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Abstract

This study has been undertaken to find what the effect of the gauge wheel is and how ground undulation can be measured and taken into account in ploughing analysis. The criteria have been good ploughing quality, good mobility and effective use of tractor power.

The ploughing quality was judged by uniform ploughing depth. The ploughing quality was divided into four classes. The first class is the ± 10 % requirement proposed by many researchers and the fourth class just keeps the ploughing in normal situations deep enough so that harrowing is not made difficult. The second class has a depth tolerance of ± 20 % and the third class has a ± 30 % tolerance.

Tractor mobility and use of engine power were judged by wheel slip, weight transfer and horizontal pulling force. When wheel slip was moderate and uniform and weight transfer was strong and uniform and pull force was moderate and uniform, then also mobility was good and power usage was effective.

The use of the gauge wheel at the end of the plough had many benefits. It reduced wheel slip and improved ploughing quality.

Undulation was measured by an inclination and a travel transducer. The system measured the profile of the field 'as seen by the tractor'. Both power spectral density and standard deviation of the profile height were calculated. The standard deviation was used in analysis because it gave better classification of the slope type and the required measuring distance was shorter. The test results showed that field undulation had a significant influence on ploughing quality.

Key words
Tractors, ploughs, gauge wheel, ground surface, power lift

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Symbols and abbreviations

a	profile coefficient
b	ploughing width
f_{Hz}	frequency, Hz
F_{HR}	force to start hitch to raise
F_{HL}	force to start hitch to lower
F_{lp}	parallel force at the end of the lower links
F_{lr}	perpendicular force at the end of the lower links
F_{ls}	standard deviation of the sensing force at the lower links
F_{lx}	horizontal force at the end of lower links
F_{ly}	vertical force at the end of lower links
F_t	upper link force
F_x	horizontal ploughing force
F_{xs}	standard deviation of ploughing draught
F_y	vertical ploughing force
F_{yt}	soil support force
F_{td}	force at the sensing element, upper link
F_{vd}	force at the sensing element, lower links
F_z	lateral ploughing force
F_{xv}	horizontal force at lower links
F_{yv}	vertical force at lower links
F_{zt}	force on the landside of the plough
H_{low}	setting value for the lowering speed of the hitch, 1 - 6
H_{mix}	setting value for the mixture control of the hitch, 1 - 6
H_{sen}	setting value for the sensitivity of the hitch, 1 - 6
H_{tv}	vertical distance of upper link connecting point from ground
H_v	vertical distance of lower links from ground
h	plough mast height
h_k	vertical distance between plough force center and lower links connecting points
h_o	distance from ground to the virtual hitch point
k	coefficient of specific resistance, total draught
k_s	static coefficient of specific resistance
L	wheelbase
l_o	distance from the virtual hitch point to the center of the rear axle
l_{tv}	horizontal distance between upper link connecting point and tractor rear axle
m	mass
n	number, profile coefficient
P	probability

P_{sp}	standard deviation of ploughing power
P_{sh}	standard deviation of the profile height
r	radius
R	regulation
R_{at}	vertical force of the gauge wheel
s	wheel slip
s_a	horizontal distance from plough force center to lower links connecting points
sd	standard deviation
s_f	tractor wheel slip, flat soil
s_{fs}	standard deviation of tractor wheel slip, flat soil
s_m	tractor wheel slip, modest slopes
s_{ms}	standard deviation of tractor wheel slip, modest slopes
s_t	horizontal distance from the gauge wheel to the connecting point of the lower links
s_c	rut slip, slip when ruts in the ground will be developed
t	ploughing depth
t_{sd}	standard deviation of the ploughing depth
V	vertical distance from the end of the lower links to the rear axle of the tractor
v	driving speed
x	distance
α_{tr}	tractor inclination
β	lower links position in relation to tractor chassis
γ	angle between the sensing element of the upper link and the longitudinal axis of the tractor
Δh	change of profile height during measuring interval
Δl	measuring interval
ΔR_e	force change at the front axle (weight transfer)
ΔR_t	force change at the rear axle (weight transfer)
ΔR_{tr}	total weight transfer of the tractor
ΔR_{trs}	standard deviation of total weight transfer of the tractor
ϵ	dynamic coefficient of specific resistance
λ	wavelength
ρ	coefficient of rolling resistance
$\Phi(f)$	power spectral density as a function of frequency
$\Phi(\Omega)$	power spectral density as a function of spatial frequency
Ω	spatial frequency, 1/m (cycles/m)
Ω_0	reference frequency, $\Omega_0 = 0.1$ 1/m

Preface

This study started at the University of Helsinki in the Department of Agricultural Engineering in 1990. During the years 1990 - 1991 a measuring system was developed to collect data during ploughing. In 1992 this system was further developed and a test series was done at the State Research Institute of Engineering in Agriculture and Forestry (VAKOLA).

I would like to thank all the persons who at these institutes have taken part in this study. Especially I would like to thank professor Aarne Pehkonen for providing me the time and the facilities to do the work and professor Jorma Pitkänen for the support during the work. DI Kauko Savolainen of Valmet Tractors I would like to thank for the modifications in the power lift. My family I would like to thank for their patience.

Vihti 24 February 1995 Jukka Ahokas

1. INTRODUCTION

Ploughing is the oldest tillage method, known from ancient sagas and drawings. Initially the plough was only a branch or a stub of wood, which did not turn the soil, but made a groove. After the middle of the 18th century the plough material changed from wood to metal, which lead to lighter pulling forces and faster working speeds. Oxen were replaced by horses. When tractors were taken into use at the end of the 19th century, working power was increased dramatically. Working speeds and working depths were increased, which necessitated a change in the shapes of ploughs. When tractors were equipped with hydraulic lifts in the late 1930s, the way of ploughing and plough design was further changed.

Ploughing has remained one of the most demanding tillage operations, over which the operator has a remarkable influence on quality, resulting in ploughing contests up to World Champion level.

Ploughing is still used in modern times and in most places it is the fundamental tillage operation. The principle has changed during the decades: no longer is it a method of harrowing the ground surface, but it is a power demanding operation where the whole ground surface is turned over. In addition to traditional uses, ploughing is undertaken to cover residuals, weeds and plant diseases.

The arable field area in Finland is 2.5 million hectares of which about 1.5 million hectares are ploughed annually. This means that 3 milliard cubic metres of soil are turned over every year. During this operation about 25 tons of iron is deposited into soil because of wear and some 15 - 20 million litres of fuel is used. In comparison the largest water canal in Finland, the Saimaa canal, has a water volume of about 6 million cubic metres and it took about five years to rebuild it.

There have been few ploughing studies during the last twenty years, the majority of them have been undertaken in countries where mechanization of agriculture is in its infancy. In western countries most of the studies or measurements have been done during product development by the tractor or plough manufacturers and these results are not usually published.

There has been an increase in the use of automation in agriculture and navigation systems will, at least in theory, make it possible to have automatic driving systems in the future. There are, however, many instances where the operator is needed, not to steer the vehicle, but to adjust and control the implement and to oversee special situations such as wet and slippery conditions. The automation of ploughing uses the same principle introduced by Harry Ferguson 60 years ago which works well in good conditions and on smooth fields. When towed ploughs were used, they were supported by their own wheels. In the Ferguson system the plough does not have a supporting wheel because the tractor supports the plough. Part of the weight of the plough is carried by the tractor thus increasing the tractive performance of the tractor. The result was that gauge wheels on ploughs were considered unnecessary because they would lessen the weight transfer and also reduce the functioning of the tractor lift. Farmers, however, have used gauge wheels widely. First they were mounted on the middle of the plough and nowadays they are at the rear end of the plough. There has been uncertainty about the use of gauge wheels and there are no broad academic studies published on the subject.

Ploughing measurements are usually performed on even and level fields to exclude one variable, the ground profile. There has not been a practical method of measuring the effect of ground undulation which in practice has a great influence on ploughing quality. The slopes, hills and valleys introduce a change in tractor and plough inclination and it is especially difficult to maintain an even working depth with long ploughs. Undulation also introduces changes in soil type, in ploughing draught and in traction conditions all of which affects the ploughing quality.

In this study two subjects have been focused on, the effect of the rear gauge wheel and the effect of the ground undulation. The aim has been to clarify the use of the gauge wheel and to introduce a method with which ploughing measurements can be performed under 'normal' conditions leading to the development of better control systems for ploughing. Up until now the driver has been needed to make adjustments during ploughing in difficult conditions: the control system of the tractor hitch cannot work reliably in variable conditions.

This study started in 1990 at the Department of Agricultural Engineering in The University of Helsinki. During the years 1990 and 1991 an instrumentation system was built on a Valmet 805-4 tractor to measure implement forces, ploughing depth and tractor performance. The system was further developed at the State Research Institute of Engineering in Agriculture and Forestry (VAKOLA) in 1992.

As the purpose of this work was to study the effect of the gauge wheel and ground undulation, not to compare different models of tractors or ploughs, the same test tractor was used in all tests. If a different type of tractor had been used, the power hitch would probably have functioned differently. The tests were performed from pure position control to pure draught control and thus the results include the whole setting area of the tractor power lift. The plough was different during tests in 1992 from those in 1990-1991. There were hardly any differences in the behaviour of these two ploughs. A different plough type, for instance a reversible plough, would have affected the results, but the effect of the gauge wheel and ground undulation would be similar.

2. REQUIREMENTS FOR PLOUGHING QUALITY AND TRACTOR DRAUGHT CONTROL SYSTEM

2.1. Ploughing depth and ploughing profile

Ploughing depth in Finnish conditions is usually between 20 - 25 cm. Going deeper should be avoided because it brings raw soil into the organic top layer reducing the yield for many years. If the subsoil, however, has minerals, this is not harmful. Ploughing force is also increased noticeably if the ploughing depth is increased. For instance when the plough penetrates the compacted soil layer, the increase in ploughing force can be almost 50 % *[1]*.

A ploughing depth of 15 - 20 cm is recommended if the condition of the subsoil is poor. If this kind of soil is ploughed too deep, the amount of organic materials in the top layer is reduced because it is mixed into a large soil volume *[2]*. A shallow working depth can also increase the amount of weeds. One of the basic purposes of ploughing is to cover plant residues and weeds and to prevent them interfering in tillage and seeding, therefore the ploughing depth should be deeper than harrowing depth. Harrowing depth for cereals is usually less than 10 cm and therefore the ploughing depth should be more than 10 cm. Thin furrow slices can also make harrowing more difficult. The thin slices do not always break into small aggregates but they will produce soil lumps. This occurs especially when harrowing takes place soon after ploughing, for instance for winter cereals. *[3],[4]*

The ground profile after ploughing has also a significant influence on tillage. If the differences in profile height on clay soils are more than 10 cm, harrowing will become difficult, because the harrow tines will not reach in the deep hollows and they are filled with dry soil resulting in poor germination *[5]*. The ploughing profile will be even if the ploughing depth is even and if tractor wheel slip is not high.

Ploughing depth depends on cutting width. If the depth is too great, then the slice does not turn over properly. The maximum working depth is therefore normally 0.7 - 0.9 times the cutting width. Ploughing depth should follow the ground surface as closely as possible. If there are ruts or other short undulation on the surface, the depth should not change but should follow the 'original' surface.

Bjerninger [6] gives for the depth changes ± 10 % tolerance from the mean value, based on experiments made with towed ploughs. *Skalweit [7]* and *Seifert [8]* suggest that ploughing depth tolerance should be ± 10 % of the mean value when the ploughing depth is about 18 - 25 cm.

Dwyer, Crolla & Pearson [9] reported that operators tried to keep the standard deviation of ploughing depth within ± 5% limit. When 99,7 % probability is used the tolerance for ploughing depth is three times the standard deviation. This means that operators would allow ± 15 % changes in working depth. If the depth variation was larger they would manually adjust it.

The ± 10 % tolerance is given at a time when either towed ploughs were mainly in use or the mounted ploughs were of two furrow type. Nowadays the ploughs are mounted and they have at least three furrows. With long mounted ploughs it is more difficult to achieve an even depth, especially on undulating fields. *Cowell & Len [10]* reported that ± 10 % tolerance could be achieved on level ground but not on an undulating field, and especially not with multifurrow ploughs. They also considered the ± 10 % tolerance as an ideal target, excursions beyond this limit may be acceptable, if not occurring too frequently. *Dwyer, Crolla & Pearson [9]* stated that there is no strong agronomic reason why ploughing depth should have ± 10 % or ± 15 % tolerance.

