + \delta)$$

Equation 7.13

Where N_a in Equation 7.14

$$N_a = \frac{\tan \beta + \cot(\beta + \phi)}{(\cos(\alpha + \delta) + \sin(\alpha + \delta) \cot(\beta + \phi)) (1 + \tan \beta \cot \alpha)}$$

Equation 7.14

$$\text{Where } \beta = \arctan\left(\frac{1}{m - \cot \alpha}\right)$$

Equation 7.15

Soil Movement

$$Hmc = \left(\frac{\gamma}{g} \right) (W_T d_T + W_W d_W) V^n (1 - (1 - \sin \theta \cdot \tan \delta) \cos \theta)$$

Equation 7.16**Potential Energy**

$$He = \gamma (d_T w_T + d_w w_W) (m d_W)$$

Equation 7.17

Where all the variables in the equations for geometry and soil relate to the same parameters as those used for the mouldboard prediction. Table 7-5 shows the description of the variables.

<u>Force Components</u>		<u>Geometry & Soil Properties</u>	
Hc	= Horizontal Cutting Force	β	= Share Approach Angle
Hmc	= Horizontal soil moving Force	θ	= Mouldboard Angle
He	= Force due to Potential Energy	γ	= Bulk Unit Weight
N	= Dimensionless Number	c	= Cohesion
<u>Suffixes</u>		δ	= Angle of Soil/Metal Friction
γ = Gravitational		ϕ	= Angle of Internal Shearing Resistance
ca = Cohesive and Adhesive		m	= Rupture Distance Ratio
a = Inertial		V	= Velocity
q = Surcharge			

Table 7-5, Variable Used in Skimmer Prediction

As with the prediction of the mouldboard forces, constants were added to the formulae to enable better correlation between measured and predicted forces. These constants accounted for the more complex shape and behaviour of the mouldboard and were considered to be useful for the skimmer prediction. The constants were of different values than used in the mouldboard prediction and can be seen in Table 7-6.

Constants

Ko	= Reduction in Crescent Failure (1)	n	= Velocity Increase, Power Term (2)
		m	= Potential Energy Soil Lift Height (2)

Table 7-6, Prediction Constants Used for Skimmer Prediction

As the rake angles were to be changed for the different configurations of the skimmer all the values that relate to the rake angle in the prediction had to be changed for each different configuration. This included N_γ , N_c , N_{ca} and N_q . Tables of the N Curves can be seen in Appendix 5.9. As the m-value graph for experimental relationship

between rupture distance and tillage tool rake angle only went as low as 20° an interpretation of this was needed for skimmer settings with rake angles of less than 20° . The m -value affected the β value, which was used to calculate the N_a value for speed effects, this was crucial to the force calculation. It was considered that the m -value graph went to infinity at zero rake angles but this was found to give a value of β that approached zero, reaching it at zero rake angle. This gave rise to a N_a values being higher for rake angles less than 20° than for rake angles more than 20° .

Through careful study of the equations and the theory behind the m -value and the N_a equation, it was found that the best solution was to limit the β to 90 degrees or 1.5708 radians. Figure 7.17 shows how the rupture distance ratio is applied. With the limited value of β it meant that the value of N_a obtained from Equation 7.14 approached zero as the rake angle was reduced.

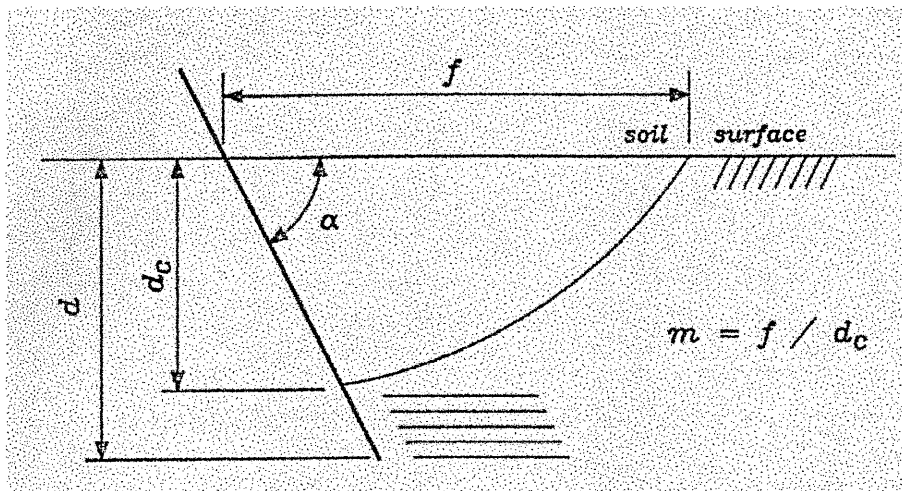


Figure 7.17, Rupture Distance Ratio

A table of the rake angles, m -values and associated β and N_a values can be seen in Appendix 5.5.

7.3.4 Results

Once the predicted forces had been calculated for all the possible skimmer configurations it was possible to compare them against the measured forces from soil bin experiments. Table 7-7 shows the mean measured forces from the soil bin experiments.

<u>Rake Angle</u>	<u>Approach Angle</u>	<u>Mean Horizontal Force (kN)</u>		
		<i>4.5 km/h</i>	<i>7.5 km/h</i>	<i>10 km/h</i>
Normal	Normal	0.2834	0.4225	0.3939
Reduced	Normal	0.5019	0.6115	0.8186
Increased	Normal	0.3674	0.5327	0.5544
Normal	Decreased	0.1732	0.2775	0.2744
Normal	Increased	0.4007	0.5393	0.6377
Increased	Decreased	0.2715	0.3733	0.3679
Increased	Increased	0.3935	0.7396	0.5531
Reduced	Decreased	0.5198	0.5209	0.6014
Reduced	Increased	1.2243	1.1821	1.4091

Table 7-7, Skimmer Configuration and Horizontal Forces

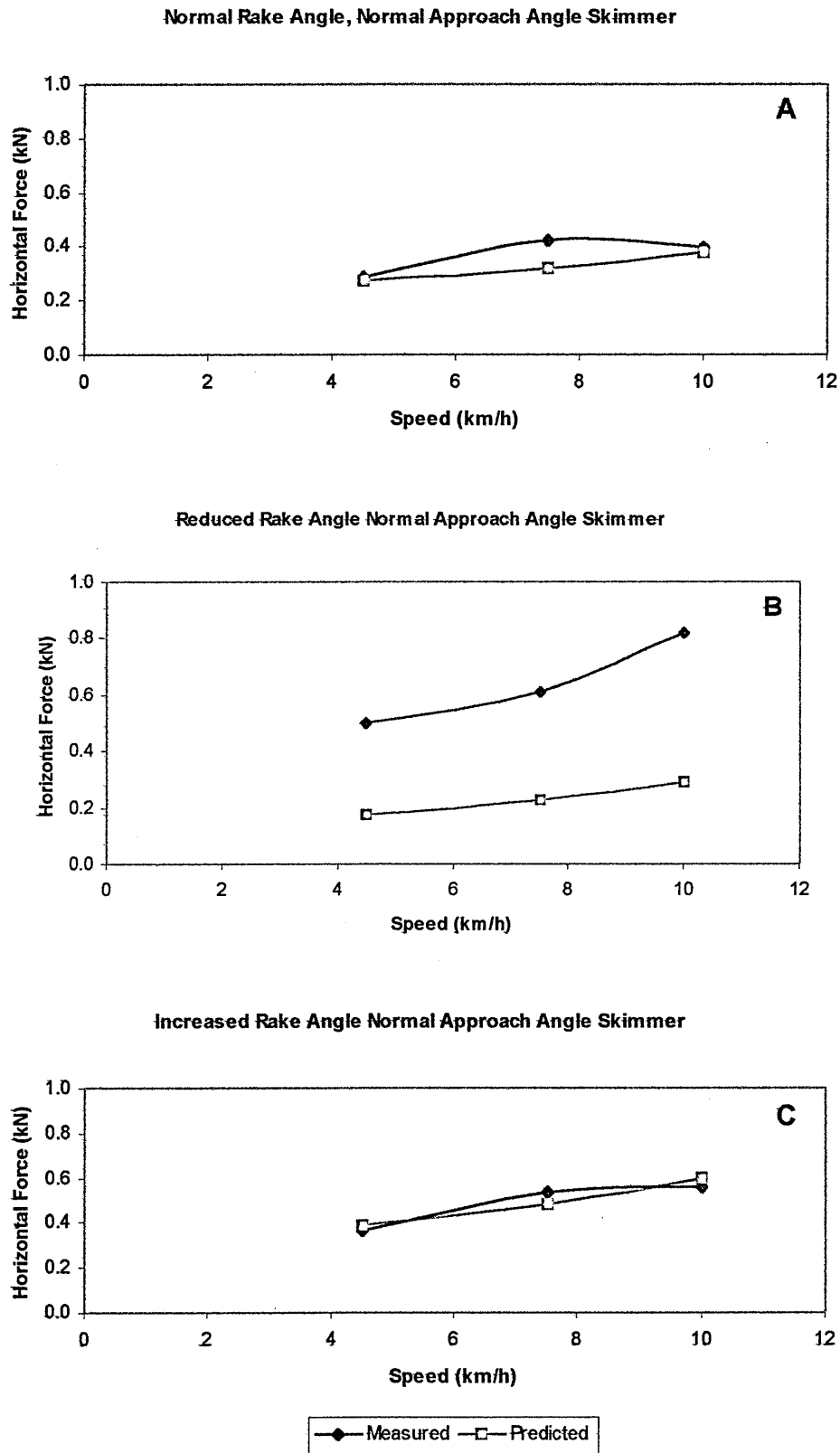


Figure 7.18, Horizontal Force, Three Skimmer Configurations

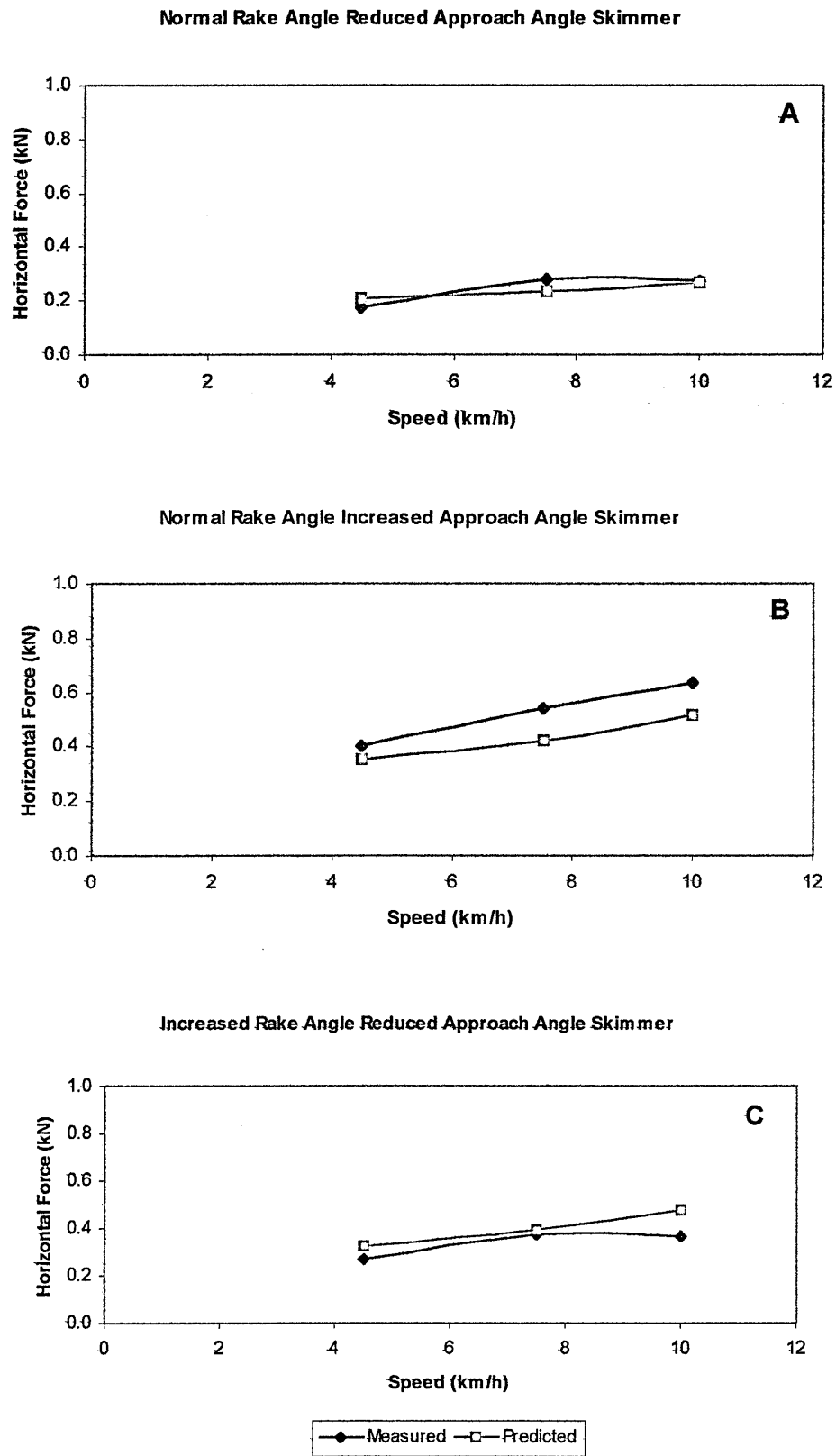


Figure 7.19, Horizontal Force, Three Skimmer Configurations

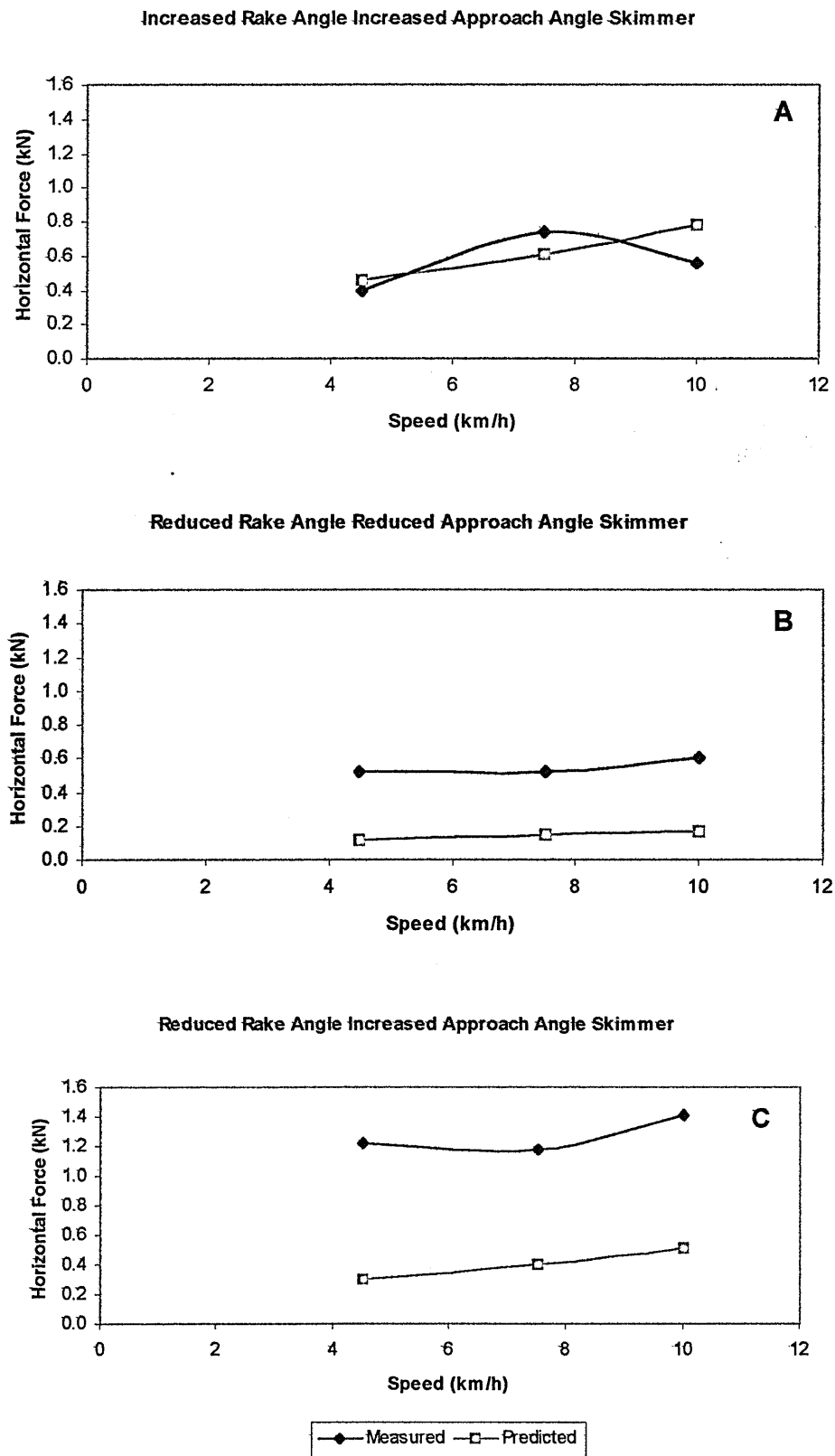


Figure 7.20, Horizontal Force, Three Skimmer Configurations

Analysis of variance was carried out on the measured soil bin results to determine the experimental errors. The statistical tables can be seen in appendix 5.8. Regression analysis was carried out on the measured and predicted forces as for the mouldboard prediction; this can be seen in Figure 7.21.

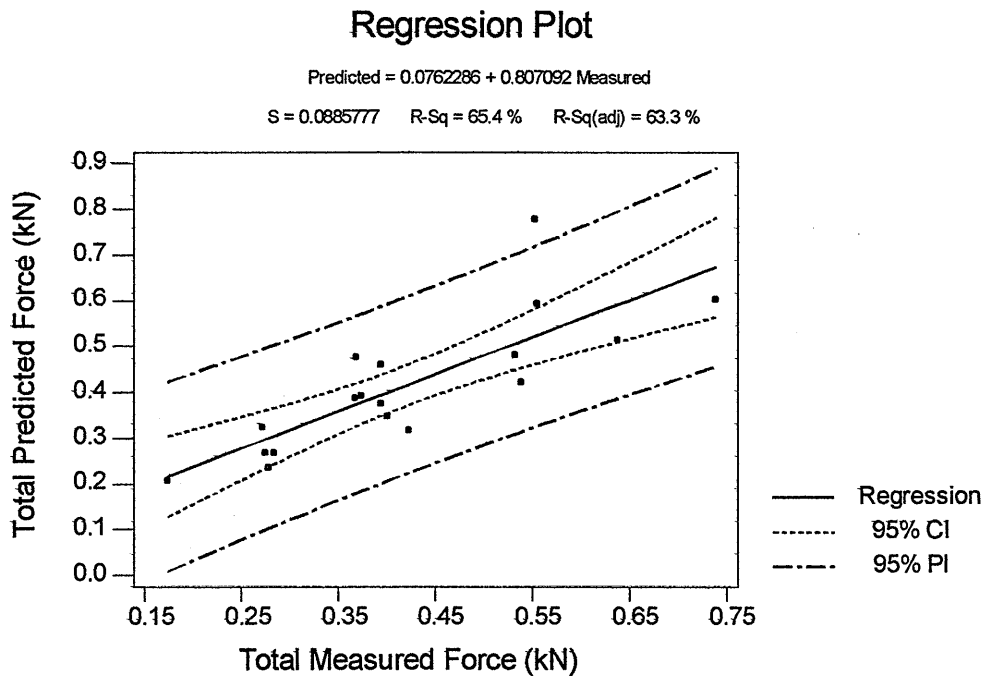


Figure 7.21, Regression Plot of the Skimmer Forces, Measured Vs Predicted

7.3.5 Summary

The combinations of rake angle and approach angle used in the experiment are shown in Table 7-7 along with mean measured horizontal force for the three speeds used. These results are presented graphically in Figure 7.18 through Figure 7.20

The predicted horizontal forces for the skimmer correlated with measured values for most of the variations. The areas where the force prediction did not correspond with the measured values can be seen in Figure 7.18 B, Figure 7.20 B and Figure 7.20 C. The main reasons for the inaccuracy of prediction are due to the large angles at which the skimmer was rotated during the experiments. These large angles were required to ensure that the skimmer was tested over its full range of possible working angles, but some adverse effects were encountered. When the skimmer was reduced in rake angle by 30° as seen in Figure 7.18 B, the clearance angle was removed from the cutting edge of the skimmer enough to cause some scrubbing effects. This means that the back of the skimmer was touching the soil after the cutting edge, these can be seen in the increase in measured horizontal force in Figure 7.18 B.

At present the prediction does not account for this increase in force due to scrubbing and therefore has under predicted the horizontal force in this case. Likewise when the skimmer rake and approach angles were reduced (Figure 7.20 B) the measured forces increased. The most increase in measured force was seen when the rake angle was reduced and the approach angle increased (Figure 7.20 C). This is mainly due to the area of skimmer scrubbing on the soil, as the force was not so high when the approach angle was reduced. The force was increased on the increased approach setting because of the increased width of scrubbing on the soil, this can be seen from the graphs which also highlight the prediction model does not account for these increases in horizontal force.

For the skimmer configurations where there is no scrubbing effect the skimmer prediction shows good correlation with the measured values. These range from 25% under predicting on the normal rake angle, normal approach angle to 41% over predicting on the increased rake angle, increased approach angle, with a mean difference of 1% across all the tests.

Being able to predict skimmer forces through a range of rake and approach angles, cutting widths and speeds could be useful. Not only to choose the most efficient skimmer configuration of currently available skimmers, but also help with new designs for skimmer shapes, whilst being able to calculate the effect of rake and approach angles changes.

CHAPTER 8 *PLOUGH ECONOMIC STUDIES*

8.1 *Aim*

To determine if the mouldboard plough is an economically viable option in the modern primary tillage machinery line up.

8.2 *Introduction*

The main concern of most modern farmers today is cost and he is interested in improving efficiency and effectiveness of machinery, especially those in high power requirement areas such as primary tillage. In the majority of cases there are ways to cut costs but they need highlighting and implementing.

If arable farming is considered as a prime example, this requires annual working of the land in some manner to produce a seedbed. This requires large amounts of money, as much as £306 per hectare Lang, (1999) to be spent on the inputs to establish the crop each year such as labour, machinery and fuel, with an additional £244 per ha on seed, fertilizer and chemicals. This is balanced against the returns made by the sale of the crop after harvested. With the following work it is the reduction of labour and machinery cost that will be considered.

Arable farming inputs have increased greatly over the last twenty years, with the ever-increasing prices of labour, fuel, and machinery along with the cost of land, fertilizer and chemicals. This has been accompanied with the inverse effect in the sale price of arable crop especially in the last five years, taking wheat as an example the price has dropped from over £120/tonne in 1995/96 to less than £70 in 2000/01. Over the same period of time there has also been no increase in the subsidies available to farmers.

This is especially when growing the standard crops such as wheat and barley, the money is available for more diverse crops that have lower yields and tend to be harder to grow, therefore needing higher time and machinery inputs or are a high risk to grow.

Putting these two facts together has led to a quite desperate situation among many farmers especially those solely dealing with an arable revenue business. For these businesses, it can be seen that a saving on inputs will have to be made in order for the farmer to sustain a viable business.

One of the major inputs in the cost of establishing an arable crop is the tillage or soil preparation, this is carried out in the same fundamental way as it was 40 years ago with a few small variations along the way. One of the major advances in technology has been the combination of the secondary cultivation with the seeding process (combination drills) this has in most cases eliminated the need for two individual passes with separate machines. Another advancement in technology has provided the minimum or no-till machinery that can plant the crop directly into many surface conditions in one pass.

The set back with both of these is that, with the advance in technology and benefits comes the increased price which farmers are finding difficult to afford with the current economic situation, this is especially true in the case of minimum or no till drill technology, which also have a tendency to be large and require high amounts of power.

The mouldboard plough is only one part of the complete tillage process that is required to prepare a seed bed for an arable crop but if it is considered as one of the more common primary tillage implements and a well regarded, especially in Northern Europe. Large sets of disc harrows are becoming more prevalent throughout the arable farming sector especially on large-scale units where the price of purchase can be spread over greater working areas. This is increasing the gap between the large and medium sized arable farms in terms of cost of production. If the work rate of the mouldboard plough can be increased, it would remain the preferred method of primary tillage for many of the smaller arable farmers, where root crops also exist regularly in

the rotation. If this increase in work rate can be achieved with little or no extra capital cost, it is one of many advantages that together would reposition the mouldboard plough into the farmers' armoury.

The advantages of a mouldboard plough over other methods of primary cultivation include the ability to produce a clean, trash free, level and aerated platform for a seedbed that requires little additional work. This includes the burial of weeds seeds and can reduce the need for one or two applications of herbicide during early crop establishment stages (ADAS Advisor, Crops 2000). Arguments suggest that the weed seeds stay dormant in the soil and are ploughed up in the following season.

If this is the case, there will still be more weed control than tillage regimes based on tine or disc implements as the research suggests that mouldboard ploughing controls 95% of weeds apposed to 48% and 5% for disc and tined implements respectively. If up to 40% of weeds seeds are ploughed back up adding to the 5% left uncontrolled by the plough, it is still less than the 52% uncontrolled by disc implements and 95% uncontrolled by tines, this was investigated by Kouwenhoven, (1992). In the case of disc and tined implements, annual herbicide has to be used to control the weeds but once again, the mouldboard plough was found to be better at controlling perennial weeds. There are two considerations with the use of herbicides, not only the cost but the environmental and political pressures.

Unpublished work from Cranfield University, Silsoe (1986) investigated the mouldboard plough working in different levels of straw residue situations, working at different depths and compared these to other primary tillage implements. Figure 8.1 shows the amount of residue cover after operations with various primary tillage implements. In addition to these trials experiments were taken through to yield and the results can be seen in Figure 8.2.

% Straw Cover - Gt Staughton September 1986

Treatment			% Straw Cover	
Straw Burnt, Shallow Disc/Tine (7-8cm)			20	
Straw Burnt, Shallow Plough (12-15cm)			4	
Shallow Disc/Tine (7-8cm)			47	
Deep Disc/Tine (15-17cm)			45	
Shallow Ploughing (12-15cm)	+ Skimmers	Premixed	15	
		Non-Premixed	18	
	+ Trash Boards	Premixed	20	
		Non-Premixed	23	
Deep Ploughing (20-22.5cm)	+ Skimmers	Premixed	10	
		Non-Premixed	11	
	+ Trash Boards	Premixed	16	
		Non-Premixed	18	
Overall Means				
Shallow Plough			*	19
Deep Plough			*	14
Tarsh Board			*	19
Skimmer			*	14
Premixed				16
Non-Premixed				17

* = Significant difference at the 0.05% Probability level

Figure 8.1, Residue Coverage using Different Tillage Implements

Operations	Winter Wheat yields (tonne/ha) at 85% Dm			
	Childerley		Gt Staughton	
	t/ha	%	t/ha	%
Straw burnt + Shallow Disc (80mm)	7.92	100	8.25	100
Straw burnt + Shallow Plough (150mm)	7.86	99	8.03	97
Straw burnt + Shallow Plough (150mm) + Roll			8.12	98
Shallow Disc (80mm)	7.13	90	8.18	99
Deep Disc and Tines (150mm)	7.17	90	8.16	99
Shallow Plough (150mm)	7.71	97	7.99	97
Shallow Plough (150mm) + Roll			8.19	99
Deep Plough (225mm)	7.93	100	7.99	97
Deep Plough (225mm) + Roll			8.2	99

Figure 8.2, Yield Variation with Various Tillage Operations

The conclusions from this work were that tine and disc harrow operations gave variable yield results, problems such as excessive volunteers, poor establishment in wet autumns and increase in grass weeds also occurred. Ploughing can give yields equal to that of burnt stubble situations and the depth of ploughing had little effect on

yield, therefore ploughing should be just deep enough to bury surface material without bringing up excessive raw sub-soil material.

There are two main ways of improving the output of a mouldboard plough, these are to increase the width of work or to increase the speed of work. The increase in width can be achieved in two ways; the first is to increase the number of furrows. This is a set width increase between one setting and another and is generally accompanied by a increase in tractor size to handle the extra physical size of the plough. This requires little technological change but the cost of an additional mouldboard assembly will be incurred, and possibly the pressure to increase tractor size. The second way to increase the width of work is to increase the furrow width; this is an adjustment that most plough manufacturers offer over a range of widths 312mm (12") to 508mm (20"). This furrow width adjustment can be manual or hydraulic and can be made on the move with the hydraulic option. This requires not additional components to increase the furrow width but the cost of technological advance is covered by the original plough capital cost.

The second way of increasing the output or work rate of a mouldboard plough is to increase the forward speed of operation, this can be done with any size of plough with no additional costs due to technology. There are many advantages of increased speed of operation when concerned with tillage activities, the result being an increase in drawbar power due to the following relationship.

$$\text{Drawbar Power} = \text{Drawbar Pull} \times \text{Speed.}$$

This allows for increased power availability without the addition of ballast to increase drawbar pull, giving better power utilization. Speed also has the least effect on forces, which is a benefit. There is also a reduction in the compacted soil density and the depth of compaction when increased forward speeds are used. This was shown by Witney, (1988) an increase in speed from 4.5 km/h to 12 km/h reduced the soil compacted density by 120kg/m³. As the average size of tractors increases, farmers will find themselves with more available power, as each tractor on a farm is renewed it will be replaced by a more powerful one. If this is not the case, the depth of ploughing

could be reduced to allow for an increase in forward speed as the effect of depth is far greater than speed on the required draught force.

The tenancy to plough deeper than necessary is occurring more often, partly due to the abundance of power as mentioned before, but also due to the size of plough mouldboards. Historically, due to power limits the depth of primary tillage operations such as ploughing was much less. It is possible in a high proportion of cases to reduce the depth of current ploughing practices to reduce the draught force on the implement and allow for increases in width and/or speed which both improve output.

8.3 Procedure

Given the two options of increasing the work rate of a plough analysis was conducted to determine the optimum combination of width and speed to give the highest work rate.

If power were unlimited, a large number of furrows working at the highest possible forward speed would give the maximum work rate. Figure 8.3 shows the work rate achieved with increasing furrow number and speed.

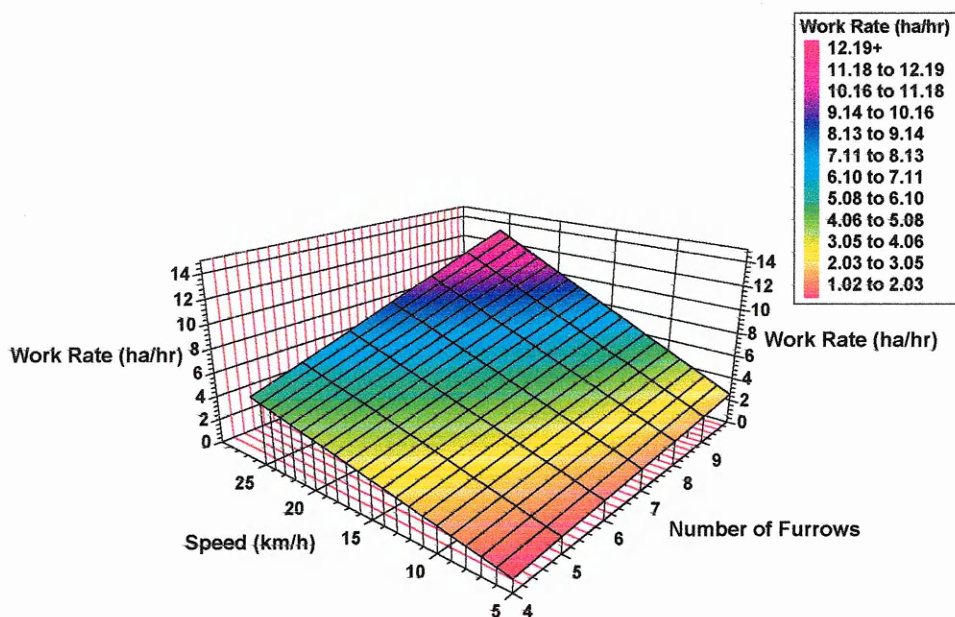


Figure 8.3, Unlimited Drawbar Pull & Drawbar Power, Work Rate Plot

If the same plough configurations are looked at in terms of the power required to achieve these work rates, it can be seen in Figure 8.4 that the power requirement would be very high. The graph reaches a maximum of approximately 500kW (670hp), which is currently unrealistic for an agricultural application.

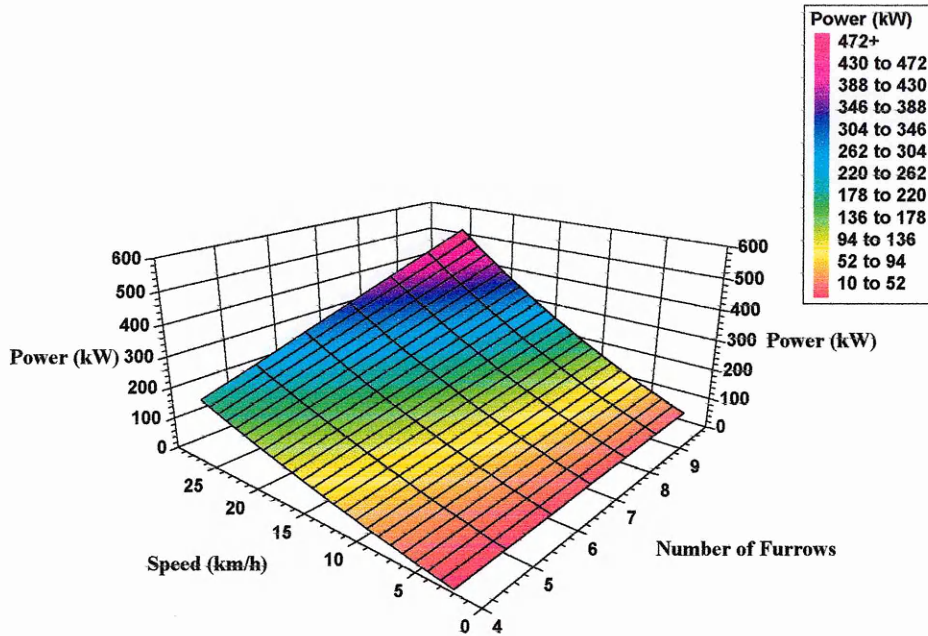


Figure 8.4, Unlimited Power Plot

Unlimited power is clearly not the case so some power limit has to be included. Tractor drawbar performance depends upon engine power, weight distribution on the drive wheels, hitch type and location and the soil surface condition. Wheel slip is a power loss but has an optimum value for the tractive efficiency ratio (TE) to be a maximum.