A uniform ploughing depth can be estimated with probabilities. Ploughing depth is a continuous value that has normal distribution. Probabilities for this can be calculated by Gaussian principle, Eqn (1).

$$P = \frac{1}{\sqrt{2\pi}} \int_{t_1}^{t_2} e^{-t^2/2} dt$$

$$t = \frac{x - x_{ka}}{sd}, \quad t_1 = \frac{x_1}{sd}, \quad t_2 = \frac{x_2}{sd} \qquad (1)$$

P = probability

x_{ka} = mean

sd = standard deviation

The probabilities of changes in depth are shown in Fig. 1 where the probability is drawn as a function of standard deviation of depth. If, for example, the standard deviation of ploughing depth is 20 mm, this means that the working depth is between ± 25 mm with 76 % probability and between ± 50 mm with 98 % probability. Under Finnish conditions the normal working depth is between 20 and 25 cm. When the mean depth is 25 cm ploughing depth evenness can be classified in the following manner:

Class 1. Working depth tolerance is ± 10 % (± 2.5 cm). With 99 % probability this means that standard deviation can be about 1 cm. It is more realistic to use 90 % probability because ploughing depth measurement has because of uneven ground and furrow surfaces a large variation. Corresponding standard deviation is 1.5 cm. This class can be designated **very good** ploughing depth evenness.

Class 2. Working depth tolerance is ± 20 % (± 5 cm). With 99 % probability standard deviation should be 2 cm. This class can be designated **good** ploughing depth evenness.

Class 3. Working depth tolerance is ± 30 % (± 7.5 cm). With 99 % probability this means 3 cm standard deviation. This class can be designated **satisfactory** ploughing depth evenness.

Class 4. Working depth tolerance is ± 40 % (± 10 cm). With 99 % probability standard deviation is 4 cm. In this class the ploughing depth is deeper than 10 cm if the mean depth is 20 cm or more. This means that there should be no problems with tillage, ploughing depth is deeper than harrowing depth. This class can be designated **fair** ploughing depth evenness.

These four classes are used in this study when evenness of ploughing depth is estimated.

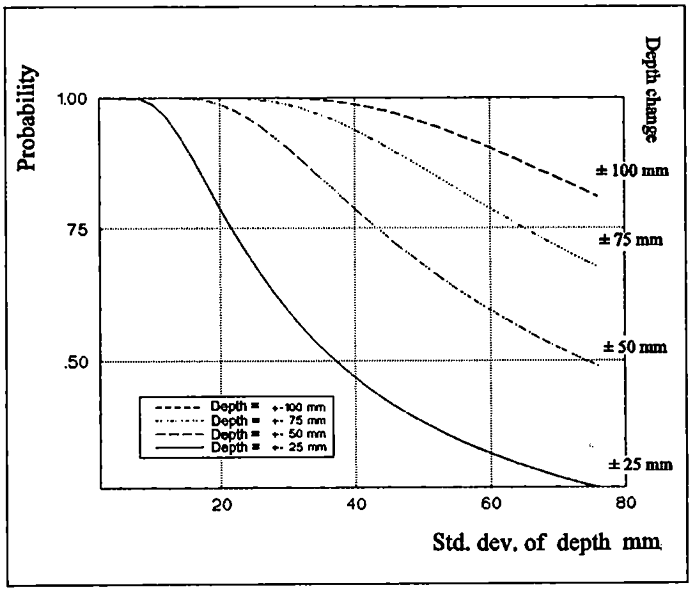


Fig. 1. Probabilities of working depth changes as a function of standard deviation.

On towed ploughs the working depth is controlled by the front and rear support wheels. With these ploughs working depth follows well ground contour. Ruts in the field or similar interferences can change the working depth temporary. On semi-mounted ploughs the depth of the last furrow is controlled by the rear wheel of the plough and the depth of the first furrow is controlled by the tractor. Because the tractor serves as front support, ploughing depth variation of the first slice is slightly greater than with towed ploughs. With mounted ploughs the working depth is mostly controlled by the tractor. This has commonly led to unsatisfactory ploughing quality. The ploughs are equipped with gauge wheels to improve depth evenness. Initially they were mid-mounted but later rear-mounted. With midmounted gauge wheels working depth is more even, but weight transfer from the plough to the tractor is poor. With rear-mounted gauge wheels ploughing depth may vary more, but weight transfer is better.

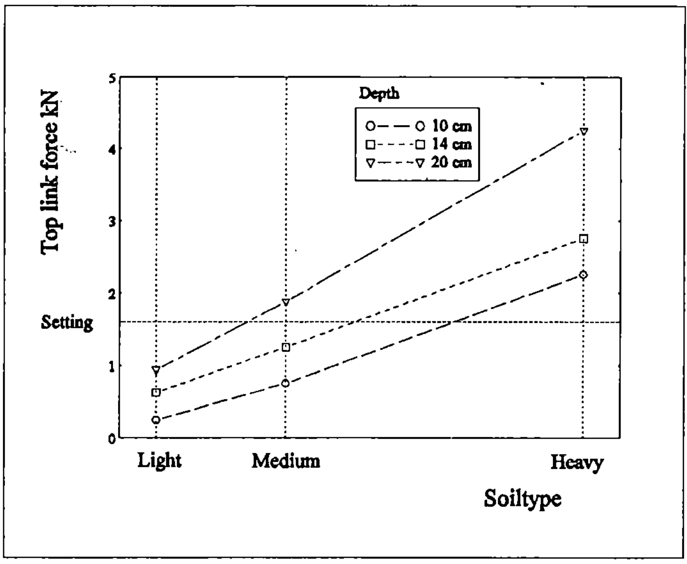


Fig. 2. Example of depth change when soil type changes. *[7]*

When the plough is controlled by the tractor power lift, changes in soil vary the sensing force of the power lift causing the ploughing depth to vary. An example of this is in Fig. 2. With the marked setting value, ploughing depth would change from under 10 cm to more than 20 cm when soil type changes from heavy to light. If the ploughing depth is to be even the operator must change the power lift settings during ploughing.

2.2 Draught force

The function of tractor draught control is to maintain an even pull. The driver sets the level and the control system will keep it within certain tolerances. This will keep both the pulling force and power of the tractor even. Tractor mobility and use of engine power will increase. With draught control, ploughs can be lighter and cheaper and they are easier to transport and safer to use (no rearward overturns).

Draught control must function in relation to agronomic demands, keeping the draught force even, it also must keep the working quality good.

2.2.1 Forces acting on plough mouldboard and tractor

Soil reactions on the plough mouldboard are presented in Fig. 3. Cutting, moving and breaking of soil causes a pressure on the mouldboard. Normally this is presented with three forces acting on the force centre. This is not a fixed point but its place changes because pressure and forces change. *[11],[12]* For instance *Bernacki & Haman [13]* place the force centre halfway along the slice width and one third of the ploughing depth. *Wilkinson & Braunbeck [14]* place it one fourth of the slice width from landside and one fourth of the ploughing depth.

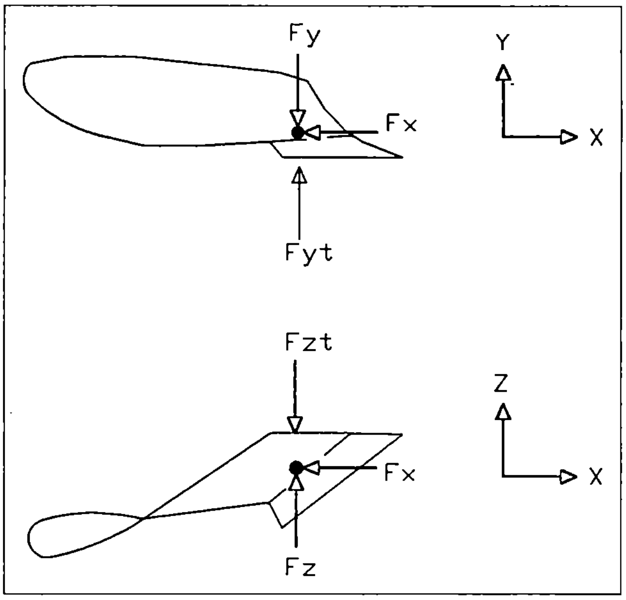


Fig. 3. Soil reaction on a mouldboard

The lateral ploughing force F_z in Fig. 3 is supported by the landside of the plough, F_{zt}. Vertical force F_y is partly supported by the soil, F_{yt} and partly by the tractor and the gauge wheel of the plough. Longitudinal force F_x is the ploughing resistance and the tractor must produce sufficient pulling force.

Specific ploughing resistance can be presented according to *Gorjatschkin (ref. Bernacki & Haman [13] p. 132*) with Eqn (2).

$$F_x = \rho mg + k_s bt + \varepsilon tbv^2 \tag{2}$$

F_x = ploughing force
ρ = coefficient of rolling resistance
m = mass of the plough
k_s = static coefficient of specific resistance
b = ploughing width
t = ploughing depth
ε = dynamic coefficient of specific resistance
v = ploughing velocity

Static coefficient of specific resistance k_s gives the draught at zero velocity. The coefficient depends mainly on soil type, moisture content and compaction. Dynamic coefficient depends on plough shape.

Often ploughing force is calculated according to Eqn (3). In this k is the total resistance coefficient. It includes both soil and plough properties and it depends also on driving speed. Normally the driving speed is also given together with k-value.

$$F_x = kbt \tag{3}$$

k = coefficient of total resistance

Longitudinal and vertical forces acting on a mouldboard plough are presented in Fig. 4. Forces F_{xv} and F_{yv} act on the tractor lower links, force F_t acts on the upper link. F_y is the total vertical force of the plough. It includes both the mass of the plough and supporting forces under the mouldboards. If the gauge wheel of the plough is used, it will carry part of the vertical F_y force. The forces on the tractor links can be calculated with Eqns (4).

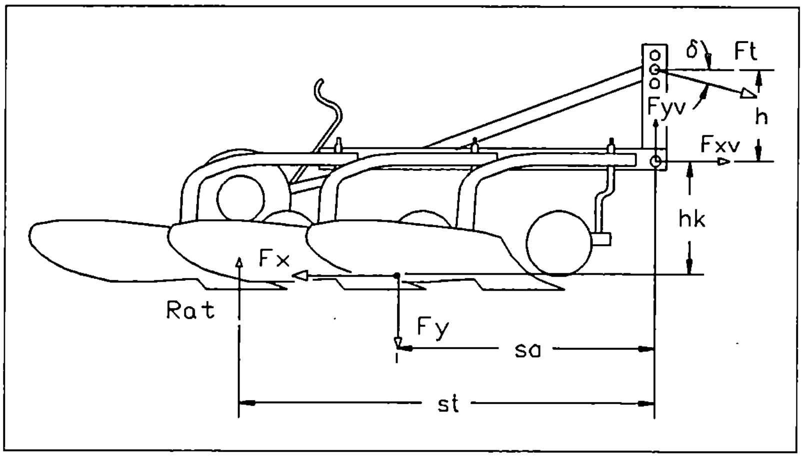


Fig. 4. Longitudinal and vertical forces acting on a plough.

$$F_{xv} = F_x\left(1+\frac{h_k}{h}\right) - F_y\frac{s_a}{h} + R_{at}\frac{s_t}{h}$$

$$F_{yv} = F_y\left(1+\frac{s_a}{h}\tan\delta\right) - R_{at}\left(1+\frac{s_t}{h}\tan\delta\right) - F_x\frac{h_k}{h}\tan\delta \tag{4}$$

$$F_t = \frac{F_y s_a - R_{at} s_t - F_x h_k}{h\cos\delta}$$

h = plough mast height

h_k = vertical distance from plough force centre to lower links connecting points

F_t = upper link force

δ = upper link angle

F_{xv} = horizontal force at lower links

F_{yv} = vertical force at lower links

R_{at} = vertical force of rear wheel

s_a = horizontal distance from plough force centre to lower links connecting points

s_t = horizontal distance from rear wheel to lower links connecting points

2.2.2 Uniform draught force

Forces at the connecting points of the plough act on the tractor as shown in Fig. 5. If the tractor draught control works with upper link sensing, then the control force is F_{td}. The upper link and the sensing element may not be parallel. In Fig. 5 the sensing element has an angle γ from the longitudinal axis of the tractor. If the draught control works with lower link sensing, then the sensing force is F_{vd}. Also the lower links may not be parallel with the longitudinal axis of the tractor. In Fig. 5 they have an angle β which angle is often near zero so that its effect is neglictable.