If a standard production tractor is taken as an example, the effects can be seen on the choice of plough configuration available. The two main limits to be considered for any given tractor are, firstly, drawbar pull, which is dependant upon the weight of the tractor or the Static Rear Axle Force (SRAF). The un-ballasted static weight of the MF 6180 was found to be 4845kg. This tractor was chosen because it is a popular and readily available 95kW tractor, and one that was actually used for some preliminary field experiments. As drawbar pull is dependant on many factors a method of determining a reasonable pull for a given tractor was needed. This was found in the

tractor drawbar performance predictor as used when carrying out the Nebraska OECD tractor tests Hunt (1995).

To be able to work the performance predictor there are a couple of assumptions that have to be made. Firstly the soil type on which the tractor is working and secondly the amount of slip that is expected or acceptable under its working conditions. Part of the performance predictor can be seen in Figure 8.5. This shows the drawbar pull divided by the Static Rear Axle Force (SRAF), plotted against the percentage wheel slip. The graph shows data for three different soil categories, these being Firm, Tilled and Soft or Sandy. Within these three soil categories there is also the type of implement that is being used as this effects the amount of force added to the rear axle of the tractor.

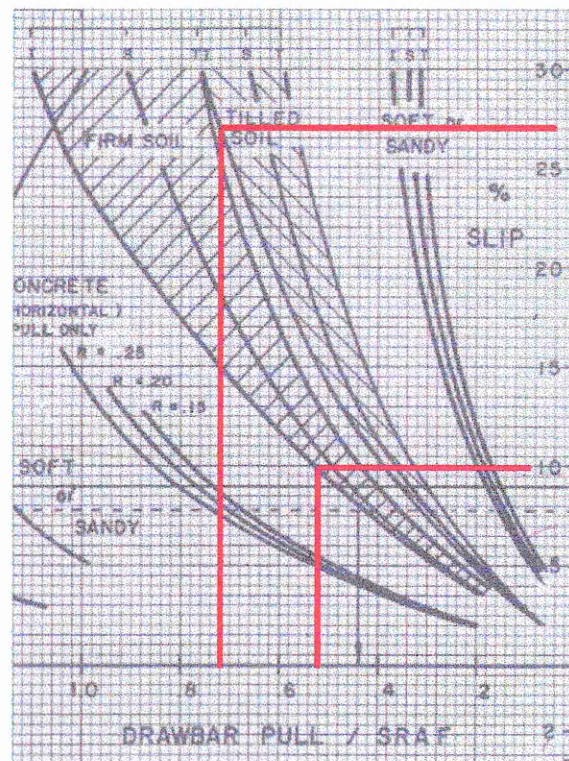


Figure 8.5, Tractor Drawbar Performance Predictor

To illustrate the example lines have been drawn on the graph to show a range of operating conditions. These being two different values of slip on two of the soil categories, both using an integrated or mounted implement. The red lines on the graph show one situation where the tractor is working at 10% slip on firm soil, giving a DB

Pull/SRAF of 0.52 and the second where the tractor is working at 27% slip on tilled soil, giving a DB Pull/SRAF of 0.72.

For the purpose of determining the limits of a tractor working over a range of conditions the mean of these two examples can be used giving a DB Pull/SRAF ratio of 0.62. This means that for a known SRAF the drawbar pull would be:

$$DBPull = SRAF * 0.62$$

Equation 8.1

The other limit of drawbar power which can be assumed to be approximately 60% of the PTO power of the tractor. Figure 8.6 shows the varying percentage of useful drawbar power depending upon the surface condition.

TABLE 2 SOIL CONDITIONS—POWER		
Condition Of Soil	Usable Drawbar Power As A Percentage Of Maximum PTO Power*	Ratio Of Maximum PTO Power To Usable Drawbar Power
Firm	67 Percent	1.5
Tilled	56 Percent	1.8
Soft or Sandy	48 Percent	2.1
*If tractor does not have a maximum PTO power rating, use an assumed rating equal to 86 percent of maximum engine power.		

Figure 8.6, Useful Drawbar Power as Percentage of PTO Power, John Deere (1981)

Applying these two limits to the MF6180 tractor enables the output of the mouldboard plough to be optimised. The MF6180 static mass is 4845kgs, which as it is a 4WD tractor can be related to 47.53 kN Static Axle Force. Using the formula above Equation 8.1 the maximum drawbar pull of the tractor would be 29.5 kN. The other limit of a tractor is the Drawbar Power, this as mentioned earlier is the combination of drawbar pull and the operating speed, but can also be estimated at 50 - 70% of the tractors PTO power.

The MF 6180 has 80.88 kW rated PTO power, and taking drawbar power as around 60% the limit of the MF 6180 is 48.53 kW. This gives the two limits for the tractor; from which it is possible to determine the range of possible plough combinations over which the tractor is capable of operating.

To enable the power to be calculated for a range of speeds in the field good estimations of field draught force were required. These were obtained by taking the field draught force data for 4.5 and 10 km/h speed as a basis and predicting the force at other speeds using the force/speed relationship obtained from soil bin studies.

From these estimated values it was possible to calculate the total pull and power at two different depths depending upon its number of furrows.

Figure 8.7, shows the possible plough configurations for the MF 6180 drawbar pull and drawbar power limits, based on a 508mm (20") furrow width working at 225 (9") deep. The plough sizes and speeds are now greatly reduced from the unlimited power graph, with only 3 and 4 furrow plough sizes available. These two plough combinations have less than 0.1ha/hr difference in total work rate, with the faster configuration slightly higher.

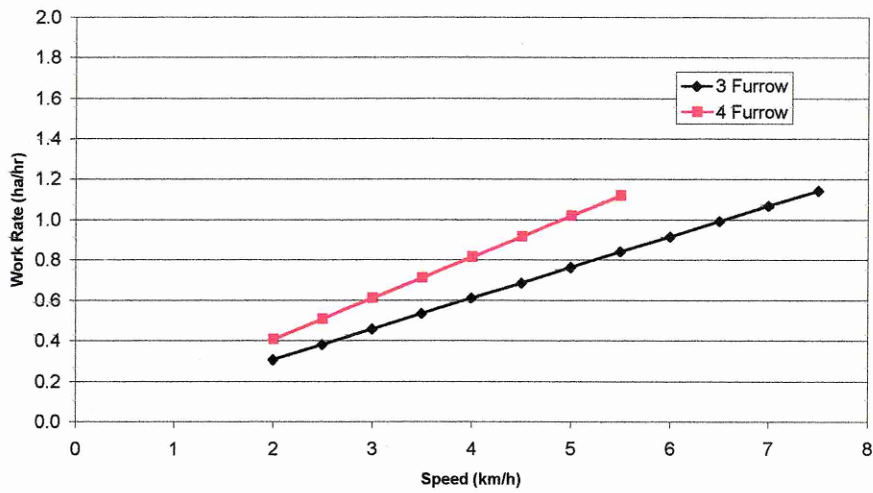


Figure 8.7, Work Rate Limits for a 508mm Furrow Width Plough, Working at 225mm Deep with the MF6180 drawbar Pull and Drawbar Power Limits

The effect of reducing the depth of the plough to 125mm (5") is shown in Figure 8.8, this shows that there are many more width and speed combinations that utilise the full pull and power capabilities of the tractor. Even though the combination with the highest work rate is 6 furrows at 6km/h, it can be seen that high work rates can be achieved with less furrows and high speeds.

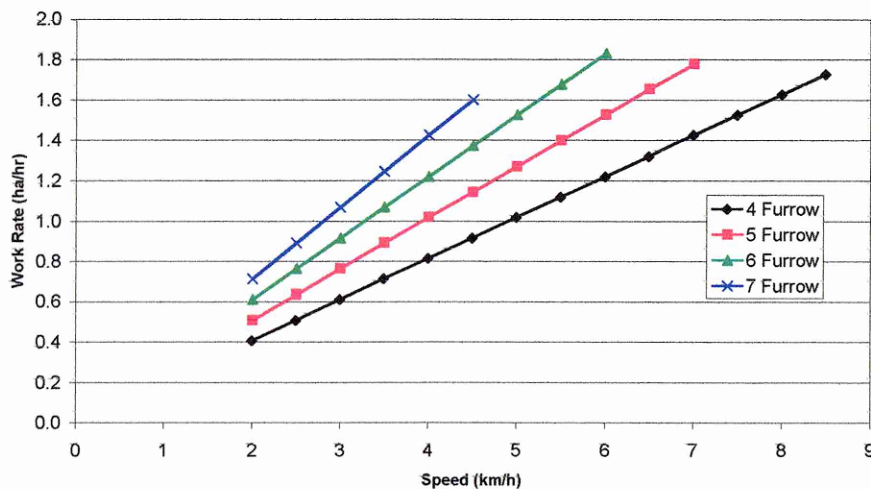


Figure 8.8, Work Rate Limits for a 508mm Furrow Width Plough, Working at 125mm Deep With the MF6180 Drawbar Pull and Drawbar Power limits

The difference in the work rates achievable from Figure 8.7 where the plough is working at 225mm deep and Figure 8.8 where the depth of work is reduced to 125mm again highlights the benefit in terms of work rate of shallow ploughing. It should be noted that the force required per furrow may change depending upon soil type and field conditions; hence the work rate values on the Y-axis may differ. This is also the case with tractor size, as the power available increases so the choice of plough combinations will increase and the total work rate for a given working window will be higher.

With only 0.2 ha/hr difference between the highest (0.182ha/hr) and the lowest (0.16ha/hr) work rates for the chosen tractor it can be seen that there is a choice of forward speed / furrow configurations that achieve the higher work rates. In order to help determine if a combination of many furrows working slowly or few furrows working at high speed is more beneficial to the farmer, the cost of each combination should be considered. Costing the different plough combinations will highlight the capital cost differences between adding additional furrows and simply increasing the speed of operation.

8.4 Tillage Machinery Costs

To investigate the economic viability of mouldboard ploughs working at greater mouldboard widths and faster speeds; the costs of the machinery system need to be compared.

There are two main areas to the input costs, these are fixed costs, which are dependent on the length of ownership of a machine and include: Depreciation, Interest, Tax and Insurance and Shelter or Storage. Secondly the running or variable costs that are involved, these vary in proportion to the utilisation of a machine and comprise of Fuel and Oil, Repairs and Maintenance and Labour.

As the area of land that is available to the farmer at a given point in time is constant, the system that is cheapest for the individual situation may be different depending upon the farmed area. For this reason it would be of advantage to determine the system that is able to complete the necessary tillage operation in the available time for the least cost.

In addition to these tillage system costs there are additional costs that have to be incurred as a result of choosing a certain type of tillage system. These include an increased application of herbicide to combat the unwanted weeds, or an extra amount of sub-soiling to alleviate compaction. These costs can soon lead to an increased overall spending on the cost of successful crop establishment and have to be considered in any tillage system choice.

The calculations of the tillage costs are then beneficial to plan finance and other outgoings. These calculations would also show if the current tillage system is the cheapest for the farming situation, therefore when machinery is up for renewal it would be possible to change the system to a cheaper one with a positive effect on the farms financial balance.

One of the most important factors in terms of the tillage situation is the number of days available; this can be very variable depending on the soil type and the month under consideration. Figure 8.9 (Witney 1988) shows the monthly field workdays for the months concerned with autumn tillage, for 18 out of 24 years in eastern Scotland for three soil types.

Month	<u>No. of field workdays</u>			Mean
	Light Soil	Medium Soil	Heavy Soil	
August	26	25	24	25
September	25	23	20	23
October	23	19	17	20
November	22	18	17	19
Total	96	85	78	87

Figure 8.9, Available Workdays Depending upon Month and Soil Type

As can be seen from Figure 8.9 the total workdays available over the four month period range from 78 to 96 with a mean of 87. For the costing examples where only the primary tillage implements are concerned i.e plough or disc harrow, 35 days has been chosen for the limit. This takes into consideration that other operations will have to be carried out such as sub-soiling, secondary cultivations and drilling within the total days available.

Where the complete system is considered the limit was increased to 50 days, it was considered that August would not always be available due to late harvesting requirements. The number of workdays chosen gives an example of likely time available; they will change depending upon each individual circumstance and can be reduced by things such as machinery breakdowns.

After considering these points a tillage costing model was developed based on an Excel spreadsheet, allowing all the variables necessary to be modified to suit an individual farm situation. As there were many variables involved in the calculation of tillage operations the spreadsheet became quite complex, but the basis of the calculations are:

- Tractor Fixed Costs
- Tractor Variable Costs
- Machinery Fixed Costs
- Machinery Variable Costs
- Labour Requirement and Cost
- Machine Work rates and available days.

The equations used in the machinery costing calculations for fixed and variable costs can be broken down into their component parts to be explained further. Firstly, Tractor Fixed Costs, Equation 8.2. This calculates the depreciation of the tractor using the usage method, which takes into account the number of hours the tractor is estimated to do over its actual life. The new price of the tractor is added to any borrowed money.

The interest rate can be changed to suit that of any funds borrowed and is applied for the time period of which it will be borrowed (FinLife). The sale price is the residual value obtained for the tractor after its actual life. To produce a cost that was relative to all tractor and machine combinations the price was needed in £/ha therefore the work rate of the individual implement that the tractor was to be associated with was used to convert £/hr into £/ha.

$$\text{Tractor Fixed Costs} = \frac{\frac{(\text{New Price} + (\text{New price} * \text{IntRate} * \text{FinLife})) - (\text{Sale Price})}{\text{LifeInYears} * \text{HoursPerYear}}}{\text{WorkRate}}$$

Equation 8.2

The variable cost of the tractor accounted for the fuel and the repairs and maintenance, this can be seen in Equation 8.3. The variable costs include the amount of fuel used by the tractor and the rate at which it uses this fuel multiplied by an Area %Covered. This will account for the effect of multiple passes, for such operations as discing or spraying. Added to this there is a percentage value for the repairs and maintenance based upon the capital cost of the tractor. The cost is spread over the hours per year the tractor is used. Once again the cost is calculated in £/ha by relating it to the work rate of the implement being used. There is a separate line for the each implement and operation on the calculation sheet hence the tractor costs relate to each of the implements and will change depending upon the work rate of the implement.

$$\text{Tractor Variable Costs} = \frac{[(\text{Costoffuel} * \text{FuelusedperLitre}) * \text{Area}\% \text{Covered}] + \left[\frac{\text{CapitalCost} * \text{Re pair \& Ma int \%}}{\text{HoursperYear}} \right]}{\text{WorkRate}}$$

Equation 8.3

Next, the cost of each implement has to be calculated; this again is broken down into fixed and variable costs as with the tractor. Firstly the fixed costs, unlike the tractor, which was depreciated using the usage method the implements, are depreciated using

the straight-line method. This is a well know and common way to depreciate machinery and was decided the best for tillage machinery. Equation 8.4, shows the calculation for machinery fixed costs. Straight line depreciation is simply the purchase price minus the resale value over the number of years. Where the resale value is the predicted value after the life in years. Annual cropped area is used to covert the yearly depreciation of the machine down to the cost for every hectare that it is used for.

$$\text{Machinery Fixed Costs} = \frac{\frac{(\text{New Price} + (\text{New price} * \text{IntRate} * \text{FinLife})) - (\text{Sale Price})}{\text{LifeInYears}}}{\text{AnnualCroppedArea}}$$

Equation 8.4

Finally, there is the variable costs of the machinery or implements, this is predominately the repairs and maintenance of the machine because none of the tillage implements require fuel. Again the repairs and maintenance is based upon a percentage of the purchase price. The Area%Covered once again accounts for any multiple passes that may be necessary with operations such as discing and will also account for a specific sub soiling regime, where only half or part of the area is worked. In these situations more or less wear is put on the machine and therefore the repairs and maintenance should reflect that. Equation 8.5, shows the equation for machinery variable costs.

$$\text{Machinery Variable Costs} = \frac{\frac{(\text{New Price} * \text{Re pairs \& Maint \%}) * \text{Area\%Covered}}{\text{Hours / pass}}}{\text{Workrate}}$$

Equation 8.5

The other major factors to be considered when costing machinery is the cost and amount of labour required, every operation of a tractor and implement has to be matched with a labour supply at some cost. For the purpose of these calculations the

labour was considered a variable cost and entered as £/hour into the costing. Finally the work rate of each machine given its working width and its achievable forward speeds had to be calculated, this allowed a time to complete the operation to be established depending upon the area that had to be covered, giving both the time per operation in days but also minutes per hectare.

With all the above equations, comparisons of the cost of different tillage systems can be made, for both deep and shallow ploughing and alternative tillage systems.

8.5 *Implement Cost Comparisons*

It is possible to calculate the cost of single tractor implement combination or the complete tillage process that is required to convert last years harvest stubble into this years seedbed accounting for the many different variables involved. The best way to show the ability of the costing spreadsheet is by example, starting with a simple tractor-implement system and then finishing with the complete tillage system.

As was shown earlier in this chapter there are many ways in which the DB Pull and the DB Power of a specified tractor can be utilized. It is possible to look at the specific cost differences between these two alternatives. Firstly we can look at the effect of number of furrows on the cost of a tillage operation.

If the data from the work rate combination graphs is taken as an example the MF 6180 Figure 8.8 could either pull a 4 Furrow plough at 8.5 km/h or 7 Furrows at 4.5km/h based on force data for a working depth of 125mm. Using these combinations it is possible to cost each plough configuration between these limits to see how they compare. If a period of 35 days is considered a median for the ploughing operation alone, it is possible to determine how plough size effects area covered, Figure 8.10.

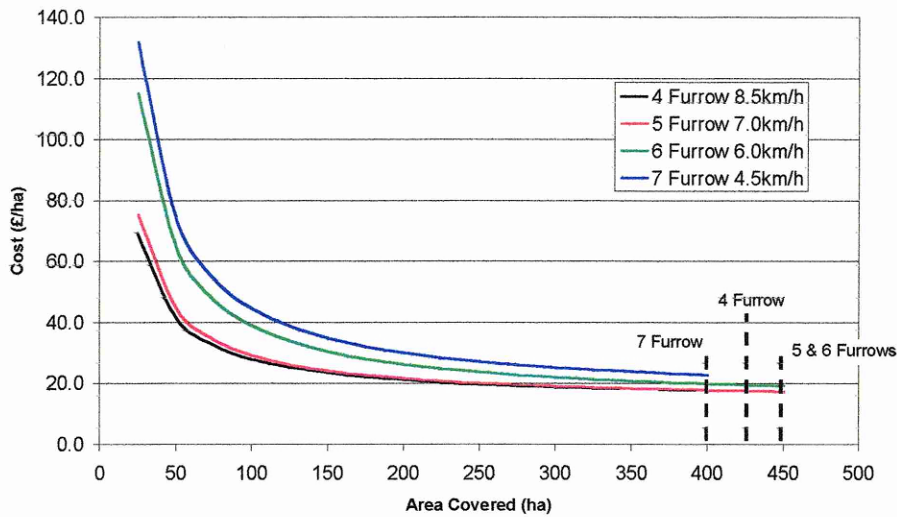


Figure 8.10, Plough Combination Utilizing Full MF 6180 DB Pull & DB Power

As can be seen the small plough configuration working at increased forward speed is the cheapest combination up to approximately 200ha where it is the same cost as the next biggest, up to its limit of 425ha which can be covered in the given 35 working days. It is only possible to increase the area covered in the given working window by 25ha with either the 5 or the 6 furrow ploughs. The 6 furrow covers this area at a slightly increased cost of £19.11/ha compared to £17.26/ha. At the maximum output of the 4 furrow plough the 6 furrow plough cost £19.44/ha. The 7 furrow configuration is always the more expensive option and in this case can only cover 400ha at a cost of 22.68/ha. This shows that the extra cost of the larger plough units cannot always be offset against their output, as when the forward speed (output) of a smaller plough is increased the cost is always less up to its maximum limit, which is dependant on available days.

It is also possible to look at many other variables to determine how they affect the work rate, the time required per operation and also the cost of operation. Starting with the working width of ploughs it is possible to determine if these have an affect on the cost of operation. There are two ways of increasing the width of the plough, the first is the addition of furrows, which is a step increase that was seen in Figure 8.10, secondly on the majority of modern plough it is possible to vary the furrow width from 300 –

500mm (12 – 20”) either on the move hydraulically or manually whilst stopped. The benefit of this width increase is that the output of the plough can be increased without an increase in initial cost of the plough, as with an additional furrow.

Looking at plough configurations that use both furrow number increase and the ability to increase furrow width, it is possible to see the costs of both. Firstly, it is possible to see the effect on cost if the number of furrows is increased. Initially the same size tractor operating at a nominal speed of 4.5 km/h will be used. Taking the manufactures recommended tractor size for a given plough, a 230hp tractor is recommended for a nine furrow plough. This size tractor can obviously be used with smaller ploughs, so it is possible to look at the output over a 35 day period and the cost of operation for the different configurations.

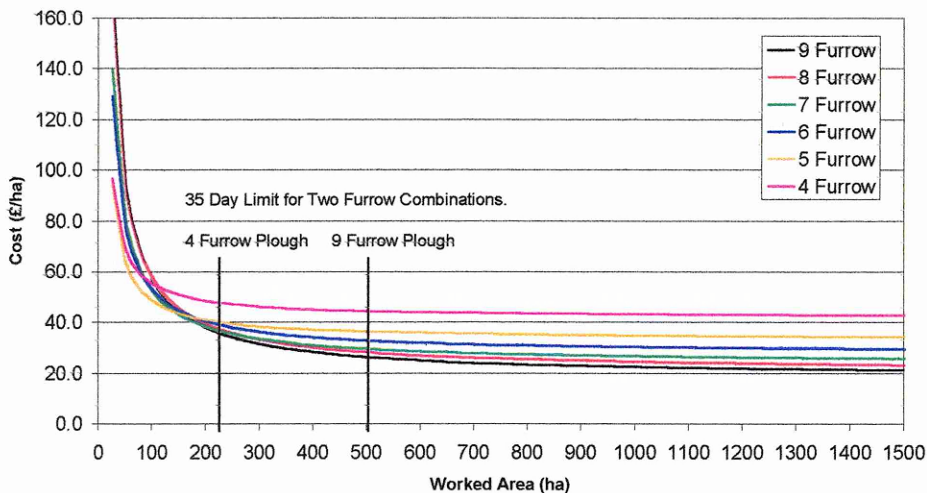


Figure 8.11, Output and Cost for Varying Furrow Numbers at 4.5 km/h

It can be seen from Figure 8.11 that as the number of furrows is reduced the cost of operation increases and the output in a 35 day period reduces from 500ha to 225ha, this was expected as the work rate is reduced with each furrow reduction and the tractor becomes oversized and expensive for the operation. As the 185-235 hp tractor can handle up to nine furrows, it would also be possible to trade the number of furrow

against the speed of operation. If the speed is increase by 1 km/h for every furrow that is removed the new outputs and costs of operation can again be compared.

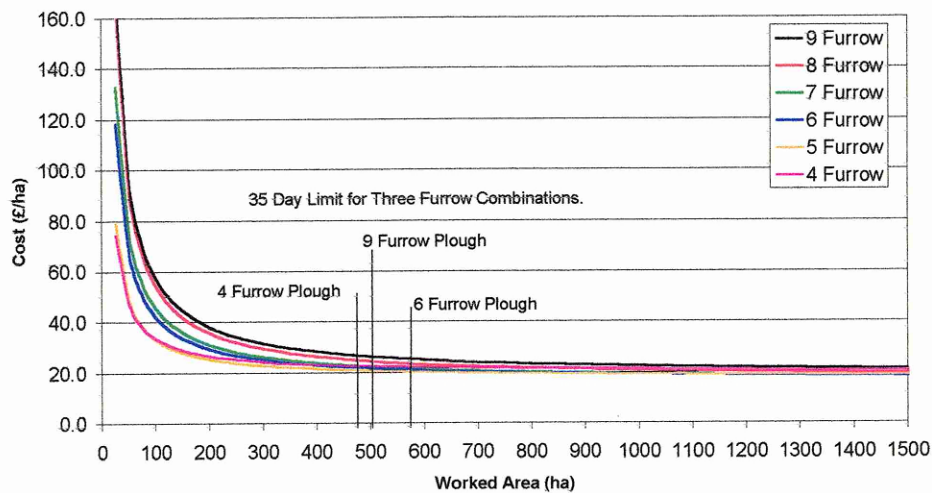


Figure 8.12, Output and Cost for Varying Furrows and Varying Speed

Figure 8.12 shows that if the speed of smaller furrow ploughs are increased the output and the cost can be better and cheaper than the larger number of furrow ploughs, £4.50/ha at 450 ha. It can be seen that the 4 and 5 furrow ploughs with this tractor are cheaper than the 9 furrow plough, but will have a slightly less total output in a 35 day period.

The next way to increase the output of the plough by increasing its width is to use the vari-width option, which is a commonly available feature of most modern mouldboard ploughs. The advantage with the vari-width option is the width can often be changed during operation so that the plough can be suited to the conditions of work. Unlike increasing the number of furrows, increasing the width using the furrow adjustment adds no cost to the operation. The equivalent width of an additional furrow can be added by increasing each furrow by a maximum of 150mm (6") in 50mm (2") increments. Figure 8.13, shows that with the same tractor and plough combination the increased furrow width setting not only gives a cost saving through out the whole range of worked area, but once again allows a greater area to be covered in a given time.

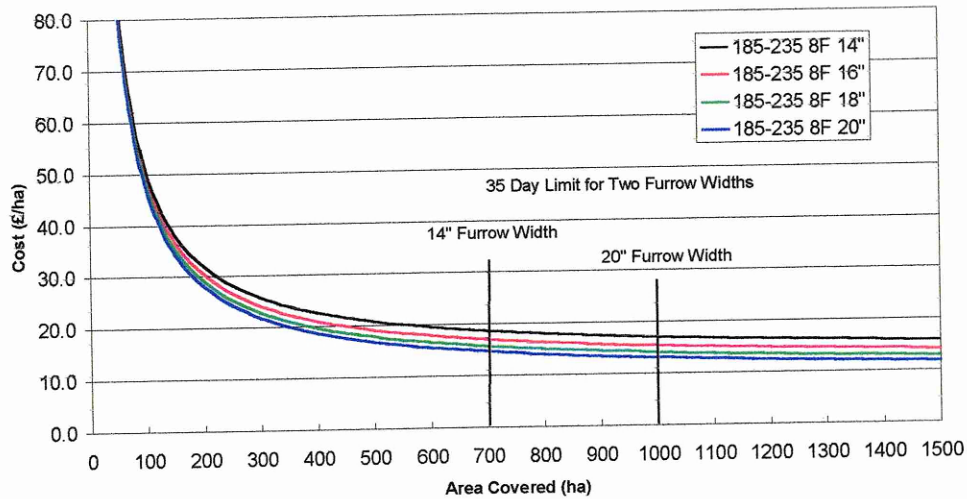


Figure 8.13, Operational Cost and Output of an 8 Furrow Plough at Increasing Furrow Widths.

There are more benefits to increasing the output of a plough than cost savings, although at the limit of the 14" plough the 20" plough is £4.01/ha less. It can be seen that the number of days available can drastically reduce the area that a tractor and plough combination can achieve. Figure 8.14, shows the number of days taken to cover a given area for four different furrow widths settings, ranging from 355mm (14") to 508mm (20") on an 8 furrow plough.

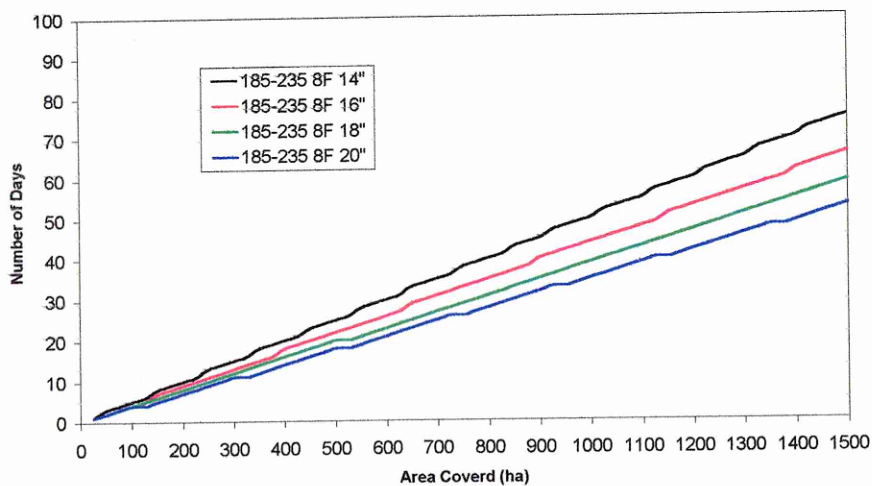


Figure 8.14, Number of Day per Area Covered with Different Furrow Width Settings

As was mentioned previously there are two ways to improve the output of a given plough, width of work and speed of operation. It is possible to calculate the cost of operation for a plough working at various forward speeds in the same way as with the width. Figure 8.15 shows the cost of an 8 furrow plough working at a range of speeds.

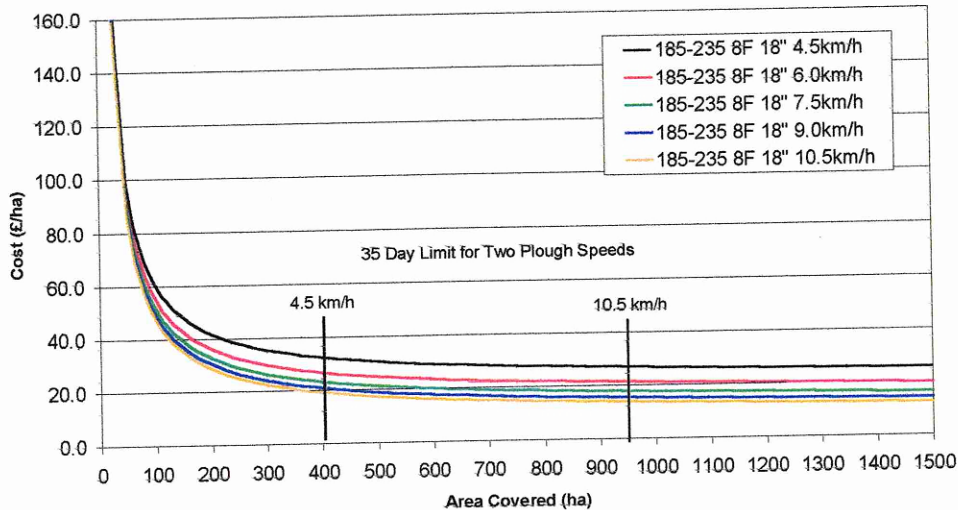


Figure 8.15, Output and Cost of Operation for an 8 Furrow Plough Over a Range of Speeds

As with both furrow number and furrow width increases the increase in forward speed reduces the cost of operation. In a similar way the area that can be covered in a given number of days is also increased. As can be seen from Figure 8.15 an eight furrow plough working at 10.5 km/h can cover more than double the area of one working at 4.5 km/h and give a cost saving of £13.08 per hectare.

This again can be related to the number of days saving possible with the increased output. Figure 8.16 shows that over an area of 500ha approximately 25 days can be saved from increasing forward speed from 4.5 km/h to 10.5 km/h using the 8 furrow plough in the example.

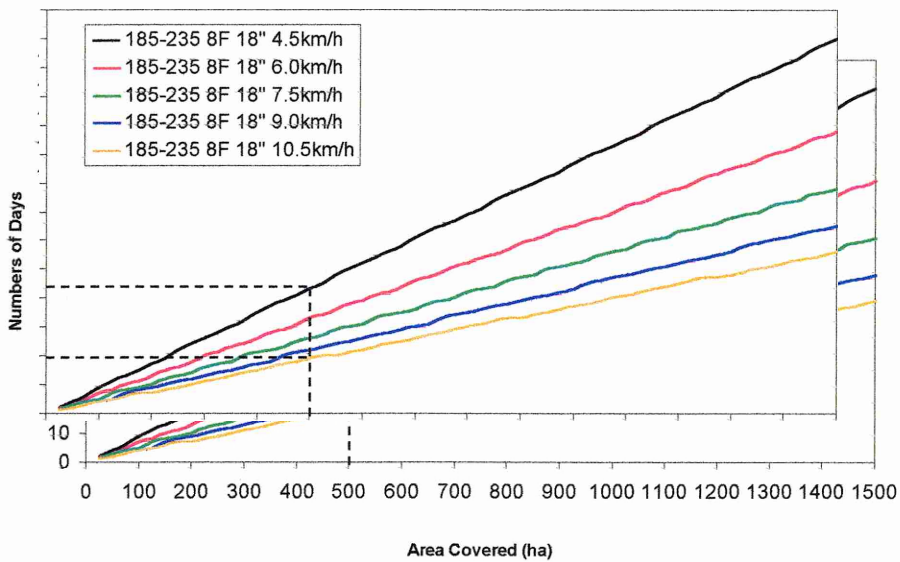


Figure 8.16, Number of Days Saving With Increased Forward Speed

Obviously large tractor and plough combination can cover larger areas in a given tillage window, Figure 8.17 shows how the increase in tractor and plough size brings about a increase in the area covered but also an increase in the cost of operation.