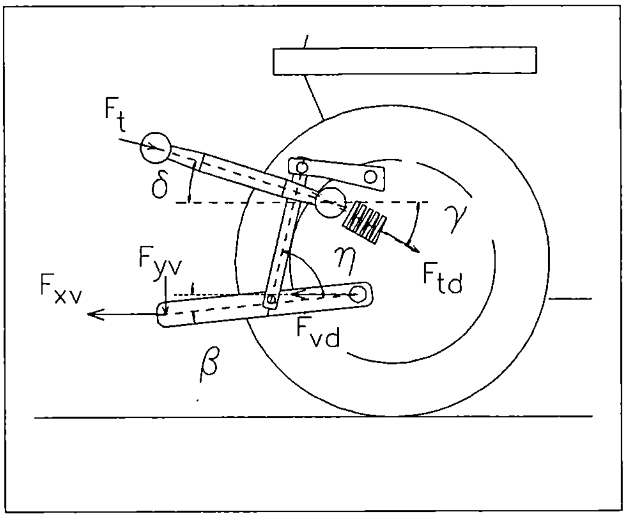


Fig. 5. Draught control forces, F_{vd} is sensing force at the sensing element of lower links, F_{td} is sensing force at sensing element of upper link.

The sensing forces can be calculated with Eqn (5).

$$F_{td} = \left(F_y \frac{s_a}{h} - R_{at} \frac{s_t}{h} - F_x \frac{h_k}{h}\right) \frac{\cos \delta}{\cos \gamma}$$

$$F_{vd} = F_x \left(1 + \frac{h_k}{h}\right) - F_y \frac{s_a}{h} + R_{at} \frac{s_t}{h} \qquad (5)$$

F_{td} = upper link sensing element force
F_{vd} = lower links sensing element force
γ = angle between upper link sensing element and longitudinal axis of the tractor

In these equations the lower link angle β is zero. In both sensing systems the sensed force depends on three forces, vertical and horizontal force of the plough and the gauge wheel support force of the plough. So not only do the draught forces affect on the control system but also the vertical forces. When the support force of the gauge wheel changes, the force at the sensing element also changes. This will happen, for instance, when the inclination of the tractor is changing. Thus the gauge wheel will help in sensing undulating ground profiles. The effect of vertical forces depends also on the lever arms: with heavier and longer ploughs the effect of vertical forces is increased.

The gauge wheel carries part of the vertical force F_y of the plough. This reduces the vertical force carried by the tractor hitch, but it will increase the pull on the lower links and compression on the upper link. When ploughing depth or ground surface profile changes, this changes the gauge wheel force. The change in sensing force will be larger than the change in draught alone would make. The gauge wheel will gain the sensing force during changes and thus it will make the power lift to function more effectively.

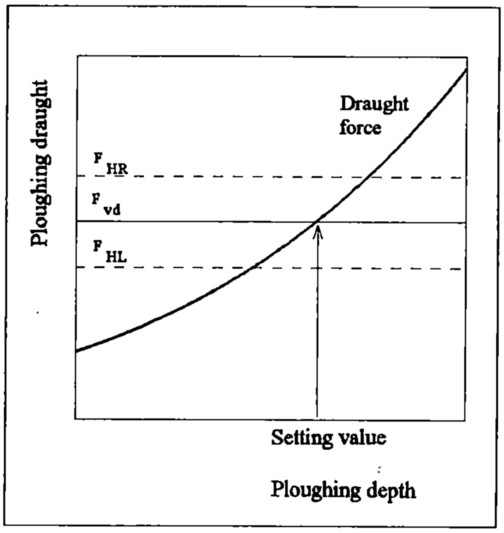


Fig. 6. Regulation forces.
F_{vd} = setting value of draught
F_{HR} = force to start hitch to raise
F_{HL} = force to start hitch to lower

In tractor power lifts, regulation is used to determine the quality of draught control. It is the difference between the average forces that cause the hitch to raise and lower itself, Eqn(6).

$$R = \frac{F_{HR} - F_{HL}}{F_{HR}} \, 100 \ \% \qquad (6)$$

R = regulation
F_{HR} = force to start hitch to raise
F_{HL} = force to start hitch to lower

This difference is compared to the average force, which caused the hitch to raise. *Morling [15]* gives 10 - 15 % regulation as an acceptable value and *Henninghaus [16]* suggests an acceptable value to be under 20 %. Regulation is used only for pure draught control. When the mixture control between draught and position control is in use regulation cannot be used. *[17],[18],[19]*

2.3 Ploughing power

The torque back-up ratio of the tractor engine is specified by the torque increase when engine speed decreases 30 % from the nominal speed. Tractors with medium-sized engines have a torque back-up ratio of 15 - 30 %. When the draught force changes remain below this value, engine power can be utilized well. If the fluctuation is greater, the driver has to change gear while working or he has to use continuously a lower gear. This will reduce the work rate and tractor engine power utilization. When draught control is in use, it will maintain the pulling force at the same level. With even draught there is also even ploughing power.

2.4 Tractor weight transfer

It is often more interesting to know the changes in axle forces than the total forces. These changes are calculated in relation to the basic axle forces of the tractor without the plough and they are called 'weight transfer'. Weight transfer is important in tractor operations. With mounted implements the tractor rear axle weight can be increased considerably making it possible to pull heavy implements with modest wheel slip and high power. It also reduces soil compaction because extra ballast is not needed. Weight transfer should stay as constant as possible, because changes in weight transfer will affect strongly the mobility of the tractor. During ploughing, the draught force is changing because soil type and ploughing depth change, causing changes in weight transfer. The gauge wheel of the plough also affects weight transfer. When it is in use, the tractor front axle will have more and the rear axle less weight.

Besides these there are other factors which influence the weight transfer and its changes. The condition and shape of the share point of the plough greatly effects weight transfer. In modern ploughs the share points are normally curved down, which increases the penetration force into the soil. If the share point is not curved down, it is more difficult to maintain this force. Should the shares be worn the landside and the share will carry a greater part of the weight of the plough and weight transfer to the tractor will be considerably reduced *[1]*.

Adjustment of the plough and the tractor hitch also affects weight transfer. If the plough is improperly adjusted, such as the mouldboard being inclined against the furrow slice, the weight transfer is weakened.

If the ploughing draught is high, then the front of the tractor will rise. This will increase weight transfer from the front axle to the rear axle, but it is also likely that the soil will carry a larger part of the weight of the plough and weight transfer from the plough will be weakened.

The ploughing forces can act on the tractor with two different ways. When the hydraulic lift is supporting the plough, the vertical ploughing force (Fy in Fig. 4) is carried by the tractor and by the gauge wheel. The tractor-plough combination is acting like a rigid system.

When the hydraulic lift does not support the plough the linkage acts as a free link system. The resultant ploughing forces pass through the virtual hitch point which is the intersection of the forces in the upper link and lower links. When the tractor lift lowers the plough the lift is not supporting it and the system acts like a free link.

2.4.1 Rigid system

When the plough is supported by the hydraulic lift the effect of ploughing forces on the tractor axle forces can be calculated according to Fig. 7 and Eqn (7). In Eqn (7) the lower link angle β is similar to that in Eqns (5) assumed to be zero.

$$\Delta R_e = \frac{F_t(l_{tv}\sin\delta - H_{tv}\cos\delta) - F_{xv}H_v - F_{yv}V}{L}$$

$$\Delta R_t = F_{yv} - F_t\sin\delta - \Delta R_e \qquad (7)$$

$$\Delta R = \Delta R_e + \Delta R_t$$

ΔR_e = weight transfer at the front axle
ΔR_t = weight transfer at the rear axle
ΔR = total weight transfer
l_{tv} = horizontal distance from upper link connecting point to tractor rear axle
H_{tv} = vertical distance of upper link connecting point from ground
H_v = vertical distance of lower links from ground
V = vertical distance from lower link ends to tractor rear axle
L = wheelbase

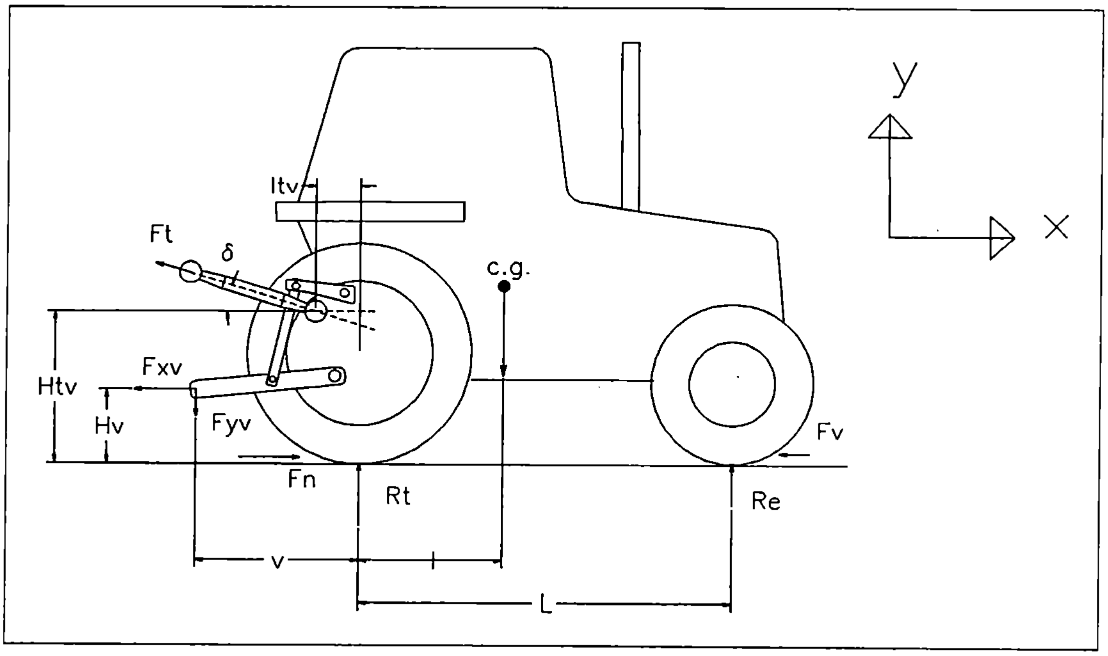


Fig. 7. Weight transfer forces in a rigid system.

In the rigid system the angle of the upper link has an effect on weight transfer. If it is inclined, then part of the vertical ploughing forces will go through it. When the ploughing draught changes, also the weight transfer will change.

2.4.2 Free-link system

When the hydraulic lift is not supporting the plough it can move vertically free. In equilibrium the ploughing resultant passes through the virtual hitch point, Fig. 8. The virtual hitch point is also the instant centre around which the implement will rotate during vertical movements. The virtual hitch point is not a fixed point but it will move during implement lowering or raising because of the tractor link geometry.