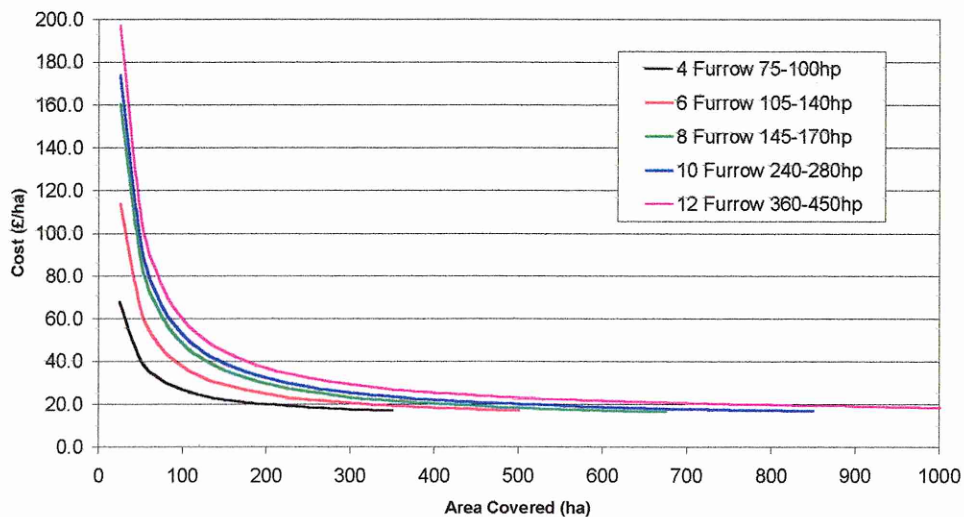


Figure 8.17, Tractor and Plough Sizes Comparison over 1500 Hectares

The 4 furrow plough combination is limited to approximately 350ha in a 35 day window, at a cost of less than £20 per hectare. The larger tractor plough combinations are all more expensive at that area, but become cheaper as the area is increased but never get as cheap as the smallest plough combination. This shows that the right size tractor plough combination should be chosen for the area required if the cheapest operating costs are to be obtained. It is cheaper to work smaller ploughs to their maximum limit than have an over capacity combination, the surplus capacity costs money. At the work rate limit of the 4 furrow combination the cost was £16.92/ha whereas the 12 furrow combination at this worked area cost £26.94/ha.

This is the case with all machinery and disc harrows are a very good example, one of their main selling points is their ability to have high work rates and low operating costs. It is possible to compare three sizes of disc harrows with three comparable plough combinations and show the difference in costs and output. Figure 8.18 shows a 6 furrow plough working at a standard setting of 18" wide and 4.5km/h, given a period of 35 days. This can be seen to be limited to 200ha and cost approximately £32 per hectare. The 3m disc harrows on the other hand have a limit of 575ha and a cost of £21 per hectare. If the plough is then operated at an increased speed of 7.5 km/h at the same furrow width the cost is reduced to below that of the disc harrows and the output increased to 500ha on the 35 day limit. The cost of the ploughing operation is now less than the disc harrows up to the plough limit, which is only 75ha less than the disc harrows.

This can be done for a range of disc harrow sizes and comparable plough sizes see Figure 8.19 and Figure 8.20. Each time the cost of the ploughing operation can be reduced below that of the disc harrows and the area covered greatly increased. It is only with the 6m disc harrow against the 12 furrow plough where the discing operation become cheaper over approximately 600 hectares.

It has to be remembered that the ploughing operation is always a one pass operation, whereas discing can sometimes need multiple passes to achieve the desired effect. The

graphs in Figure 8.18 through Figure 8.20 are all based on one pass of the disc harrows.

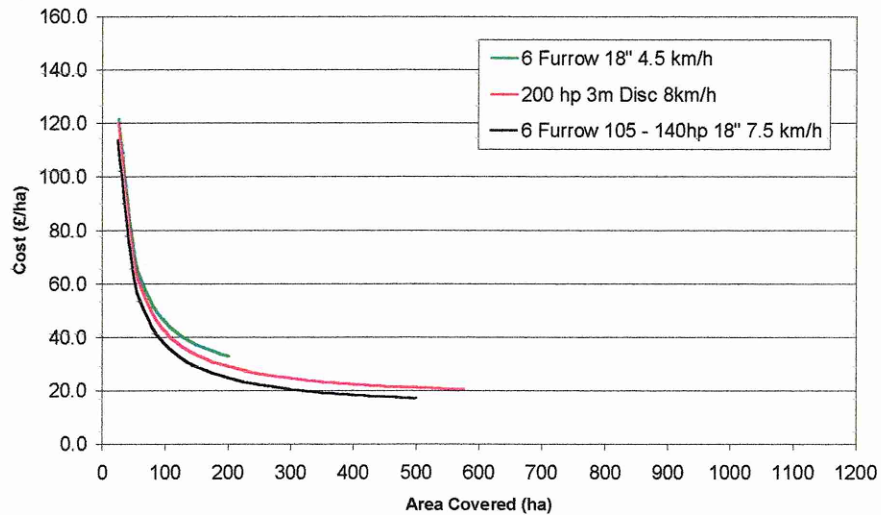


Figure 8.18, 3m Disc harrow Compared to a 6 Furrow Plough

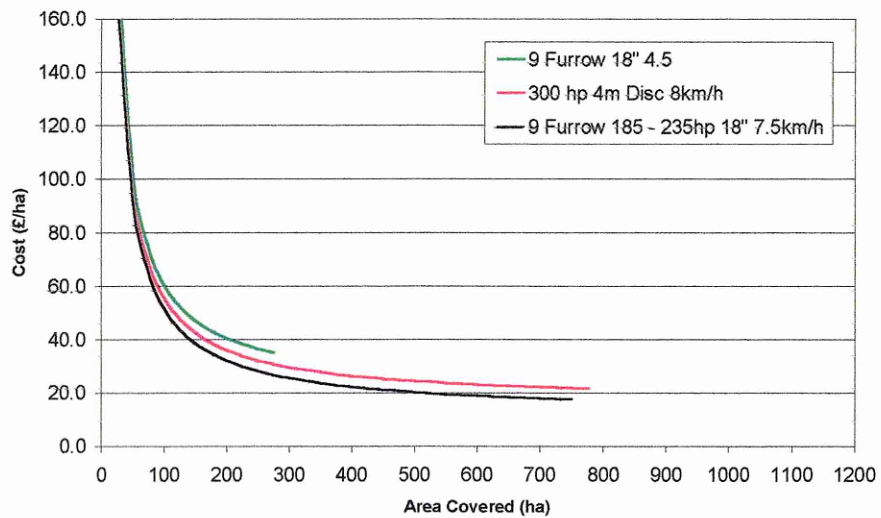


Figure 8.19, 4m Disc harrow Compared to a 9 Furrow Plough

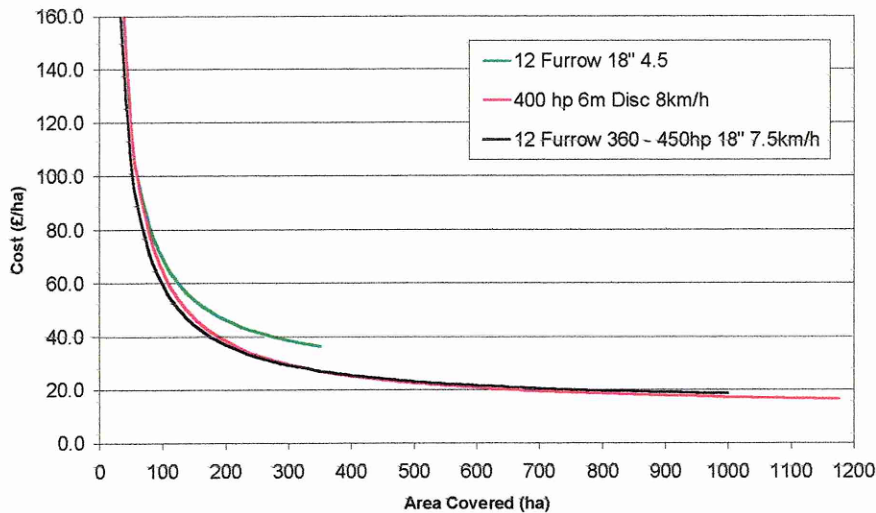


Figure 8.20, 6m Disc harrows Compared to a 12 Furrow Plough

8.6 System Cost Comparisons

Finally, it is possible include all the other machinery involved with complete tillage systems, such as the power harrows, the drills and the rolls. Also for direct drill practices there would often be a pre-cultivation spray, which adds both an operation and a chemical cost to the tillage system.

It can be seen for Figure 8.21 that for a 50 day working window and system comprising of 6 meter disc harrow and a 6 m drill has the highest output, but not the lowest cost. The slower plough configuration along with a power harrow drill combination and Cambridge roll is cheaper than the discing or direct drilling systems up to 125ha at which point the direct drilling system becomes cheaper.

This slower plough based system remains cheaper than both disc harrow systems up to 250ha and has a limit of 300ha where it is still cheaper than the large disc harrow system by £15.31. The smaller disc harrow systems has an increased capacity of 375ha, which is the 25ha less than the increased speed plough system. At the

maximum output of the small disc harrow system, the increased plough based system is £10.43 per hectare cheaper.

At approximately 300ha the faster plough based system is replaced as the cheapest system by the direct drill system which has a maximum output of 550ha at a cost of £44.76/ha. This is the cheapest system overall above 300ha mainly due to the limited number of operation involved. Even though the 6m disc harrow and drill system has the highest output of 650ha in the 50 days it is approximately £12/ha more expensive than the direct drill system and approximately £3/ha more expensive than the faster plough system. Once again the price of high capacity is highlighted.

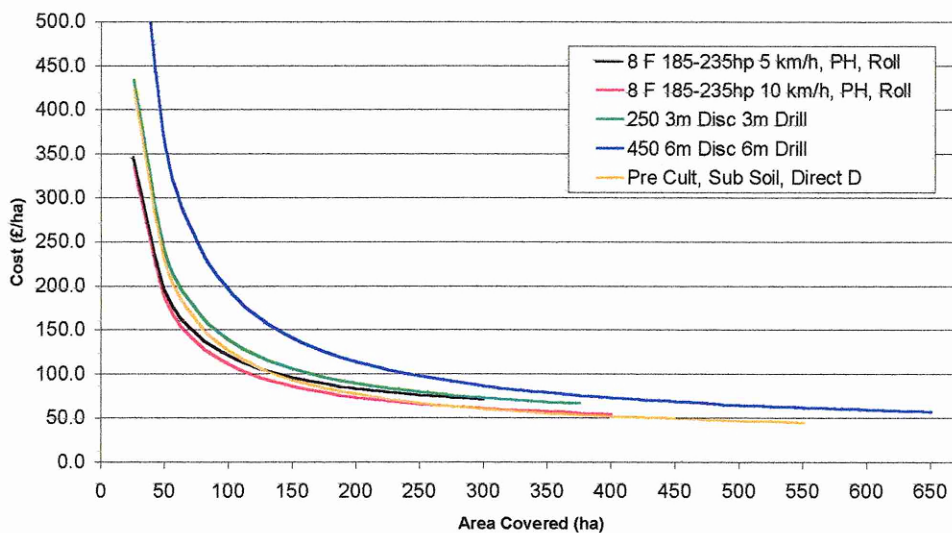


Figure 8.21, Three Tillage Systems Compared with 50 Available Workdays

8.7 *Summary*

Increasing the working width, either by number of furrow or by furrow width increase can increase the work rate of the mouldboard plough and reduce the cost of operation. Likewise increasing the speed of operation can increase the output and reduce the cost. This is not only seen in the ploughing operation but also in the complete tillage system, where it can reduce the cost and enable the plough based system to compete with discing and direct drilling systems.

Increasing the speed of operation should be the preferred way of increasing the output as there are many other advantages that come along with it. At present the average power of tractors is increasing year on year and the ability to utilise this power in terms of both transmission and tyre and track technology is becoming better all the time. Using this power to operate tillage implements at higher speeds could benefit the cost of agricultural production greatly and improve the efficiency of a necessary part of crop establishment.

At present the ability to plough at depths in excess of 225mm (9") is commonplace, which is far deeper than is required for competitive crop establishment. By utilising this reduction in depth to operate at the increased speeds shown in the graphs, the cost saving will be real and significant.

8.7.1 *Optimising the Mouldboard Plough Output.*

From this economic analysis along with basic work rate comparisons it can be seen that the mouldboard plough should be operated at the maximum forward speed possible for a given tractor under the prevailing conditions. This is to say that the depth and speed of ploughing may be different for any given field condition, this is due to the inherent heterogeneous nature of soil under field conditions and the presence of surface trash. This being the case, to quote a figure for the minimum ploughing depth

or the optimum speed is not possible. What is possible is to describe the method of obtaining the optimum work rate from a tractor plough combination.

Firstly the depth should be considered, and reduced as much as is possible. Once this is at the minimum for the given soil and trash condition the speed should be increased as much as possible. This will be limited by either the power availability or the ability to control the tractor comfortably for a sustainable period. This will depend upon the tractor and plough combination and the surface roughness of the field.

If the roughness of the soil surface and the comfort level is the limit of the plough tractor combination and power is still available the width should be increased. Initially if the plough is fitted with a variable furrow option this should be used as not extra cost is incurred and it can be again suited to the current field conditions.

If the increase in furrow width is still not utilizing all the available power or the surface conditions do not suit greatly increased furrow widths, additional furrow should be added. Even if the furrow depth has been greatly reduced, it is unlikely that more than a 1 to 2 furrow increase could be achieved. If this is possible, it could be said that the tractor and plough were not initially suited. This may be the case after the purchase of an increased power tractor.

Furrow number increase would be the last choice for increasing the output of a given tractor plough combination. Figure 8.22 highlights that the speed needs to be maintained when the number of furrows is increased to maintain the work rate of the plough.

A 4 furrow plough with a 16" furrow width, working at 4.5 km/h has a work rate of 0.511 ha/hr. If this is changed to a 5 furrow plough working at the same width a speed of at least 3.6km/h has to be achieved to ensure no reduction in work rate.

Work Rate ha/hr	4 Furrow km/h	5 Furrow km/h	Maximum Reduction km/h
0.51	4.5	3.6	0.9
0.62	5.5	4.4	1.1
0.74	6.5	5.2	1.3
0.85	7.5	6.0	1.5
0.97	8.5	6.8	1.7
1.08	9.5	7.6	1.9

Figure 8.22, Maximum Reduction in Speed with Furrow Increase, Whilst Maintaining Work Rate

Each tractor plough combination will have a limit to the area achievable in a given tillage window, obviously larger tractor and plough combinations will ultimately be able to cover more land and a system that matches the required area should be chosen.

Within these tillage windows each plough should be operated at its maximum possible work rate to reduce the costs of operation. If the limit of a tractor plough combination is reached and more capacity is needed, there are two options. The first would be to opt for a larger combination, and the second would be to add additional units to the system, i.e. increase the tractor and plough size or have two small tractors and ploughs.

Figure 8.23, shows the possible total area covered in 35 days with a range of tractor plough sizes. The maximum output of each plough is when the system is being operated at the highest speed with the furrow width as wide as possible (20"). If the maximum area is not enough within the time limit available the next tractor and plough size should be chosen. It can be seen that this will incur a cost increase unless the larger combination is operated at its maximum capacity.

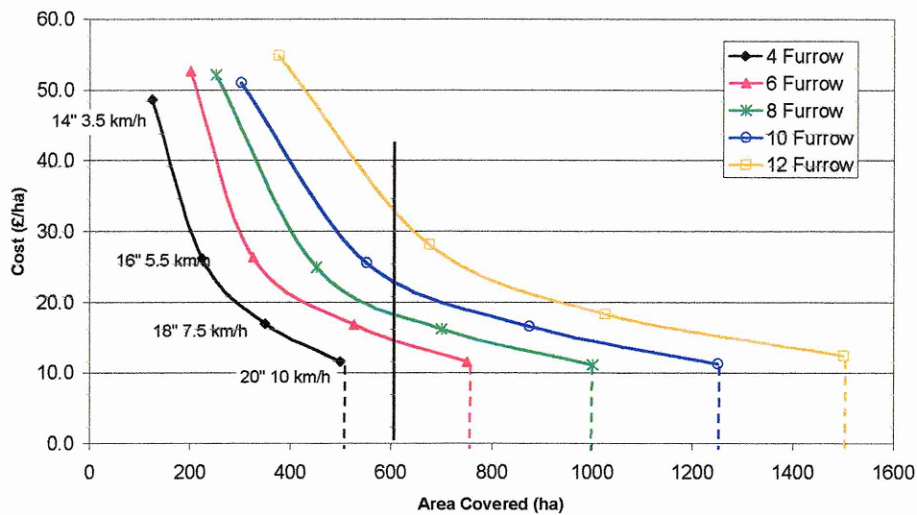


Figure 8.23, Maximum Area Covered and Costs For Various Tractor/Plough Combinations

As an example if 600ha have to be ploughed in 35 days there are 4 choices available on the graph. The 6 furrow plough is the cheapest as long as it is possible to operate the combination at between 18 and 20" and at a forward speed of between 7.5 and 10 km/h. This may be possible on flat land with light soil conditions, but due to soil and topographical conditions this may not be possible and therefore the 8 furrow combination would be the next cheapest, as long as it can be operated above approximately 6 km/h and 16 to 18".

This continues up to the largest combination of 12 furrows, which is the most expensive; mainly due to tractor and plough capital cost, but would give the output at more combinations of speed and furrow width. This would also give the opportunity to complete the area in a shorter time period and give some cushion in difficult years.

The main trade off against the cost of the system is the capacity or cushion that is required. Although 35 days was used in most of the examples every year is different and this may not always be the case, the decision is can more than 35 days be afforded to carry out primary tillage.

The arguments will always arise due to the fear of change, that it is not possible to plough any shallower or any faster. But as the economic pressure rises there will be no option and every last hectare of output will be required from all machinery in whichever way possible. This may mean a compromise between width, depth and speed to suit the individual conditions, to get a balance between time and cost of operation and the yield obtained.

CHAPTER 9 CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

It is possible to make the following conclusions from the research carried out with a modern mouldboard plough assembly.

- 1) From the experimental work carried out it was possible to quantify the operating effects of depth, width and speed on a modern mouldboard plough assembly.
 - a) Relationships obtained showed that depth had the greatest effect on horizontal (draught) force; width had the next greatest effect and speed had the least effect on the force.
 - b) The current mouldboard design adopted by Kverneland for use with their No 8 mouldboard body follows the suggestions of previous researchers in terms of the design parameters for higher speed ploughs. This is for both the low increase in horizontal force with speed and the soil handling abilities.
 - c) Depth/width ratios between 1.75 and 4.0 were tested and good soil inversion achieved under soil bin conditions. There were some limits with the current design of mouldboard regarding the width of furrow, which were discovered during the early experimental stages especially under field conditions.
- 2) Extensive testing of the standard manure skimmer allowed the effect of skimmer geometry and orientation (pitch and yaw) on the soil forces and the soil throw to be investigated and understood.
 - a) Increased rake angles reduce the control of soil flow over the skimmer and increase the forces required, partly due to a scrubbing effect.

- b) Reduced rake angles moves a smaller section of soil under better control over speed.
 - c) Increasing the approach angle forces the soil to the on-land side of the furrow and increases the horizontal force slightly
 - d) Reducing the approach angle give good performance at high speed but may be prone to scrubbing.
- 3) Theoretical models were developed to predict the soil horizontal forces on the mouldboard assembly as a complete unit and on the mouldboard individually. This was done with the use of a modified soil dynamics equation making use of Mohr Coulomb soil properties and the effects of inertia for soil flow. When compared to the measured values for a range of depths widths and speeds the model predicts total horizontal force with an average error of 7.4%.

Using a similar procedure as for the mouldboard assembly, the soil forces on the skimmer were predicted for a range of rake angles, approach angles and speeds. These were correlated to measured soil bin values and range from 25% under prediction and 41% over prediction. Scrubbing effects of the skimmer working at reduced rake angles were highlighted and were these are removed the over all prediction is within 1% of the measured values.

- 4) Plough work rates and economic calculations show that plough configurations that are shallower, faster and wider are of great benefit in terms of cost savings. With a given limit on power, reducing the number of furrow and increasing the speed may reduce the work rate by 0.1ha/hr from the maximum configuration but can reduce the cost by £5.42/ha. Reducing the depth and increasing the speed of a given size plough can reduce the cost by £13.08/ha, increasing the number of furrows can save £11.11/ha and increasing the furrow width can save £4.01/ha. The cost of the ploughing operation was looked at for a variety of working areas, tractor/plough configurations and plough setting giving different work rates and the cost in £/ha found for each one.

- 5) The mouldboard plough as part of a tillage system was used to compare, conventional tillage practices with those of minimum and zero tillage systems. A standard plough configuration was the cheapest system up to 125ha and remains cheaper than two sizes of disc harrow based systems up to 225ha. An increased speed mouldboard plough based system is cheaper than all the other systems up to 300ha and cheaper than two disc based systems up to its limit of 400ha. The larger disc system cost £21.12/ha more at this area but is reduced to £3.0/ha more at its limit of 650ha. The direct drill system becomes the cheapest at 300ha and is cheapest up to its limit; the maximum output was achieved with the largest disc based system. This positions a mouldboard plough based tillage system as being the most economically viable for farms below 300 ha especially if used at shallower and faster configurations.
- 6) Through extensive testing of the mouldboard within controlled soil bin conditions and in the field, two specific problems were highlighted. One being the increase of furrow bottom widths to allow wider tyres into the furrow bottom, and two; the ability of the skimmer to work effectively at increased forward speeds. Both of these were addressed with soil bin and field studies. The outcome was that an increased width mouldboard, which left a furrow bottom that corresponds with the widest available share width was designed and under test required no additional horizontal force. Recommendations for improved skimmer rake and approach angles were also highlighted to enable more effective soil and trash handling at increased speeds.
- 7) The company input of this project encouraged several practical aspects of the mouldboard plough to be investigated and solutions discovered, which has led to the company taking the initial designs forward to prototype and development on a commercial scale.

9.2 Recommendations

The main recommendations that come from this research are:

The understanding of the modern mouldboard plough in operation at increased forward speeds and the cost savings associated with this should be conveyed to the farmer so that the benefits can be realised.

The skimmer should be modified and used at reduced approach angle in order to both reduce the horizontal force requirement and to improve the soil flow characteristics. Increased curvature and higher rake angles especially on the upper section of the skimmer assembly would also be beneficial to improve trash handling capabilities.

Extensive field experiments should be carried out with mouldboard ploughs operating at reduced depths to determine the agronomic effects of shallow ploughing. These should include a range of speeds that are as high as possible for the given configuration. Areas investigated should include inversion, trash burial, soil break-up and most importantly a yield comparison. This would help to highlight that shallower ploughing is really a viable alternative. This along with the cost savings that have been shown in this work could really enhance the presence of one of the oldest primary tillage implements.

An area concerned with the work rate and output of all tillage implements not just the mouldboard ploughs is the number of workdays that are actually available during the autumn tillage period. A long-term study should be conducted into the actual time needed for successful crop establishment using different tillage processes on a farm scale together with a study of the actual measured workable days that are available in many areas of the UK during the season. This could then be used to advise on choice of tillage and plan the operations more closely, managing the time and machinery available to make better use of it.

CHAPTER 10 REFERENCES.

- Al-Jalil, H. F., Marley, S. F. and Buchele, W. F. (1979)** Spring-Damper Control of Lateral Cutting Angle for a Variable-Speed Mouldboard Plough *Trans American Society of Agricultural Engineers*, **22**, 494-497.
- Bailey (1750)** Bailey' theory on turning on a stiff soil beam .
- Desbiolles, J. M. A., Godwin, R. J., Kilgour, J. and Blackmore, B. S. (1997)** A Novel Approach to the Prediction of Tillage Tool Draught using a Standard Tine *J. Agric. Engng Res.*, **66**, 295-309.
- Desbiolles, J. M. A., Godwin, R. J., Kilgour, J. and Blackmore, B. S. (1999)** Prediction of Tillage Implement Draught using Cone Penetrometer Data. *J. Agric. Engng Res.*, **73**, 65 - 76.
- Gebresenbet, G. (1989)** Multicomponent Dynanometer for Measurement of Forces on Plough Bodies. *J. Agric. Engng Res.*, **42**, 85-96.
- Getzlaff, G. (1953)** Comparative Studies on the Forces Acting on Standard Plough Bodies. *Grundlagen der Landtechnik NIAE Trans. 6*, **5**, 16 - 35.
- Girma, G. (1989)** Measurement and prediction of Forces on Plough Bodies -- 1 Measurement of Forces and the Soil Dynamic Parameters *Land and Water Use*, Dodd & Grace (eds), © Balkema, Rotterdam. 1539,1546.
- Godwin, R. J. (1975)** An Extended Octagonal Ring Transducer for use in Tillage Studies *J. Agric. Engng Res.*, **20**, 347-352.
- Godwin, R. J. and Spoor, G. (1977)** Soil failure with narrow tines. *J. Agric. Engng Res.*, **22**, 213-228.
- Godwin, R. J., Spoor, G. and Soomro, M. S. (1984)** The effect of tine arrangement on soil forces and disturbances. *J. Agric. Engng Res.*, **30**, 47-56.
- Goryachkin, V. P. (1968a)** *Agricultural Mechanics. Collected Works in Three Volumes*, Israel Program for Scientific Translations, Moskva.
- Goryachkin, V. P. (1968b)** The Theory of Cutting In *Collected Works in Three Volumes*, Vol. One (Ed, Luchinskii, N. D.) Moskova, pp. 564 - 583.
- Gyachev, L. V. (1985)** *Theory of Surfaces of Plow Bottoms*, Amerind Publishing Co. Pvt. Ltd, New York.

- Hakansson, I., Stenberg, M. and Rydberg, T. (1998)** Long-Term Experiments with Different Depths of Mouldboard Ploughing in Sweden *Soil & Tillage research*, 46, 208-223.
- Hettiaratchi, D. R. P., Witney, B. D. and Reece, A. R. (1966)** The calculation of passive pressure in two-dimensional soil failure. *J. Agric. Engng Res.*, 11, 89-107.
- Hunt, D. (1995)** *Farm Power and Machinery Management*, Iowa State University Press.
- Kaburaki, H., Kisu, M. (1959)** Studies on cutting Characteristics of Ploughs *Journal of the Kanto-Tosan Agricultural Experiment Station*, 12.
- Kepner, R. A., Bainer, R. and Barger, E. L. (1978)** *Principles of Farm Machinery*, The AVI Publishing Company INC.
- Kermis, L. H. (1978)** A Theoretical Approach to High-Speed Plough Design *J. Agric. Engng Res.*, 23, 343-368.
- Korotkevich, V. A. (1972)** Effect of Speed on the Normal Specific Pressure on the Surface of Plough Shares and Mouldboards. *NIAE Translation*, 305.
- Kouwenhoven, J.K. (1992)** Reduction of Herbicide use by Mechanical Weed Control in the Netherlands *Proc. Cong. Agriculture and Environment in Eastern Europe and the Netherlands*, pp 257-264.
- Lang, B. (1999)** *Report on Farming in The Eastern Counties of England 1999/2000*, Centre for Rural Economics, University of Cambridge.
- Likhoedenko, K. I. (1963)** Operation of Tractor Ploughs at High Speeds *Traktory i Selkhoz mashinery*, 30, 17 - 20.
- Lucian, N. (1992)** Effects of hitches on Mechanical plowing. *ASAE Paper No 92-1016*, .
- McKibben, E. G., Reed, I.F. (1952)** The Influence of Speed on the Performance characteristics of Implements. In *SAE National Tractor meeting* Milwaukee, Wisconsin.
- McKyes, E. (1985)** *Soil Cutting and Tillage*, Elsevier, Amsterdam.
- Miltsev, A. I. (1974)** Draught and Efficiency of a Plough *NIAE Translation* 380 , *Mekan. Elektrif. Sel Khoz.*, 4, 7-8.

- National-Institute-of-Agricultural-Engineering (1971)** Forces on Implements, A Review of Past Work National Institute of Agricultural Engineering, .
- Nichols, M. L., Reed, I.F. (1934)** Physical Reactions of Soils to Mouldboard Surfaces *Agricultural Engineering*, **15**, 190.
- Nichols, M. L. and Kummer, T. H. (1932)** The Dynamic Properties of Soil *Agricultural Engineering*, **13**, 279-285.
- O'Callaghan, J. R. and McCoy, J. G. (1965)** The Handling of Soil by Mouldboard Ploughs. *J. Agric. Engng Res.*, **10**, 23-35.
- Oskoui, K. E. and Witney, B. D. (1982)** The determination of plough draught- part1. Prediction from soil and meteorological data with cone index as the soil strength parameter. *Journal of Terramechanics*, **19**, 97 - 106.
- Plouffe, C., Tessier, S., McLaughlin, N. B. and Lague, C. (1995)** Plowing Performance with Two Helical Plow Bottoms at Shallow Operating Depths. *American Society of Agricultural Engineers*, **38**, 1677 - 1683.
- Prihoda, Z. (1964)** Plough Bodies for high-speed Operation *Zemed. Tech. NIAE Translation 193*, **10**, 465-476.
- Qiong, G., Pitt, R. E. and Ruina, A. (1986)** A Model to Predict Soil Forces on the Plough Mouldboard. *Journal Of Agricultural Engineering Research*, **35**, 141 - 155.
- Quickstad, L. (1971)** High-Speed Tillage Equipment In *National Farm, Construction and Industrial Machinery Meeting*. Society of Automotive Engineers., Milwaukee.
- Randolph, J. W., Reed, I.F. (1938)** Tests of Tillage Tools II Effects of Several Factors on the Reaction of Fourteen-Inch Moldboard Plows *JAER*, **19**, 29-33.
- Reaves, C. A. and Schafer, R. L. (1975)** Force Versus Width of Cut for Mouldboard Bottoms. *ASAE*, **18**, 852 - 854.
- Rogers, O. J. J. and Hawkins, J. C. (1956)** Soil Loads on Plough Bodies, Part II The forces Acting on General Purpose, Semi Digger Bodies under Varying Conditions of Soil and Speed *NIAE Tech Memo 105*, **II**.
- Seig, D. A. (1982)** An Investigation into the Forces Acting on the Plough Share Point In *National College of Agricultural Engineering* Cranfield Institute of Technology, Bedford.

- Söhne, W. (1959)** Investigation on the Shape of plough Bodies for Higher Speed
Grundi Landtech 11 (NIAE Translation 87), , 22.
- Söhne, W. (1960)** Suiting the Plough Body Shape to Higher Speeds. *Grundlagen der Landtechnik 12 (Translation 101)*, **12**, 51-62.
- Söhne, W. (1985)** Soil Dynamics Research at the National Tillage Machinery Laboratory: An International Perspective In *International Conference on Soil Dynamics* Auburn, Alabama.
- Söhne, W. and Moller, R. (1962)** The Design of Mouldboards with Particular Reference to High-speed Ploughing *Grundlagen der Landtechnik, NIAE Trans. 146*, **15**, 15 - 27.
- Tanner, D. W. and Dean, J. R. (1963)** The Soil Forces acting on the Body and on the Disc Coulter of a Plough *J. Agric. Engng Res.*, **8**, 194-201.
- Wheeler, P. N. and Godwin, R. J. (1996)** Soil Dynamics of Single and Multiple Tines at Speeds up to 20 km/h *J. Agric. Engng Res.*, **63**, 243-250.
- Witney, B. (1988)** Choosing and Using Farm Machines (Ed, Technical, L. S.) Longman Scientific & Technical, Harlow, pp. 270-.

APPENDIX 1 PRELIMINARY SOIL BIN EXPERIMENTS

A 1.1 Moisture Content and Bulk Density Results

Test No 1			Test No 5		
	% Moisture	Bulk Density (Mg/m ³)		% Moisture	Bulk Density (Mg/m ³)
Sample 1	9.58	1.29	Sample 1	9.48	1.46
Sample 2	9.35	1.28	Sample 2	9.49	1.61
Sample 3	9.26	1.25	Sample 3	9.52	1.43
Average	9.40	1.27	Average	9.50	1.50
Test No 2			Test No 6		
	% Moisture	Bulk Density (Mg/m ³)		% Moisture	Bulk Density (Mg/m ³)
Sample 1	9.37	1.45	Sample 1	9.89	1.54
Sample 2	10.21	1.45	Sample 2	9.79	1.47
Sample 3	9.11	1.39	Sample 3	9.87	1.45
Average	9.56	1.43	Average	9.85	1.49
Test No 3			Test No 7		
	% Moisture	Bulk Density (Mg/m ³)		% Moisture	Bulk Density (Mg/m ³)
Sample 1	9.50	1.42	Sample 1	9.78	1.47
Sample 2	9.37	1.44	Sample 2	9.74	1.45
Sample 3	9.61	1.46	Sample 3	9.69	1.50
Average	9.49	1.44	Average	9.74	1.47
Test No 4			Test No 8		
	% Moisture	Bulk Density (Mg/m ³)		% Moisture	Bulk Density (Mg/m ³)
Sample 1	9.73	1.39	Sample 1	9.31	1.36
Sample 2	8.91	1.20	Sample 2	9.85	1.47
Sample 3	10.03	1.43	Sample 3	9.87	1.43
Average	9.56	1.34	Average	9.68	1.42

The average moisture for the tests was 9.6 % over a range of 8.91 % minimum and 10.21 % maximum, with a standard deviation of 0.30 % moisture. The LSD was 0.552 for 16 degrees of freedom. The average bulk density was 1.42 Mg/m³ over a range of 1.2 Mg/m³ minimum and 1.61 Mg/m³ maximum, with a standard deviation of 0.09 Mg/m³. This shows the uniformity of the soil bin under test conditions.