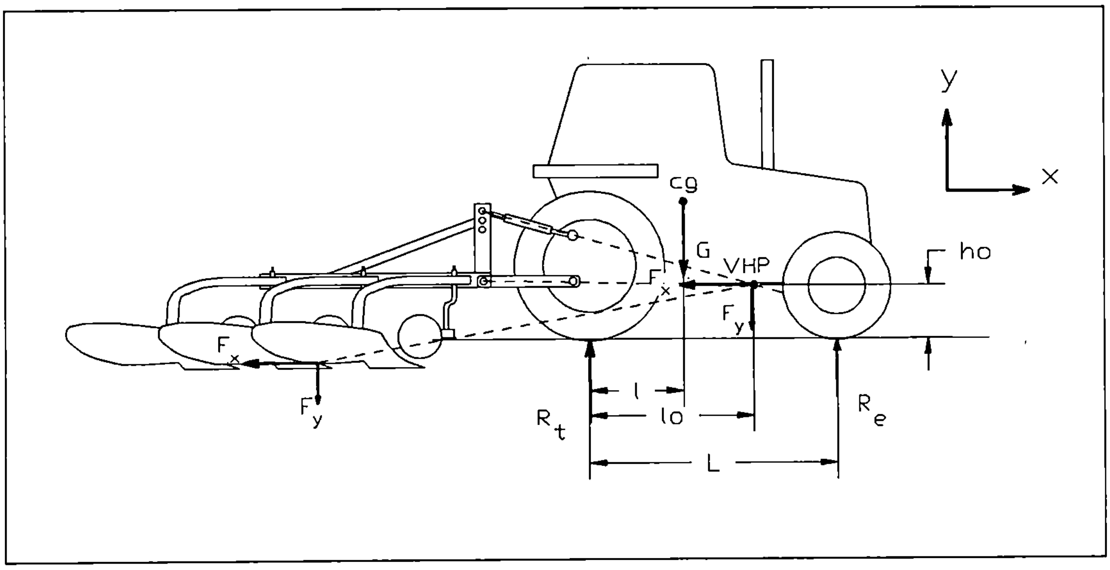


Fig. 8. Weight transfer forces in a free link system. VHP = virtual hitch point.

The effect of ploughing forces on the tractor axle forces can be calculated according to Eqn (8).

$$\Delta R_t = \frac{L - l_o}{L} F_y + \frac{h_o}{L} F_x \qquad (8)$$

$$\Delta R_e = \frac{l_o}{L} F_y - \frac{h_o}{L} F_x$$

l_o = horizontal distance from virtual hitch point to tractor rear axle

h_o = vertical distance from virtual hitch point to ground

In the free link system the angle of the upper link has an effect on weight transfer and ploughing depth. By changing its inclination also the virtual hitch point will move and ploughing depth and weight transfer will change.

The plough acts according to the free link system only when the tractor lift does not have a vertical supporting force. This can happen at the start of the ploughing when the plough penetrates into the soil and during ploughing when the tractor power lift makes a lowering correction.

2.5 Wheel slip

Wheel slip has an effect on soil structure and traction efficiency. If wheel slip is too high, the wheels will dig ruts into the field and destroy the soil structure. Increased slip also decreases traction efficiency because power is consumed in slippage.

Ruts will be formed when the wheel slip exceeds a certain limit. This limit can be calculated using Eqn (9). *[20], [21],[22]*

$$s_c = \frac{2\pi r}{nx}$$

$$x = r \Rightarrow s_c = \frac{2\pi}{n} \tag{9}$$

s_c = wheel slip, when ruts will be developed
x = distance, starting point from the front of tyre-soil contact area
r = wheel radius
n = number of lugs on circumference

The soil between two tyre lugs will be completely cut off when the soil displacement under the tyre is equal to lug clearance. When the tyre or soil deflection is about 15 % of the tyre radius, the contact length is supposed to be equal to the tyre radius. There are normally some 20 lugs on a tractor tyre. This means that a rut will be formed when the wheel slip is about 30 %. If the soil block is cut off, it will easily stick between the tyre lugs and the tread becomes clogged.

Wheel slip varies during work, Fig. 9 shows the changes in wheel slip when the standard deviation is 25 % of the mean value. At about 20 % wheel slip the maximum wheel slip is about the same as the cutting slip in a normal agricultural tyre. From this a recommendation can be given that over 20 % wheel slips should be avoided, because slip ruts will occur in the ground.

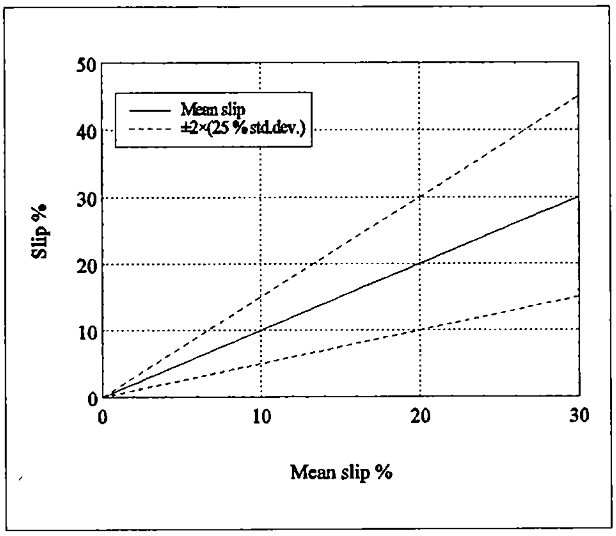


Fig. 9. Slip variation as a function of mean slip. Standard deviation of slip is 25 % and propability is 95 %.

Wheel slippage is also dependent on the draught force and weight transfer. When these are uniform then often wheel slippage is also uniform. If soil conditions are changing, traction is changing and this causes variations in wheel slippage.

3. INSTRUMENTATION AND MEASURING METHODS

3.1 The tractor and the plough

The test tractor was a Valmet 805-4 four-wheel-drive tractor. It was equipped with Bosch Hitch-Tronic electronic hitch control system, Fig. 10. The maximum PTO power was 66.6 kW and the mass of the tractor was 3840 kg. The technical specifications of the tractor are shown in Appendix 1.

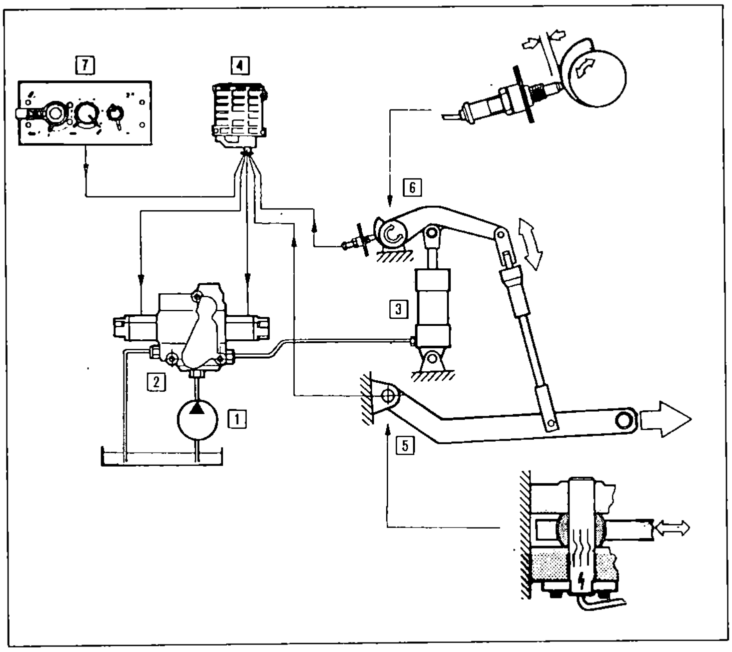


Fig. 10. Principle of the Bosch Hitch-Tronic hitch control system.
1 = hydraulic pump
2 = control valve
3 = lift cylinder
4 = electronic control unit
5 = force sensors
6 = position sensor
7 = control panel.

Table 1. Power lift settings of the test tractor

Control	Setting value 1 - 6
Lowering speed	Slow - Fast
Sensitivity	Low - High
Mixture	Position - Draught

The control panel of the power lift had settings for lowering speed, sensitivity control and mixture control. In the tests the power lift settings were numbered from one to six. The meaning of the setting values are in Table 1 and the functioning principle of the power lift is in Fig. 11. A low setting value means slow lowering speed, low sensitivity or position control. A high setting value means fast lowering speed, high sensitivity or pure draught control.

The tests were run with the front axle drive engaged. The front axle had an automatic differential lock. The rear axle differential lock was not engaged during the test runs.

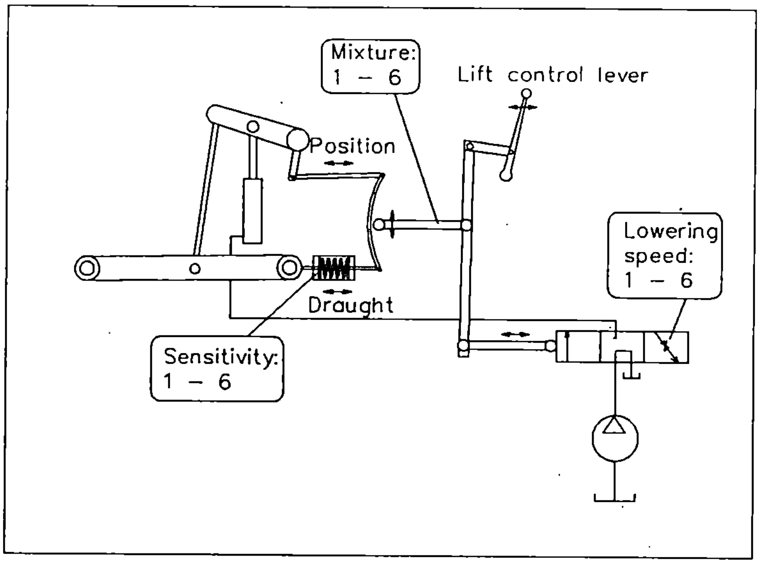


Fig. 11. Functioning principle of tractor power lift.

The test plough was a four-furrow Överum CI 487. During the tests the cutting width was adjusted to 36 cm and the total ploughing width was 144 cm. The total mass of the plough was 850 kg. The technical specifications of the plough are shown in Appendix 2. The plough was equipped with a gauge wheel at its rear.

3.2 Instrumentation

The principle of the test instrumentation is shown in Fig. 12. The system was first used in 1991 and the system, its calibration procedures and inaccuracies are described in detail in reference *[21]*. In 1992 it was developed further. Measurements of front depth, first slice width and support force of the gauge wheel were added. The measured data was collected with a portable PC-computer, which had a data acquisition board inside. In 1991 a Toshiba 5200 computer with National Instruments AT-MIO 16 acquisition board was used. In 1992 a Compaq Portable computer with Data Translation DT2835 acquisition card was used. The measuring frequency was between 20 - 50 Hz in one measuring channel. The measured data was saved in files and they were analysed with a PC-computer.

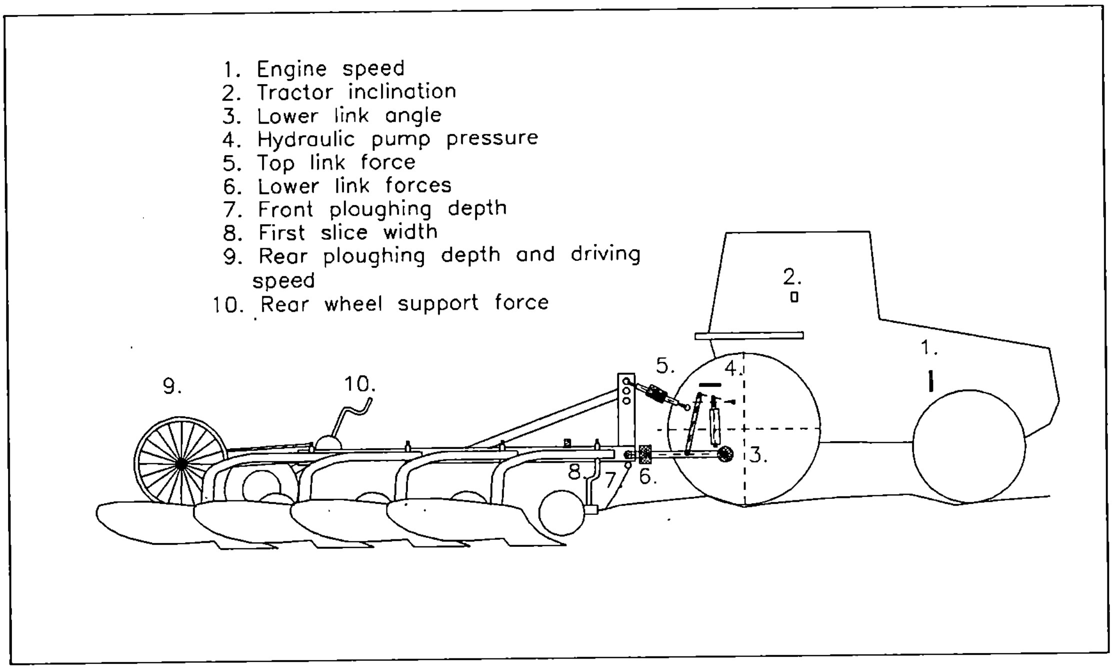


Fig. 12. Instrumentation principle

3.3 Ploughing depth

Ploughing depth was measured both at the front and at the rear of the plough, Fig. 12, sections 7 and 9. The front ploughing depth was measured as the distance from the plough chassis to the soil surface, Fig. 13. This method could be used because the measuring ski was in the middle of the lower links connecting points. In this location sideways inclinations of the plough do not affect the measurement.

The rear ploughing depth was measured with two wheels. One wheel was in the furrow and the other wheel was on the ground surface, Fig. 13. The picture shows that the surface of the ground was not even. The accurate measurement of the depth was hindered because there were lumps of soil left within the furrow. To reduce the disturbances the measured values were filtered with digital FIR low pass filtering *[32]*. The cutoff frequency was calculated from a situation when the wheel went over a lump of soil, Fig. 14. The length of the disturbance can be calculated with Eqn (10).

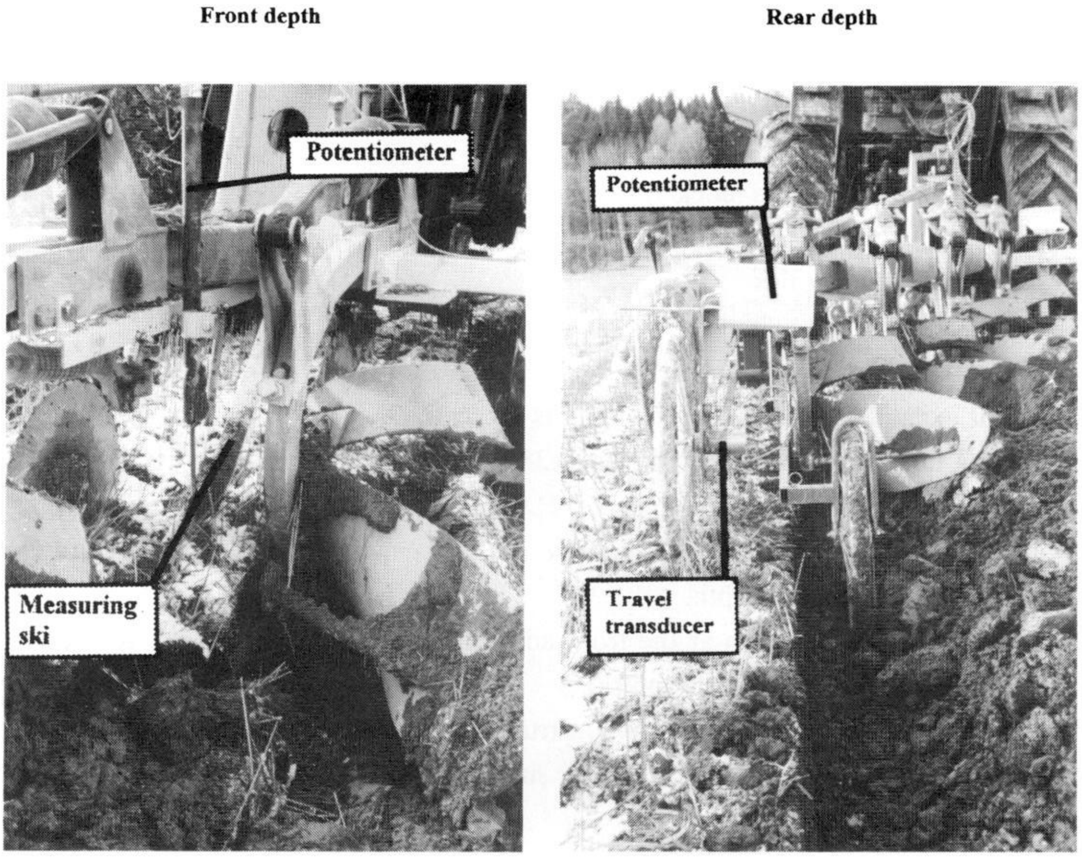


Fig. 13. Ploughing depths at the rear and front of the plough.

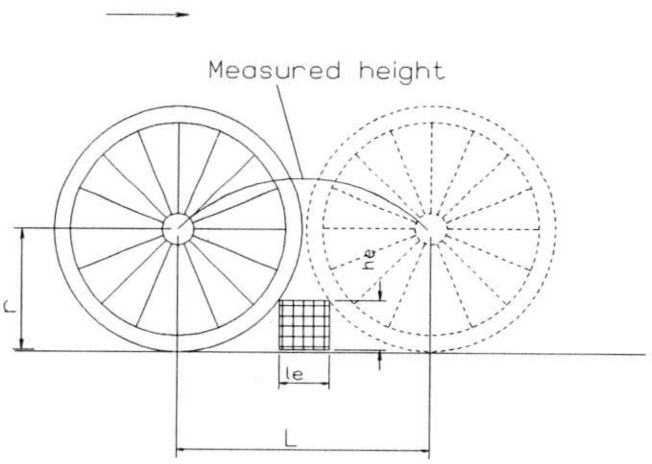


Fig. 14. Disturbance length during lump crossing.

$$L = l_e + 2\sqrt{r^2 - (r - h_e)^2} \tag{10}$$

L = length of disturbance
l_e = length of a block
h_e = height of a block
r = tyre radius

When for example the length of the lump is 8 cm, the height is 5 cm and the driving speed is 1.4 m/s, the disturbance will last 0.35 s, which means a frequency of 2.9 Hz. The cutoff frequency was chosen to be 2.0 Hz. Hydraulic lift is able to produce faster movements than this, but a lower frequency was chosen, because usually there are no rapid changes in ploughing depth.

Gas springs were used both at the front and at the rear measuring point to reduce vibration of the measuring wheels and ski.

The inaccuracy of the depth measuring instrumentation was ± 0,3 % of the measuring range. Soil lumps, uneven field and furrow surfaces and soil deformation increase the inaccuracy by increasing variation.

3.4 Ploughing width

Ploughing width was measured from the first furrow slice, Fig. 15. The other slices have a fixed width and only the first width can change. The measuring system was attached to the plough body. At the lower part of the measuring system was a wing, which was pressed by a gas spring against the furrow edge. The position of the blade was measured by a potentiometer. The inaccuracy of the instrumentation was the same as in the ploughing depth measurements ± 0,3 %. Also in the ploughing width measurement soil lumps and soil deformations increased inaccuracy by increasing variation.

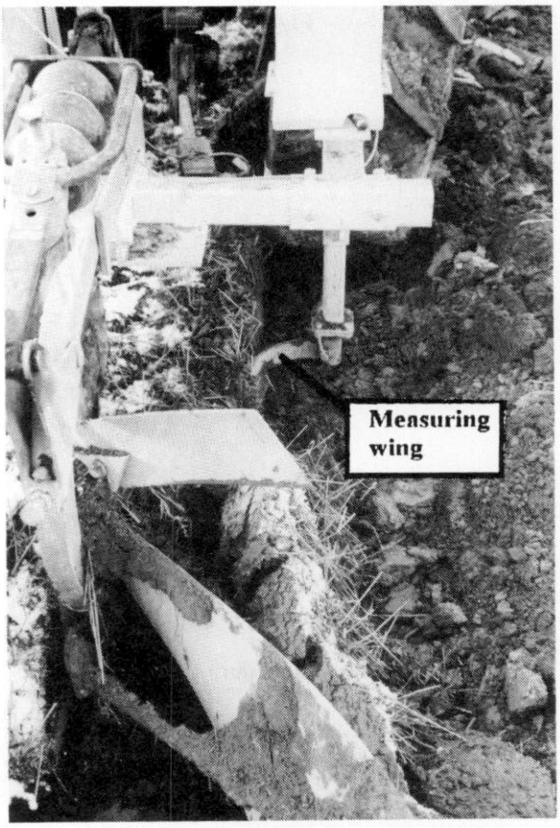


Fig. 15. Cutting width of the first furrow slice.

3.5 Ploughing forces

Ploughing forces were measured from the links of the hitch and from the gauge wheel of the plough, Fig. 12, sections 5,6 and 10. Ploughing forces at the lower links were measured with octagonal force transducers, Fig. 16. With these transducers it was possible to measure both vertical and horizontal forces. The transducer on the upper link measured the upper link pull or push forces. The position of the lower links was measured by a potentiometer. The position of the upper link was calculated from the position of the lower links. When the forces and the positions were known the vertical and horizontal forces at the end of lower links could be calculated, Eqn (11).

$$F_{ly} = F_{lr}\cos\beta - F_{lp}\sin\beta$$
$$F_{lx} = F_{lp}\cos\beta + F_{lr}\sin\beta \qquad (11)$$

F_{ly} = vertical force at the end of lower links
F_{lx} = horizontal force at the end of lower links
F_{lp} = force parallel with the lower links
F_{lr} = force perpendicular to the lower links
β = lower links position in relation to the tractor chassis

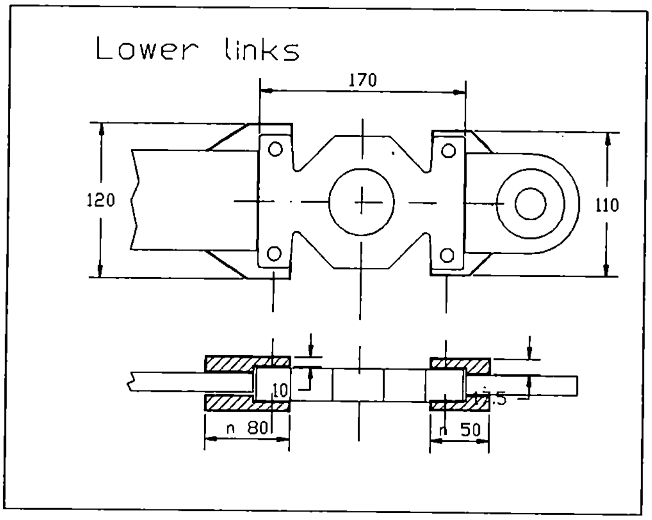


Fig. 16. The octagonal force transducer at the lower link.

By means of link forces the draught forces of the plough could be calculated as in chapter 2.2.1. Weight transfer could be calculated according to chapter 2.4.1.

The support force of the gauge wheel was measured with a force transducer. It was assembled between the chassis of the plough and the gauge wheel, Fig. 17. The support force of the gauge wheel could be changed by adjusting the wheel height.

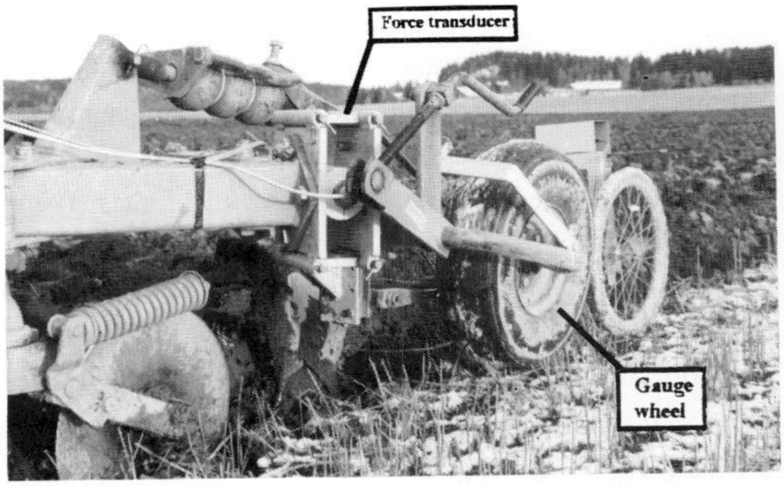


Fig. 17. Force transducer at the gauge wheel.