A 1.2 Mean Results From Preliminary Soil Bin Studies for 3 Widths

Depth mm	Ave Draught kN	Ave Vertical kN	Ave Moment kNm	Mean % M _c %	Mean Bulk Density Mg/m ³	Width mm	Theoretical Area m ²	Specific Resistance kN/m ²
90	1.304	-0.154	-1.318	9.56	1.341	355	0.023	57.648
120	1.506	-0.315	-1.477	9.49	1.441	355	0.030	50.515
160	2.106	-0.599	-1.965	9.56	1.432	355	0.041	51.991
200	2.754	-0.523	-2.702	9.40	1.272	355	0.051	54.137
225	3.453	-0.918	-3.192	9.53	1.521	355	0.057	60.565
110	2.046	0.024	-2.199	10.87	1.587	450	0.038	46.246
140	2.368	-0.286	-2.316	9.96	1.548	450	0.049	43.667
180	2.780	-0.334	-2.805	10.37	1.622	450	0.063	40.742
230	3.603	-0.471	-3.662	10.72	1.586	450	0.080	46.954
120	2.190	-0.303	-1.994	9.68	1.418	508	0.049	44.912
170	2.388	-0.823	-2.311	9.74	1.475	508	0.069	34.567
225	3.218	-0.944	-3.023	9.85	1.487	508	0.091	35.193
290	4.736	-1.229	-4.735	9.50	1.500	508	0.118	40.185

A 1.3 Initial Field Tests Pictures

		
355mm (14") Furrow, 165mm (6-7") Deep, 4.5 m/h	355mm (14") Furrow, 165mm (6-7") Deep, 7.5 m/h	355mm (14") Furrow, 165mm (6-7") Deep, 10 m/h
		
508mm (20") Furrow, 165mm (6-7") Deep, 4.5 m/h	508mm (20") Furrow, 165mm (6-7") Deep, 7.5 m/h	508mm (20") Furrow, 165mm (6-7") Deep, 10 m/h

In addition to these test variables, a number of runs were carried out at as shallow a depth as was possible. This being 115mm (4 – 5 “) at a furrow width of 508mm (20”) and at 7.5 km/h



508mm (20”) Furrow,
115mm (4 - 5”) Deep, 7.5 m/h

APPENDIX 2 MOULDBOARD SOIL BIN STUDIES

A 2.1 Mean Moisture Content and Bulk Density Results

Bulk Density & Moisture Content Tables.

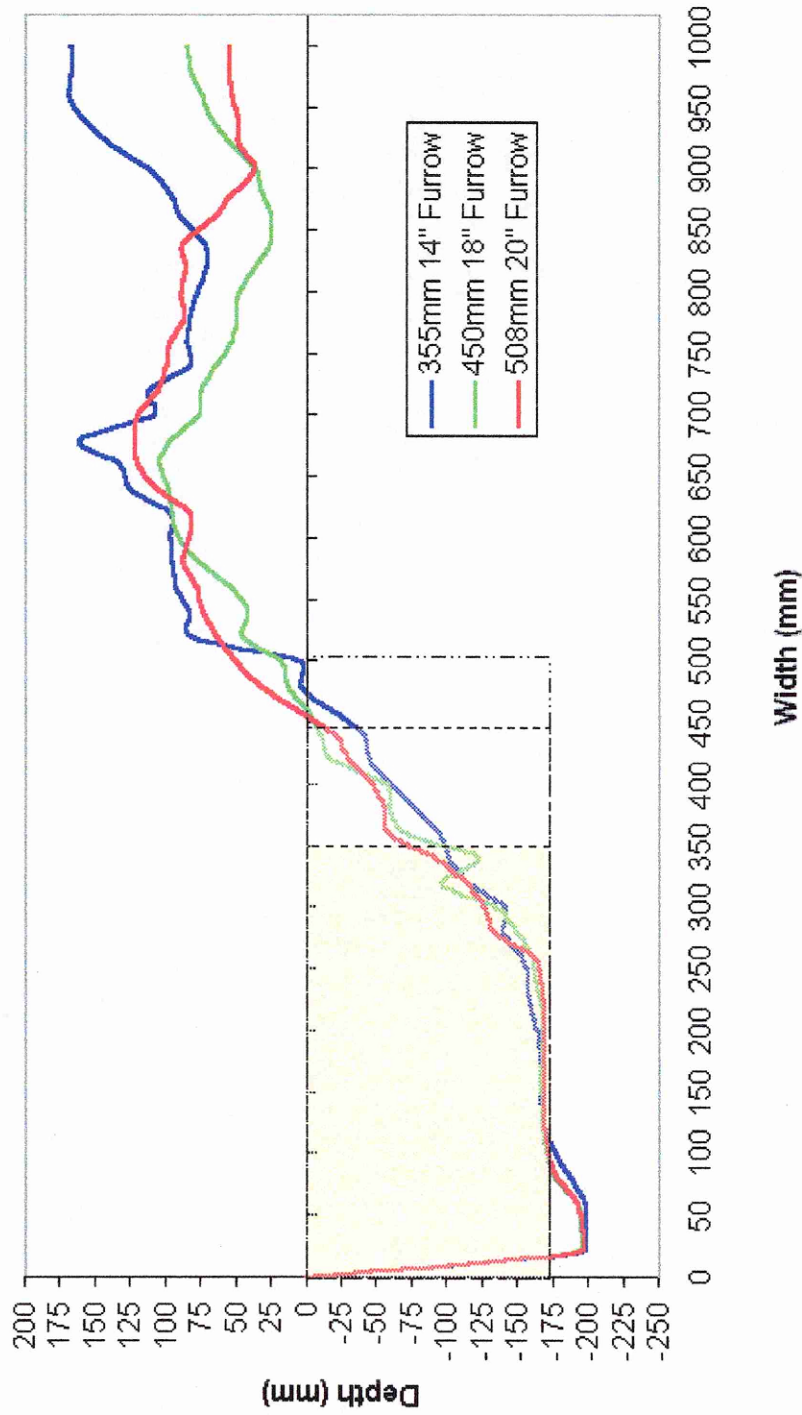
Test No	Configuration	Mean % Moisture	Mean Bulk Density (Mg/m3)
1	wss01	10.77	1.53
2	wss02	10.16	1.56
3	wss03	10.91	1.56
4	wds01	10.72	1.52
5	wds02	10.45	1.54
6	wds03	10.82	1.51
7	wvds01	10.71	1.53
8	wvds02	11.14	1.51
9	wvds03	11.15	1.55
10	wsm01	10.91	1.55
11	wsm02	10.88	1.57
12	wsm03	10.87	1.55
13	wdm01	11.69	1.52
14	wdm02	11.38	1.53
15	wdm03	10.58	1.57
16	wvdm01	11.02	1.53
17	wvdm02	10.91	1.54
18	wvdm03	10.67	1.58
19	wsf01	11.35	1.49
20	wsf02	10.79	1.50
21	wsf03	10.63	1.50
22	wdf01	11.14	1.53
23	wdf02	10.93	1.51
24	wdf03	10.59	1.53
25	wvdf01	11.16	1.57
26	wvdf02	10.80	1.48
27	wvdf03	10.84	1.52
28	vnds01	10.79	1.52
29	vnds02	10.72	1.56
30	vnds03	11.18	1.50
31	nds01	10.55	1.51
32	nds02	10.59	1.50
33	nds03	10.57	1.55

A 2.2 Soil Bin Results Mouldboard Studies

File Name	Width (mm)	Depth (mm)	Speed (km/h)	Vel. M/s	Rep. No	Mean Draught Force (kN)	Mean Vertical Force (kN)	Mean Moment (kNm)	Theoretical Area m2	Specific Resistance kN/m2
VNDS01	355	175	4.5	1.22	1	2.454	-0.435	-2.350	0.044	55.339
VNDS02	355	175	4.5	1.16	2	2.649	-0.683	-2.395	0.044	59.746
VNDS03	355	175	4.5	1.14	3	2.372	-0.283	-2.488	0.044	53.496
	355	175	4.5	1.18	Mean	2.492	-0.467	-2.411	0.044	56.194
				4.236						
NDS01	450	175	4.5	1.17	1	2.803	-0.190	-2.965	0.061	45.973
NDS02	450	175	4.5	1.27	2	3.738	-0.171	-3.993	0.061	61.316
NDS03	450	175	4.5	1.27	3	3.169	-0.046	-3.373	0.061	51.981
	450	175	4.5	1.23	Mean	3.237	-0.136	-3.444	0.061	53.090
				4.446						
WSS01	508	125	4.5	1.18	1	2.848	-0.172	-3.060	0.051	56.067
WSS02	508	125	4.5	1.13	2	2.992	-0.163	-3.316	0.051	58.892
WSS03	508	125	4.5	1.37	3	2.641	-0.303	-2.638	0.051	51.982
	508	125	4.5	1.23	Mean	2.827	-0.213	-3.005	0.051	55.647
				4.42						
WDS01	508	175	4.5	1.17	1	3.727	-0.672	-3.865	0.071	52.406
WDS02	508	175	4.5	1.38	2	4.005	-0.751	-4.048	0.071	56.308
WDS03	508	175	4.5	1.24	3	3.890	-0.195	-4.316	0.071	54.697
	508	175	4.5	1.26	Mean	3.874	-0.539	-4.077	0.071	54.470
				4.550						
WVDS01	508	225	4.5	1.33	1	5.149	-0.760	-5.476	0.091	56.306
WVDS02	508	225	4.5	1.29	2	5.030	-0.880	-5.377	0.091	55.013
WVDS03	508	225	4.5	1.21	3	4.648	-1.068	-4.948	0.091	50.831
	508	225	4.5	1.28	Mean	4.942	-0.903	-5.267	0.091	54.050
				4.593						
WSM01	508	125	7.5	2.05	1	3.146	-0.503	-3.310	0.051	61.927
WSM02	508	125	7.5	2.25	2	3.444	-0.107	-4.032	0.051	67.792
WSM03	508	125	7.5	2.16	3	3.503	-0.114	-3.999	0.051	68.953
	508	125	7.5	2.15	Mean	3.364	-0.241	-3.780	0.051	66.224
				7.757						
WDM01	508	175	7.5	2.11	1	3.644	-0.784	-3.525	0.071	51.233
WDM02	508	175	7.5	2.24	2	3.725	-0.780	-4.172	0.071	52.371
WDM03	508	175	7.5	2.23	3	4.696	-0.578	-4.971	0.071	66.036
	508	175	7.5	2.19	Mean	4.022	-0.714	-4.223	0.071	56.547
				7.895						
WVDM01	508	225	7.5	2.07	1	5.430	-1.504	-5.591	0.091	59.379
WVDM02	508	225	7.5	2.11	2	5.282	-1.230	-5.604	0.091	57.762
WVDM03	508	225	7.5	2.18	3	5.067	-1.040	-5.349	0.091	55.412
	508	225	7.5	2.12	Mean	5.259	-1.258	-5.515	0.091	57.518
				7.633						
WSF01	508	125	10	2.45	1	3.130	-0.742	-3.233	0.051	61.607
WSF02	508	125	10	2.81	2	3.256	-0.915	-2.906	0.051	64.086
WSF03	508	125	10	2.81	3	3.877	-0.422	-4.089	0.051	76.327
	508	125	10	2.69	Mean	3.421	-0.693	-3.409	0.051	67.340
				9.697						
WDF01	508	175	10	2.85	1	4.305	-1.568	-3.805	0.071	60.534
WDF02	508	175	10	2.75	2	4.320	-1.045	-4.485	0.071	60.748
WDF03	508	175	10	2.67	3	4.364	-0.987	-4.696	0.071	61.358
	508	175	10	2.76	Mean	4.330	-1.200	-4.328	0.071	60.880
				9.921						
WVDF01	508	225	10	2.83	1	5.587	-1.592	-5.714	0.091	61.096
WVDF02	508	225	10	2.75	2	5.465	-0.816	-6.135	0.091	59.766
WVDF03	508	225	10	2.75	3	5.442	-0.927	-5.913	0.091	59.512
	508	225	10	2.78	Mean	5.498	-1.112	-5.921	0.091	60.125
				10.005						

A 2.3 Soil Profiles for Three Share Widths

Soil Profiles for Three Different Share Widths
at 4.5 km/h and 175 mm Deep.



APPENDIX 3 MOULDBOARD WIDTH STUDIES

A 3.1 Mean Moisture Content and Bulk Density Results

File Name	Rep. No	Mean % Moisture %	Mean Bulk Density (Mg/m ³)
45 Nor R1	1	9.06	1.45
45 Nor R2	2	8.82	1.48
45 Nor R3	3	9.15	1.50
<i>Means</i>		9.0082	1.4746
75 Nor R1	1	8.84	1.48
75 Nor R2	2	8.87	1.47
75 Nor R3	3	9.34	1.47
<i>Means</i>		9.0166	1.4755
10 Nor R1	1	8.27	1.43
10 Nor R2	2	8.95	1.49
10 Nor R3	3	9.12	1.46
<i>Means</i>		8.7805	1.4622
45 Ext R1	1	8.86	1.47
45 Ext R2	2	9.44	1.46
45 Ext R3	3	9.40	1.50
<i>Means</i>		9.2335	1.4765
75 Ext R1	1	8.32	1.42
75 Ext R2	2	9.00	1.46
75 Ext R3	3	9.18	1.45
<i>Means</i>		8.8336	1.4439
10 Ext R1	1	9.55	1.45
10 Ext R2	2	9.14	1.47
10 Ext R3	3	9.11	1.49
<i>Means</i>		9.2659	1.4710

A 3.2 Table of Results from Extended Mouldboard Experiment

File Name	Width (mm)	Depth (mm)	Speed (km/h)	Velocity (m/sec)	Mean Draught		Mean Vertical		Theoretical		Actual Area (m ²)	Specific Resistance kN/m ²	Actual SR kN/m ²
					Force (kN)	Force (kN)	Force (kN)	Force (kN)	Mean Moment (kNm)	Area (m ²)			
45 Nor R1	508	175	4.5	1.279	3.681	-0.063	-4.314	0.0711	51.753				
45 Nor R2	508	175	4.5	1.255	3.103	-0.202	-3.816	0.0711	43.633				
45 Nor R3	508	175	4.5	1.471	3.340	-0.177	-3.891	0.0711	46.963				
Means			4.5	1.335	3.375	-0.013	-4.007	0.0711	47.450	0.055		61.335	
75 Nor R1	508	175	7.5	2.332	3.735	-0.607	-4.018	0.0711	52.513				
75 Nor R2	508	175	7.5	2.371	3.232	-0.481	-3.140	0.0711	45.445				
75 Nor R3	508	175	7.5	2.501	3.314	-0.119	-3.921	0.0711	46.598				
Means			7.5	2.402	3.427	-0.323	-3.693	0.0711	48.185	0.058		58.977	
10 Nor R1	508	175	10	2.920	3.959	-1.024	-3.988	0.0711	55.669				
10 Nor R2	508	175	10	2.875	2.794	-0.316	-3.040	0.0711	39.284				
10 Nor R3	508	175	10	2.968	3.914	-0.970	-3.764	0.0711	55.031				
Means			10	2.928	3.556	-0.770	-3.597	0.0711	49.995	0.059		60.075	
45 Ext R1	508	175	4.5	1.190	3.695	-0.149	-4.406	0.0711	51.948				
45 Ext R2	508	175	4.5	1.172	3.806	-0.125	-4.376	0.0711	53.511				
45 Ext R3	508	175	4.5	1.169	2.956	-0.035	-3.657	0.0711	41.557				
Means			4.5	1.177	3.485	-0.103	-4.146	0.0711	49.005	0.062		55.768	
75 Ext R1	508	175	7.5	2.352	3.652	-0.841	-3.721	0.0711	51.351				
75 Ext R2	508	175	7.5	2.387	3.612	-0.388	-4.191	0.0711	53.593				
75 Ext R3	508	175	7.5	2.412	4.086	-0.436	-4.623	0.0711	57.452				
Means			7.5	2.364	3.650	-0.555	-4.179	0.0711	54.132	0.066		58.769	
10 Ext R1	508	175	10	2.787	3.930	-1.074	-3.752	0.0711	55.252				
10 Ext R2	508	175	10	2.912	3.929	-1.059	-3.792	0.0711	55.248				
10 Ext R3	508	175	10	2.855	4.108	-0.508	-4.350	0.0711	57.765				
Means			10	2.851	3.969	-0.860	-3.965	0.0711	56.088	0.070		57.277	

A 3.3 Analysis of Variance for Extended Mouldboard Soil Bin Studies

***** Analysis of variance *****

Variate: Horizontal_Force

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
MB	1	0.4675	0.4675	3.24	0.097
Speed	2	0.3572	0.1786	1.24	0.324
MB.Speed	2	0.100	0.0504	0.35	0.712
Residual	12	1.730	0.1442		
Total	17	2.6557			

* MESSAGE: the following units have large residuals.