All the force transducers were calibrated in the laboratory by comparing them to a factory calibrated force transducer. The lower link force transducers were calibrated in a calibration bench where the angle of the calibration force could be changed between horizontal and vertical. The inaccuracy of the force measurement system was depending on the transducer between ± 0,4 - 0,7 kN. *[21]*

3.6 Driving speed and wheel slip

Driving speed was measured with the same wheel which was used for rear ploughing depth measurements. The wheel was equipped with a pulse transducer, Fig. 13. It gave 300 pulses per revolution, which corresponded to 0.0054 m/imp. The tractor wheel speed was calculated from the engine speed and the wheel slip was calculated from the driving speed and the wheel speed. The same driving gear was used in almost all the tests. The nominal speed was 6.3 km/h. Therefore driving speed is not a variable in analysis.

Driving speed and wheel speed were calibrated by driving a known distance. The inaccuracy of speed measurements were ± 0,2 % and the inaccuracy of slip measurement was ± 1 percentage at 10 % slip.

3.7 Surface profile of field

Field surfaces have an influence on ploughing work. Smaller or larger undulations in the field surface interfere with ploughing because the mounted plough and tractor is a long rigid combination. Power lift should help the combination to articulate and keep the working depth and draught constant.

3.7.1 Profile classification

Surface profiles are considered random and their properties are described statistically. This is done by computing the spectral density of the surface profile. For spectral density calculations, height and distance of the profile has to be measured.

When the spectral density data is drawn on a full logarithmic scale, this line is usually almost straight. It can be approximated by Eqn (12). The coefficients of the equation can be calculated using regression analysis. *[20],[23],[24],[25],[26],[27], [28],[29],[30]*

$$\phi(\Omega) = a\,\Omega^{n} \tag{12}$$

$\phi(\Omega)$ = power spectral density as a function of spatial frequency
a = profile coefficient
n = profile coefficient, exponent
Ω = spatial frequency 1/m (cycles/m)

In Eqn (12) the coefficient a is related to the amplitude of the profile and the exponent n gives the proportion of short and long wavelengths. When the profile becomes rougher, amplitude increases and coefficient a increases. Exponent n has negative values and its absolute value is increased when long wavelengths are dominant.

Eqn (12) uses spatial frequency. If the denomination is changed from spatial frequency 1/m to frequency Hz, the conversion can be done with Eqn (13).

$$f_{Hz} = \Omega\,(1/m)\;v\,(m/s)$$

$$\phi(f) = \frac{\phi(\Omega)}{v} \tag{13}$$

$$\Omega = \frac{1}{\lambda}$$

f_{Hz} = frequency that corresponds to driving speed v and spatial frequency Ω
$\Phi(f)$ = spectral density as a function of frequency
λ = wavelength

Surface classification is needed especially for road profile measurements. The draft standard ISO/DIS 8608 *[28]* is under work to establish a norm. In addition to road classification it can be used for off-road work. The standard includes a calculation and a classification method for measured data. If the calculations use constant bandwidth, the standard gives a smoothing method. Power spectrum density without smoothing will overemphasize higher frequencies. The smoothing is done in a such a way that low frequencies up to 0.0312 1/m will be calculated by full-octave basis. Between the last full octave band and 0.25 1/m the third-octave method is used. For higher frequencies a twelfth-octave method is used. The fitted regression coefficients are calculated from smoothed values between frequencies 0.011 and 2.83 1/m in ISO/DIS 8608. For off-road calculations a different range can be used. The equation, which is used in regression calculations is given in Eqn (14).

$$\phi(\Omega) = \phi(\Omega_0)\left(\frac{\Omega}{\Omega_0}\right)^{-n} \qquad (14)$$

Ω_0 = 0.1 1/m, reference frequency

In the equation, 0.1 1/m frequency (10 m wavelength) is used as the reference frequency. Compared with Eqn (12) this equation has only one calculated variable. The coefficient a is taken directly from the measured values at 0.1 1/m frequency.

3.7.2 Profile measuring system

Ground profile can be measured either manually or with special instrumentation. Manual methods are time consuming and they demand much work with a measuring tape and a theodolite. The sampling distance has usually been from 15 to 30 cm. The measuring rod has a sphere contact area in order to reduce the effect of small irregularities of the surface. *[23],[30]*

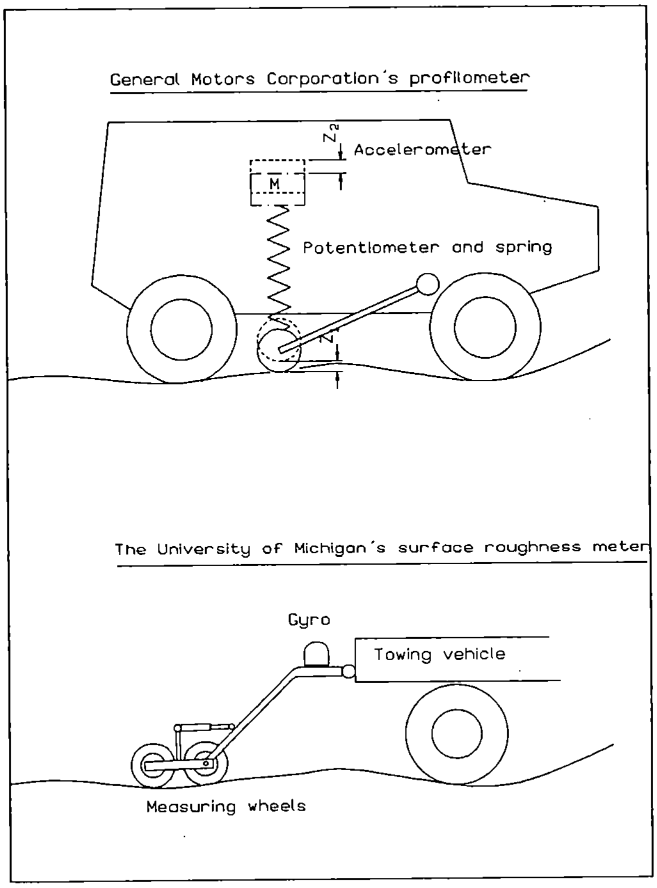


Fig. 18. Examples of ground profilometers. *[27]*

Fig. 18 shows two examples of ground profilometers: the upper one developed at General Motors Corporation, USA. The surface is measured with a wheel and the vehicle motion is measured with an accelerometer. The true ground profile is the difference between these two motions.

The lower illustration shows a profilometer developed at The University of Michigan, USA. It measures the inclination with a tandem wheel and the travelled distance with a measuring wheel. With these figures the surface profile can be calculated.

Ohmiya & Matsui [31] used a system which is similar to the profilometer of the University of Michigan when they measured farm roads and meadows. They used a three-wheel gyroscope with a 150 mm wheelbase. The shortest wavelength they could measure was approximately 0.3 m. Correlation to the actual profile was good, Fig. 19.

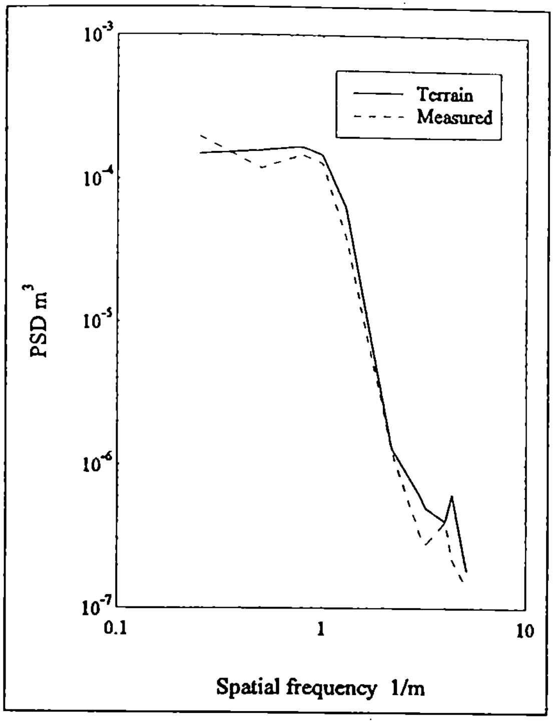


Fig. 19. Comparison between the measured and the original power spectral densities. *[31]*

In the present study the field profile was measured with an inclinometer and a travel transducer. The inclinometer was mounted in the tractor cabin, Fig. 12 section 2. The cab and the transducer are insulated from excess vibration by being rubber mounted to the tractor chassis. Because the inclinometer measured the tractor inclination, the measured value differed from the true surface. The measured value was an average reading of the four tractor tyres. The difference between the measured value and the profile is largest when the wavelength of the undulation is shorter than the tractor wheelbase in which case the undulation or obstacle is 'seen' twice. Changes in tyre deflections and the rise of the tractor front during hard pulling affected the inclination of the tractor. Thus on a horizontal field the tractor was usually travelling with the front up and because of this, the mean value of the tractor inclination was subtracted from inclination values. Thus the calculated profile did not show the actual slope but the profile changes. The starting and ending point of the profile had zero values and no windowing function was needed in the Fourier-calculations. Profile in this study was 'as seen by the four wheels of the tractor and with the trend (slope) removed'.

The distance was measured with a pulse transducer. The measuring system is described in chapter 3.6. The change in profile height between two measuring points was calculated with Eqn (15). This change was added to the previous height value to get the next point of the profile.

$$\Delta h = \Delta l \sin \alpha_{tr} \tag{15}$$

Δh = change in profile height during measuring interval
Δl = measuring interval, m
α_{tr} = tractor inclination, trend removed

In profile measurement the digitizing interval and the total length dictate the longest and the shortest wavelengths that can be calculated. The highest spatial frequency is limited by the sampling frequency. According to the Nyquist criterion the highest frequency that can be measured is half of the sampling frequency. To avoid frequency aliasing the *ISO/DIS 8608 [28]* standard recommends that the highest frequency should not be higher than one third of the sampling frequency. The correlation between the frequency resolution and the recording length is shown in Eqn (16).

$$\begin{gathered} L_m = \frac{N}{n_s} \\ \Omega_r = \frac{n_s}{N} = \frac{1}{L_m} \end{gathered} \tag{16}$$

L_m = measuring distance, m
N = number of measuring points
n_s = spatial sampling frequency, m^{-1}
Ω_r = spatial frequency resolution, m^{-1}

According to the *ISO/DIS 8608* standard in off-road measurements the lowest spatial frequency is normally 0.05 m^{-1} and in on-road measurements 0.01 m^{-1}. If, for instance, 0.05 m^{-1} would be the lowest spatial frequency measured, the measuring distance must be at least 20 m. In frequency smoothing, there must be enough adjacent frequencies from which the average value is calculated, otherwise random error will be high. Taking this into account, the recommended measuring distance is more than 100 m.

The highest spatial frequency depends on the application. For general on-road measurements the recommended upper spatial frequency is 10 m^{-1}. Measuring distance and sampling frequency define the number of measuring points. If the highest spatial frequency is 10 m^{-1} and the measuring distance is 100 m, this means 2000 sampling points when the Nyquist criterion is used. For off-road measurements the highest spatial frequency can, however, be lower than for onroad measurements.

Profile coefficients a and n (Eqn (12)) were calculated from the measured values by means of Eqn (15). The *ISO/DIS* 8608 Eqn (14) was not practical, because much longer measuring distances and more measuring points would have been needed. This would have lead to increased changes in soil properties. Also the variance of the surface amplitude and mean square values of amplitudes were calculated. The calculation of spectral density was undertaken using the Fourier analysis and Discrete Fourier Transform *[32]*.

3.8 Functioning of the hitch

The lowering and lifting movements of the tractor hitch were measured with the lower link angle transducer and with the hydraulic pump pressure transducer, Fig. 12, points 3 and 4. The angle transducer showed the position of the lower links. The pressure transducer showed the pressure of the hydraulic pump. When the hydraulic pressure exceeded the normal idling pressure, it was counted as a lifting correction. If the pressure exceeded idling pressure less than 2 % of the total test time, the hitch was considered to function with position control. This was necessary because the functioning of the power lift depends on the soil and on the lift settings. The power lift corrections were low especially when sensitivity control had a low setting value. Only the tests where power lift had functioned were included in statistical analysis when the lift settings were used as independent variables.

3.9 Test fields and test design

The ploughing test results included in this study were obtained during the autumn of 1992. The test site was at the State Research Institute of Engineering in Agriculture and Forestry in Vihti.

The tests were performed on different kinds of soil, light and hard soils and also on even and undulating soils. The number of test runs used in this study numbered nearly 400. In each measurement there were from 500 to 1500 measured values in 12 channels. The measurements were made on eight different field parcels. From these measurements five test series were mainly used. The test fields and test series are shown in Table 2.

Table 2. Test fields

Field	Number of tests /mean test length m	Soil type	Specific resistance kN/m²			Cone-index 15 cm/30cm kPa	Standard deviation of field profile cm
			Mean	Std.dev. of mean values	Mean std.dev. in driving direction		
Vihti, Hovi *'Flat surface'*	203/23 m	Clay	48	4	6	630/1340	2
Vihti, Hovi *'Gentle slopes'*	50/190 m	Clay	53	6	10	580/1060	55
Vihti, Hovi 'Interference'	111/-	Organic clay	-			350/710	-
Vihti, Uutela 'Modest slopes'	27/160 m	Clay	62	7	19	600/1080	112
Vihti, Luhta 'Gauge wheel'	133/35 m	Clay	40	5	6	670/880	

The soil properties were measured with the soil penetrometer *[33]* from which mean penetrating pressure were calculated at 15 cm and at 30 cm depths. The pressure values can be used to estimate trafficability. Using 15 cm cone penetrometer values the field was classified per Table 3.

Table 3. Soil types and cone pressures at 15 cm depth.

Soil type	Cone pressure kPa
Wet and soft	200
Dry and soft	400
Wet stubble	500
Dry stubble	1000

The ploughing properties of soils can be qualified by the specific resistance values. Because the same driving gear was used in almost every test, the coefficient of total resistance, k was used (chapter 2.2.1). The soils can be classified according to Table 4 *[34]*. The measured values of specific resistance together with the standard deviation values are shown in Table 2. The mean standard deviation in driving direction represents changes during a test run. Standard deviation of mean values represent changes in adjacent tests. The data shows that longer testing travel has increased the standard deviation in driving direction. The profiles have more peaks and valleys and also the soil conditions change more.

Table 4. Specific resistance and soil types

Soil type	Specific resistance (5 km/h) kN/m^2
Light	22 - 35
From light to medium	25 - 40
Medium	30 - 55
From medium to hard	35 - 60
From hard to very hard	60 - 120
Special soils	120 - 180

In each test series the power lift settings were changed systematically in two or four levels from the minimum value to the maximum value, Fig. 20. The number of levels depended on the field area, on larger area more levels were used. Besides these setting values position and poor draught control were included in each test sere. Total number of tests in each test series was normally between 30 and 80.

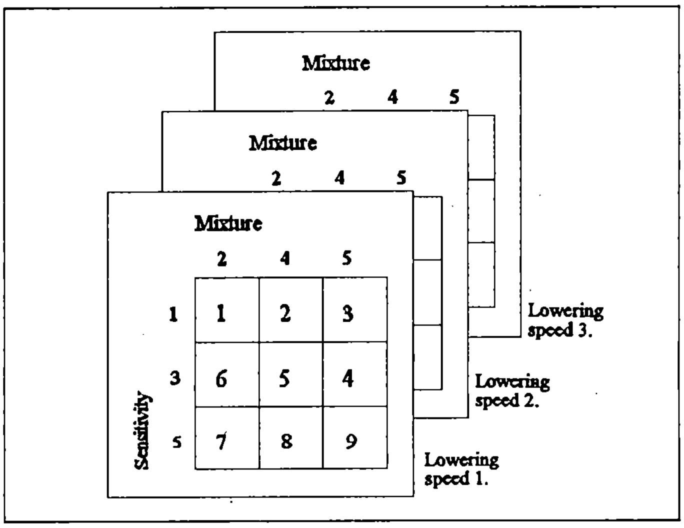


Fig. 20. An example of test numbering and test design. Mixture, sensitivity and lowering speed settings have three levels.

4. TEST RESULTS

4.1 Surface profile

4.1.1 Profile measurement

In the upper part of Fig. 21 is an example of a measured ground profile and working depth. The front of the tractor has risen at 90 and 100 m travel. This can be seen in the profile as a sharp change. The measured profile is not the true ground profile because it includes also tractor movements as interference.

Examples of measured field profiles on the test fields are shown in Fig. 22. It shows the differences in altitude very clearly. On flat surface the profile height has changed only about 10 cm and on gentle and modest slopes the change was some metres. The mean standard deviation of the profile height was 2 cm on flat surface, 55 cm on modest slopes and 112 cm on gentle slopes.

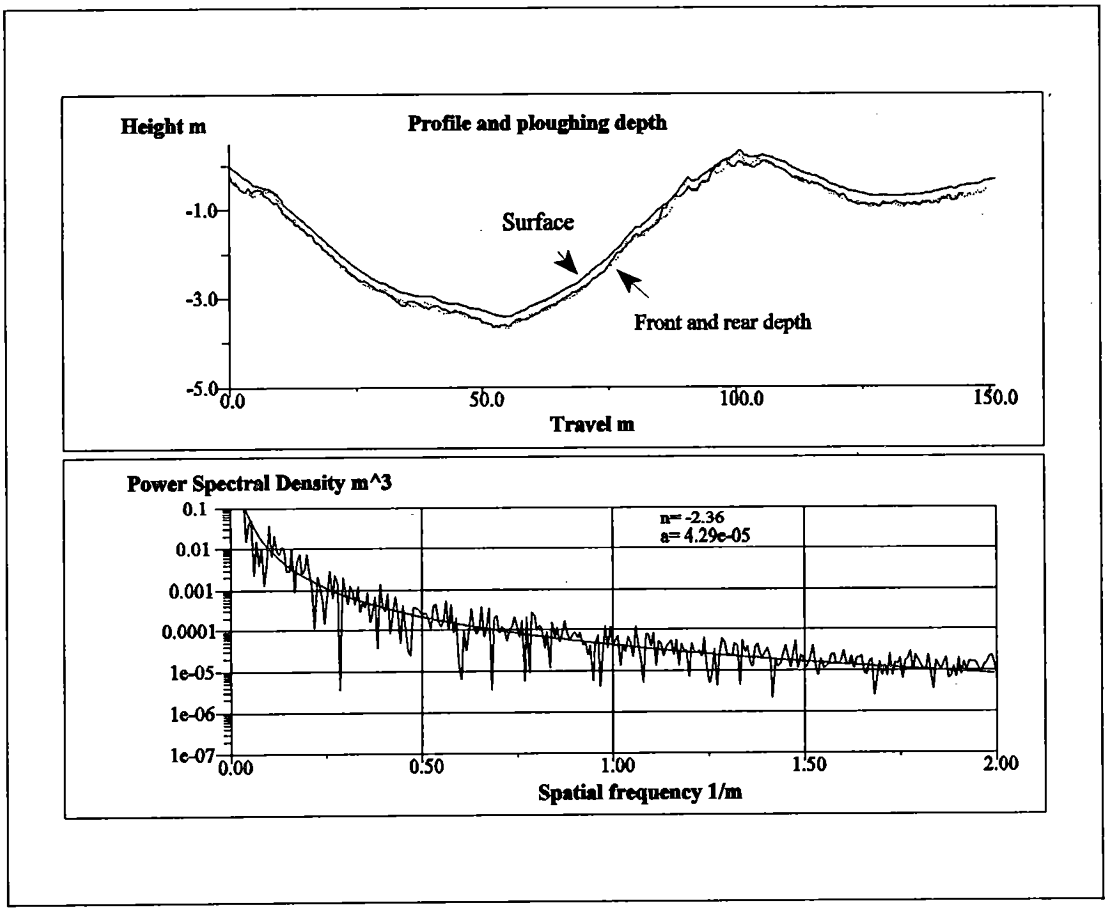


Fig. 21. Example of a measured field profile, ploughing depth and power spectral. density.

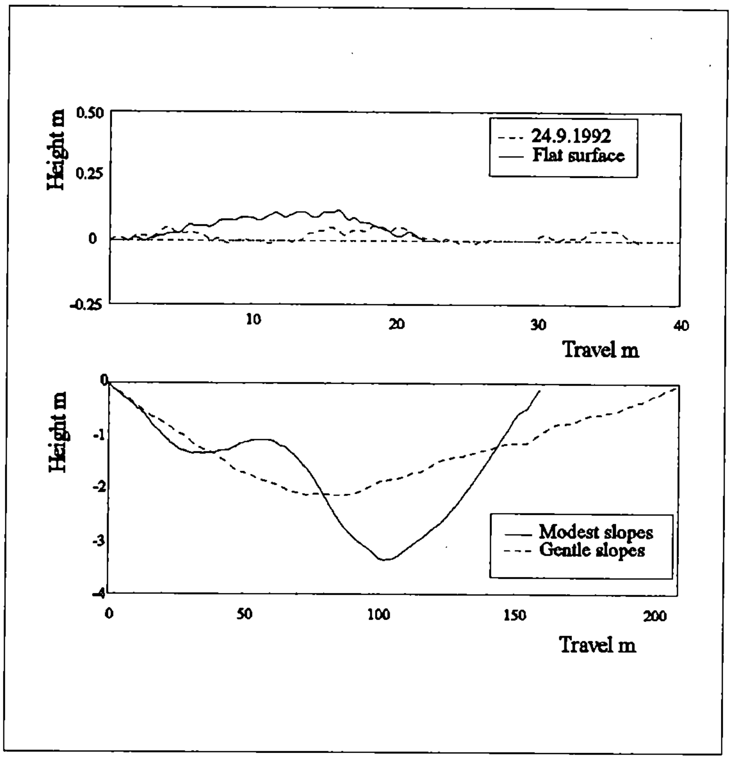


Fig. 22. Field profiles of test fields, lower: modest and gentle slopes, upper: flat surface and test dated 24.9.1992.

Ohmiya & Matsui *[31]* used a gyroscope when they measured farm roads and meadows. There is an example of meadow profile in Fig. 23. The profile was defined with a 2.5 m distance between adjacent measurements. The profile height has changed about 40 cm on the meadow.

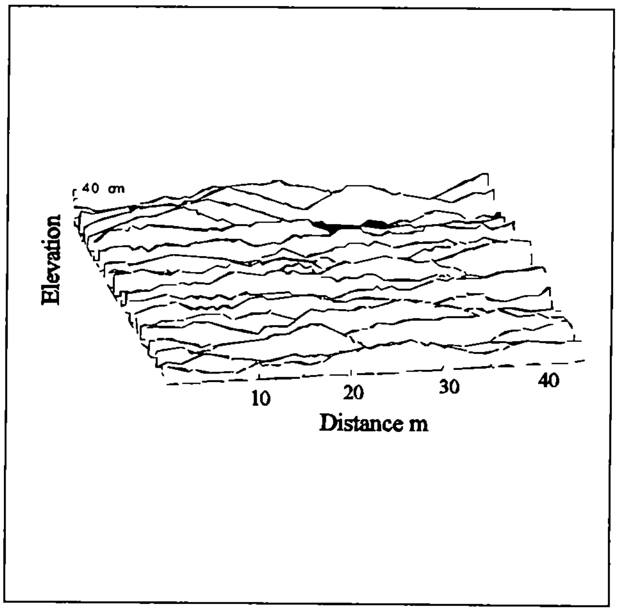


Fig. 23. Profile of a meadow. *[31]*

A combined field profile is shown in Fig. 24. It has been drawn by connecting adjacent field profiles and it shows that with the profile measuring system it was possible to calculate and design field profiles. In addition to field profiles, it is also possible to produce draught and depth profiles.

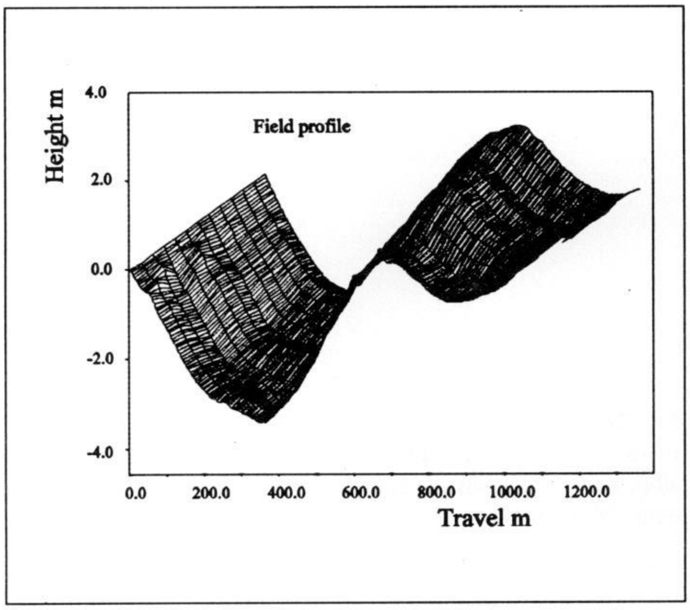


Fig. 24. Field profile of a test series, modest slopes.