units 14 -0.762 s.e. 0.310

***** Tables of effects and residuals *****

Variate: Horizontal_Force

MB response -0.322 s.e. 0.1790 rep. 9

Speed effects e.s.e. 0.1550 rep. 6

Speed	4.50	7.50	10.00
	-0.184	0.025	0.159

MB.Speed effects e.s.e. 0.2192 rep. 3

MB	Speed	4.50	7.50	10.00
Ext		-0.106	0.050	0.056
Nor		0.106	-0.050	-0.056

Units residuals s.e. 0.3100 rep. 1

units	1	2	3	4	5	6	7
	0.306	-0.271	-0.035	0.209	0.320	-0.530	0.308

units	8	9	10	11	12	13	14
	-0.195	-0.113	-0.198	-0.038	0.236	0.404	-0.762

units	15	16	17	18
	0.358	-0.059	-0.060	0.119

***** Tables of means *****

Variate: Horizontal_Force

Grand mean 3.614

	MB	Ext	Nor	
		3.775	3.452	
Speed	4.50	7.50	10.00	
	3.430	3.638	3.772	
MB	Speed	4.50	7.50	10.00
Ext		3.485	3.850	3.989
Nor		3.375	3.427	3.556

*** Standard errors of means ***

Table	MB	Speed	MB
			Speed
rep.	9	6	3
d.f.	12	12	12
e.s.e.	0.1266	0.1550	0.2192

*** Standard errors of differences of means ***

Table	MB	Speed	MB Speed
rep.	9	6	3
d.f.	12	12	12
s.e.d.	0.1790	0.2192	0.3100

*** Least significant differences of means (5% level) ***

Table	MB	Speed	MB Speed
rep.	9	6	3
d.f.	12	12	12
l.s.d.	0.3900	0.4777	0.6755

A 3.4 Analysis of Variance for Extended Mouldboard Field Experiment

***** Analysis of variance *****

Variate: Extended Mouldboard Field Data

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
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Blocks stratum	2	156.588	78.294	3.94	
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Blocks.WPLOTS stratum

Depth	1	127.596	127.596	6.42	0.127
-------	---	---------	---------	------	-------

Residual	2	39.752	19.876	27.02	
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Blocks.WPLOTS.SPLOTS stratum

Speed	1	249.706	249.706	339.42	<.001
-------	---	---------	---------	--------	-------

Depth.Speed	1	0.005	0.005	0.01	0.937
-------------	---	-------	-------	------	-------

Residual	4	2.943	0.736	0.72	
----------	---	-------	-------	------	--

Blocks.WPLOTS.SPLOTS.*Units* stratum

Mb	1	6.616	6.616	6.49	0.016
----	---	-------	-------	------	-------

Depth.Mb	1	2.117	2.117	2.08	0.159
----------	---	-------	-------	------	-------

Speed.Mb	1	0.913	0.913	0.9	0.351
----------	---	-------	-------	-----	-------

Depth.Speed.Mb	1	1.191	1.191	1.17	0.288
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Residual	32	32.62	1.019		
----------	----	-------	-------	--	--

Total	47	620.047			
-------	----	---------	--	--	--

* MESSAGE: the following units have large residuals.

Blocks 3 WPLOTS 5 SPLOTS 10

units 1 -2.39 s.e. 0.82

Blocks 3 WPLOTS 5 SPLOTS 10

units 4 2.07 s.e. 0.82

***** Tables of means *****

Variate: Linked_D

Grand mean 16.81

Depth	150	225
	15.18	18.44

Speed	4.5	10
	14.53	19.09

Mb	Ext	Nor
	16.44	17.18

Depth	Speed	4.5	10
	150	12.91	17.45
	225	16.15	20.73

Depth	Mb	Ext	Nor
	150	14.6	15.76
	225	18.28	18.6

Speed	Mb	Ext	Nor
	4.5	14.3	14.76
	10	18.58	19.6

Speed		4.5		10	
Depth	Mb	Ext	Nor	Ext	Nor
	150	12.62	13.19	16.57	18.33
	225	15.97	16.33	20.59	20.87

*** Standard errors of means ***

Table	Depth	Speed	Mb	Depth
	Speed			
rep.	24	24	24	12
e.s.e.	0.91	0.175	0.206	0.927
d.f.	2 4	32	2.15	

Except when comparing means with the same level(s) of

Depth	0.248
d.f.	4

Table	Depth	Speed	Depth
	Mb	Mb	Speed
	Mb		
rep.	12	12	6
e.s.e.	0.933	0.27	0.971
d.f.	2.21	18.36	2.59

Except when comparing means with the same level(s) of

Depth	0.291	0.382
d.f.	32	18.36
Speed	0.291	
d.f.	32	
Depth.Speed	0.412	
d.f.	32	
Depth.Mb	0.382	
d.f.	18.36	

*** Least significant differences of means (5% level) ***

Table	Depth	Speed	Mb	Depth
	Speed			
rep.	24	24	24	12
l.s.d.	5.537	0.687	0.594	5.28
d.f.	2 4	32	2.15	

Except when comparing means with the same level(s) of

Depth	0.972
d.f.	4

Table	Depth	Speed	Depth
	Mb	Mb	Speed
	Mb		
rep.	12	12	6
l.s.d.	5.191	0.802	4.786
d.f.	2.21	18.36	2.59

Except when comparing means with the same level(s) of

Depth	0.84	1.135
d.f.	32	18.36
Speed	0.84	
d.f.	32	
Depth.Speed	1.187	
d.f.	32	
Depth.Mb	1.135	
d.f.	18.36	

* Stratum standard errors and coefficients of variation *

Variate: Extended Mouldboard Field Data

Stratum	d.f.	s.e.	cv%
Blocks	2	2.212	13.2
Blocks.WPLOTS	2	1.576	9.4
Blocks.WPLOTS.SPLOTS	4	0.429	2.6
Blocks.WPLOTS.SPLOTS.*Units*			
	32	1.01	6

APPENDIX 4 SKIMMER STUDIES**A 4.1 Moisture Content From Skimmer Soil Bin Studies**

Soil Bin Prep	Moisture Content %	Density Mg/m3
1	8.1%	1.500
	7.7%	1.519
	7.4%	1.482
2	7.5%	1.476
	7.6%	1.582
	7.6%	1.572
3	8.2%	1.480
	9.1%	1.518
	8.1%	1.472
4	8.4%	1.537
	8.7%	1.602
	8.4%	1.536
5	8.6%	1.482
	7.9%	1.616
	8.4%	1.452
6	8.2%	1.526
	8.7%	1.597
	8.5%	1.490
7	8.3%	1.540
	8.4%	1.564
	8.4%	1.457

A 4.2 Complete Skimmer Soil Bin Results

Depth	Speed	Rake Angle	Approach. Angle	Draught (kN)	Vertical (kN)	Moment (kN)	Actual Speed (km/h)
50 mm	4.5	Normal	Normal	0.283	-0.017	-1.039	4.38
50 mm	7.5	Normal	Normal	0.423	-0.037	-1.569	8.28
50 mm	10	Normal	Normal	0.394	-0.037	-1.432	9.78
50 mm	4.5	Reduced	Normal	0.502	-0.070	-1.376	4.64
50 mm	7.5	Reduced	Normal	0.612	-0.057	-1.945	8.23
50 mm	10	Reduced	Normal	0.819	-0.122	-2.254	9.51
50 mm	4.5	Increased	Normal	0.367	0.063	-1.624	4.38
50 mm	7.5	Increased	Normal	0.533	0.158	-2.062	8.28
50 mm	10	Increased	Normal	0.554	0.107	-2.571	9.67
50 mm	4.5	Increased	Decreased	0.272	0.018	-1.089	4.62
50 mm	7.5	Increased	Decreased	0.373	0.020	-1.517	8.28
50 mm	10	Increased	Decreased	0.368	0.023	-1.546	9.62
50 mm	4.5	Normal	Decreased	0.173	-0.046	-0.596	4.34
50 mm	7.5	Normal	Decreased	0.277	-0.001	-1.219	7.41
50 mm	10	Normal	Decreased	0.274	-0.082	-0.922	10.03
50 mm	4.5	Reduced	Decreased	0.520	0.186	-1.812	4.43
50 mm	7.5	Reduced	Decreased	0.521	0.171	-1.895	8.00
50 mm	10	Reduced	Decreased	0.601	0.158	-1.934	9.77

50 mm	4.5	Reduced	Increased	1.224	-0.018	-3.302	4.30
50 mm	7.5	Reduced	Increased	1.182	-0.098	-2.512	8.05
50 mm	10	Reduced	Increased	1.409	-0.175	-3.577	9.51
50 mm	4.5	Normal	Increased	0.401	0.006	-1.460	4.24
50 mm	7.5	Normal	Increased	0.539	0.004	-1.975	7.91
50 mm	10	Normal	Increased	0.638	-0.016	-2.276	9.38
50 mm	4.5	Increased	Increased	0.393	0.071	-1.751	4.48
50 mm	7.5	Increased	Increased	0.740	0.029	-2.532	8.38
50 mm	10	Increased	Increased	0.535	0.108	-2.388	9.46

pushed to the extent of the cut width and was left partially across the bottom of the furrow. The profiles does, however slope away from the open furrow at the given mouldboard angle as for the 355mm wide furrow.

Finally, observations can be made of the soil throw and inversion achieved by each furrow setting by examining the chalk dust traces before and after each test run with the 355mm and 508mm wide furrows. Figure 3.18 to Figure 3.21 shows the soil surface and chalk traces before and after each test for the 355mm wide furrow setting.

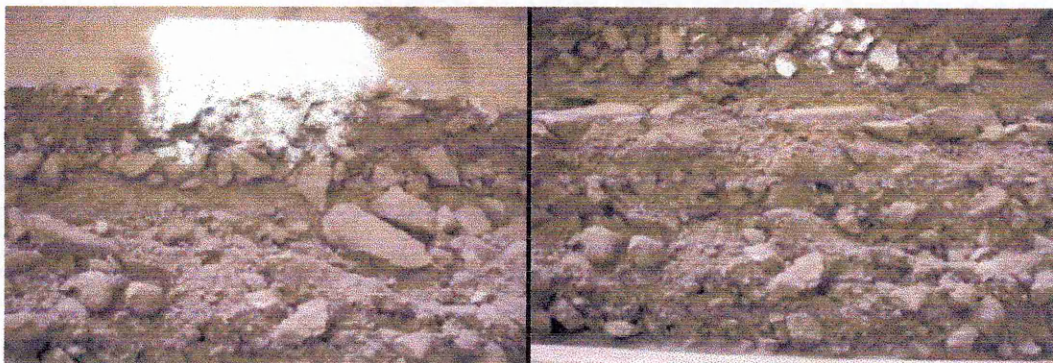


Figure 3.18, Before and After Photo, 355mm Wide, 200mm Deep

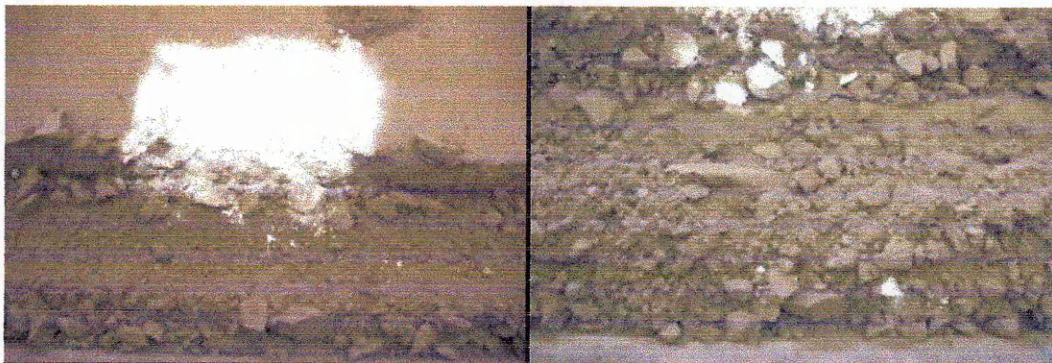


Figure 3.19, Before and After Photo, 355mm Wide, 160 mm Deep

Approach_Angle.Rake_Angle.Speed effects e.s.e. 0.1061 rep. 3

Approach_Angle	Rake_Angle	Speed	4.50	7.50	10.00
Decreased	Increased		0.017	-0.058	0.041
	Normal		-0.008	-0.004	0.012
	Reduced		-0.009	0.062	-0.053
Increased	Increased		-0.043	0.113	-0.069
	Normal		-0.029	-0.004	0.033
	Reduced		0.072	-0.109	0.036
Normal	Increased		0.026	-0.055	0.029
	Normal		0.037	0.008	-0.045
	Reduced		-0.063	0.047	0.016

Units residuals s.e. 0.1500 rep. 1

units	1	2	3	4	5	6	7
	-0.040	-0.010	0.051	-0.041	0.019	0.021	-0.077
units	8	9	10	11	12	13	14
	0.001	0.075	-0.034	-0.055	0.089	0.145	-0.158
units	15	16	17	18	19	20	21
	0.012	-0.048	-0.049	0.096	0.023	-0.025	0.003
units	22	23	24	25	26	27	28
	-0.145	0.164	-0.020	-0.123	0.001	0.123	-0.029
units	29	30	31	32	33	34	35
	0.071	-0.041	-0.080	0.056	0.025	-0.010	-0.084
units	36	37	38	39	40	41	42
	0.093	0.004	-0.024	0.021	-0.041	-0.031	0.073
units	43	44	45	46	47	48	49
	0.036	-0.055	0.019	0.021	-0.180	0.158	0.051
units	50	51	52	53	54	55	56
	-0.118	0.067	-0.033	-0.123	0.157	-0.272	0.041

units	57	58	59	60	61	62	63
	0.232	-0.687	0.306	0.381	-0.255	0.119	0.136
units	64	65	66	67	68	69	70
	-0.014	-0.007	0.020	-0.065	0.035	0.031	0.071
units	71	72	73	74	75	76	77
	-0.120	0.048	0.032	0.002	-0.035	-0.402	0.570
units	78	79	80	81			
	-0.167	-0.034	0.025	0.009			

***** Tables of means *****

Variate: Draught

Grand mean 0.546

Approach_Angle	Decreased	Increased	Normal
	0.375	0.763	0.498

Rake_Angle	Increased	Normal	Reduced
	0.460	0.378	0.800

Speed	4.50	7.50	10.00
	0.460	0.556	0.621

Approach_Angle	Rake_Angle	Increased	Normal	Reduced
Decreased		0.337	0.242	0.547
Increased		0.557	0.526	1.207
Normal		0.485	0.367	0.644

Approach_Angle	Speed	4.50	7.50	10.00
Decreased		0.321	0.391	0.414
Increased		0.673	0.757	0.861
Normal		0.384	0.522	0.589

Rake_Angle	Speed	4.50	7.50	10.00
Increased		0.344	0.549	0.486
Normal		0.286	0.413	0.435
Reduced		0.749	0.707	0.943

Approach_Angle	Rake_Angle	Speed	4.50	7.50	10.00
Decreased	Increased		0.271	0.373	0.368
	Normal		0.173	0.277	0.274
	Reduced		0.520	0.521	0.601
Increased	Increased		0.394	0.741	0.535
	Normal		0.401	0.539	0.638
	Reduced		1.224	0.989	1.409
Normal	Increased		0.367	0.533	0.554
	Normal		0.283	0.423	0.394
	Reduced		0.502	0.612	0.819

*** Standard errors of means ***

Table	Approach_Angle	Rake_Angle	Speed	Approach_Angle Rake_Angle
rep.	27	27	27	9
d.f.	54	54	54	54
e.s.e.	0.0354	0.0354	0.0354	0.0612

Table	Approach_Angle Speed	Rake_Angle Speed	Approach_Angle Rake_Angle Speed
rep.	9	9	3
d.f.	54	54	54
e.s.e.	0.0612	0.0612	0.1061

*** Standard errors of differences of means ***

Table	Approach_Angle	Rake_Angle	Speed	Approach_Angle Rake_Angle
rep.	27	27	27	9
d.f.	54	54	54	54
s.e.d.	0.0500	0.0500	0.0500	0.0866

Table	Approach_Angle	Rake_Angle	Approach_Angle
	Speed	Speed	Rake_Angle
			Speed
rep.	9	9	3
d.f.	54	54	54
s.e.d.	0.0866	0.0866	0.1500

*** Least significant differences of means (5% level) ***

Table	Approach_Angle	Rake_Angle	Speed	Approach_Angle
				Rake_Angle
rep.	27	27	27	9
d.f.	54	54	54	54
l.s.d.	0.1002	0.1002	0.1002	0.1736

Table	Approach_Angle	Rake_Angle	Approach_Angle
	Speed	Speed	Rake_Angle
			Speed
rep.	9	9	3
d.f.	54	54	54
l.s.d.	0.1736	0.1736	0.3007

***** No combined estimates (design orthogonal) *****

***** Stratum standard errors and coefficients of variation *****

Variate: Draught

d.f.	s.e.	cv%
54	0.1837	33.7

A 5.9 Reference Data, Ngamma, Nca and Nq Curves