The profile measuring system responded to different wavelengths in a different way. When the wavelength was shorter than the tractor wheelbase, both front and rear wheels climbed separately over it and the rut was 'seen' twice. When the wavelength was longer than the wheelbase the measured profile was the mean value of front and rear wheels. The longer the wavelength was, the smaller the profile error was.

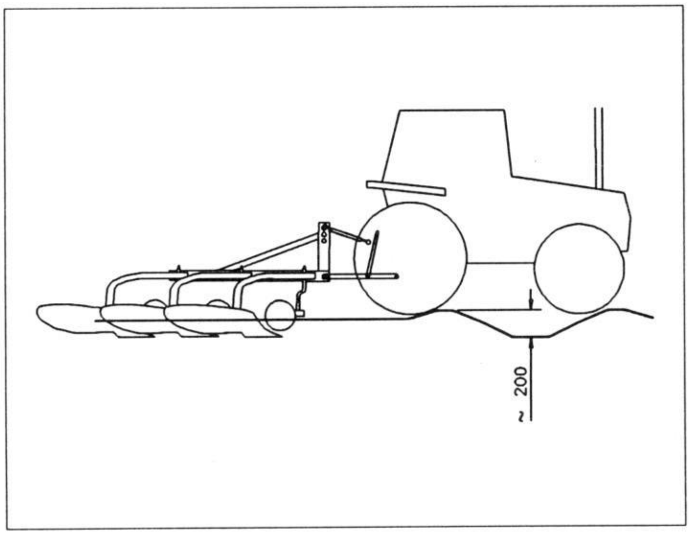


Fig. 25. Tractor traversing a rut.

The effect of surface wavelength can be seen from a test in which the tractor was driven over a rut, Fig. 25. The rut was made by ploughing a 20 cm deep furrow into the field and compacting it with the test tractor. The measured profile is shown in Fig. 26. The tractor crossed the rut between 4 and 8 m travel. First the front wheels went into the rut and after that the rear wheels. At a distance of six metres the front wheels are on the right bank and the rear wheels on the left bank. Because front and rear wheels went into the rut separately, there are two valleys in the measured profile in Fig. 26 (between 4 and 8 m).

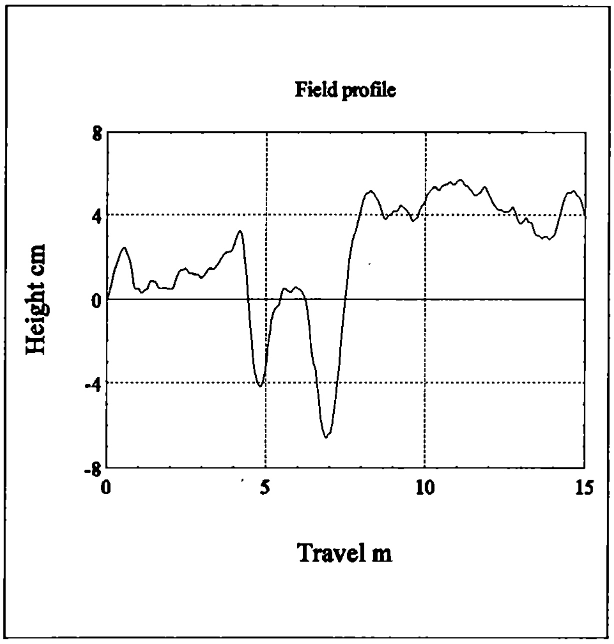


Fig. 26. Measured profile during rut crossing.

4.1.2 Profile densities

The draft ISO 8608 standard *[28]* recommends the use of smoothed power spectral density because constant bandwidth calculations overemphasize higher frequencies. This method, however, requires long measuring distances. The test runs were chosen according to ploughing demands, so they were usually short and the smoothed method could not be used. There is an example of an unsmoothed power spectral density and its regression function in the lower part of Fig. 21. Here the regression function has followed well the power spectral density.

Examples of smoothed octave values on three different fields are shown in Fig. 27. On flat surface the measuring distance was about 20 m which brought variation and error into the octave values because there are only a few frequency bins in the low frequency octave bands. On gentle and modest slopes the measuring distance was about 150 m and this reduced the variation. Modest slopes had a greater altitude variation and this is shown in the lowest octave band (0.0156 1/m) values. It has higher values than the same octave band on gentle slopes. The modest slope values are from adjacent measurements. Values on gentle slopes include tests from both ploughing directions. This increased variations because long distances between tests cause changes in the profile. On modest slopes it is difficult to represent the power spectral density with one linear regression line. Two lines would be needed, one for the lower frequencies and one for the higher frequencies.

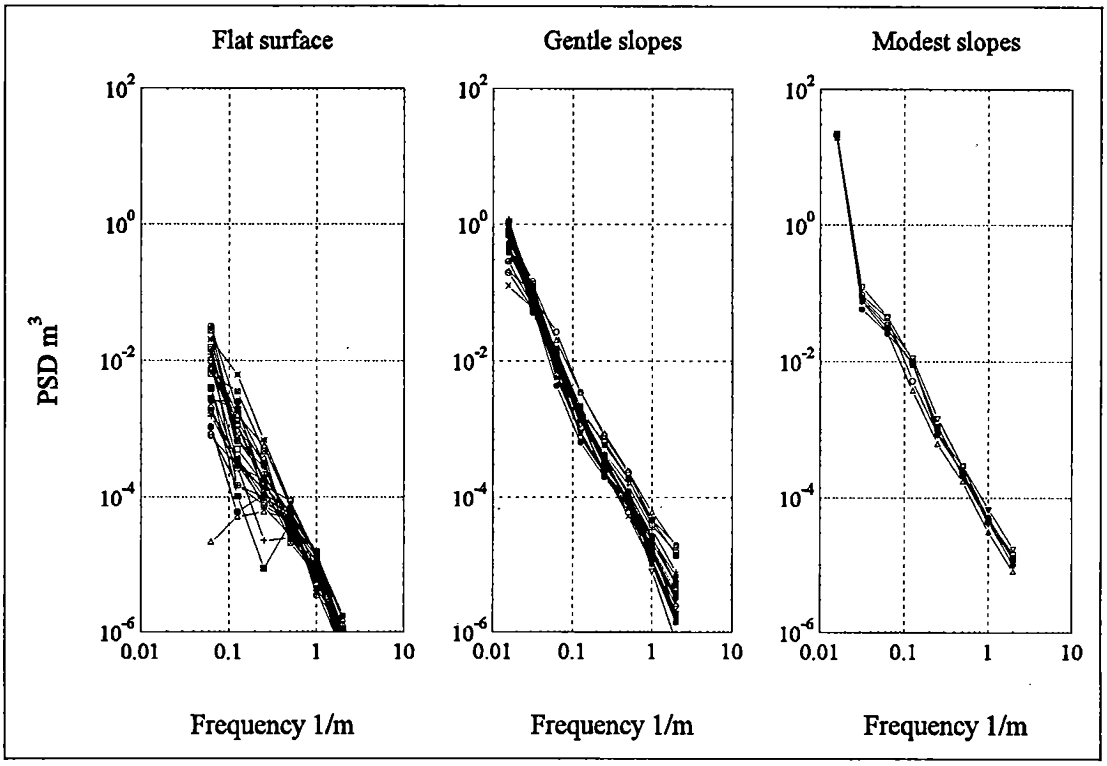


Fig. 27. Power spectral density values on three different fields, octave smoothing. Left: flat surface, middle: gentle slopes, right: modest slopes.

The power spectral density of the meadow profile of Fig. 23 is in Fig. 28. Fig. 28 shows that the power spectral density has changed between adjacent measurements considerable. *Ohmiya & Matsui [31]* did not calculate the fitted regression line, but they used the earlier ISO/DIS 8608 *[28]* calculation method that used two fitted lines. They concluded that in their measurements one fitted line in the logarithmic scale was sufficient. According to Fig. 27 the number of fitted lines depends on the surface. If there are great height variations, then it may be difficult to use only one fitted line.

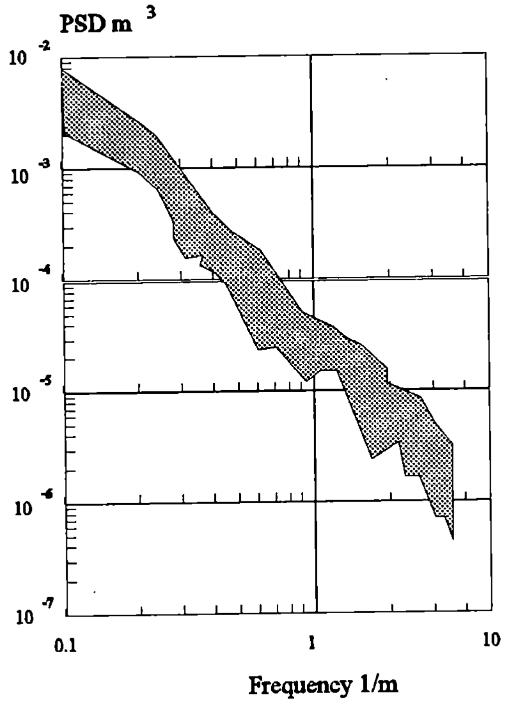


Fig. 28. Area of power spectral density values on a meadow *[31]*

Table 5 shows measured profile coefficients of the present study together with values found in the literature. Profile coefficient n describes the relation between low and high frequencies. If the absolute value of n is large then long wavelengths dominate. Profile coefficient a is related to the profile amplitude. A large a-value means a rough profile. The a-values in the table are approximately of the same magnitude, although there are some inconsistencies which are due to differences in measuring methods, sample size, sample frequency and measuring device. In the present study the profile was measured on the test tractor. Because of tyre and soil deflections and a four point mean value measurement this method reduces the effect of small wavelengths.

Table 5. Measured profile coefficients

Profile	Profile coefficient a m^3	Profile coefficient n
Source: Wong *[20]*		
Smooth highway	$4.8 \cdot 10^{-7}$	- 2.1
Highway with gravel	$4.4 \cdot 10^{-6}$	- 2.1
Pasture	$3.0 \cdot 10^{-4}$	- 1.6
Ploughed field	$6.5 \cdot 10^{-4}$	- 1.6
Source: Aho *[23]*		
Farm road	$1.2 \cdot 10^{-6}$	- 1.4
Forest road	$2.4 \cdot 10^{-6}$	- 2.1
Forest, easy	$6.9 \cdot 10^{-5}$	- 1.7
Forest, hard	$8.9 \cdot 10^{-5}$	- 2.8
Source: Wendeborn *[30]*		
Highway	$0.3 \cdot 10^{-6}$	- 2.3
Farm road	$2.9 \cdot 10^{-6}$	- 2.3
Field	$7.4 \cdot 10^{-6}$	- 1.8
Field with periodics	$2.3 \cdot 10^{-5}$	- 1.2
Measured values		
Stubble, flat surface	$2.9 \cdot 10^{-6}$	- 2.6
Stubble, gentle slopes	$2.0 \cdot 10^{-5}$	- 2.3
Stubble, modest slopes	$2.9 \cdot 10^{-5}$	- 2.4

4.1.3 Standard deviation of the profile

Besides profile coefficients the standard deviation of the profile height was calculated. In Fig. 29 the profile coefficient a is compared with the standard deviations of the profiles. The tests were performed on flat surface, on gentle slopes and on modest slopes. The variation of the profile coefficient is large. It does not show on which kind of ground the test was performed.The standard deviation of the profile however classifies the fields clearly into three categories. The changes in the standard deviation of the profile on a field are much less than in a-coefficient, for example on gentle slopes the profile coefficient a varied between $3 \cdot 10^{-6}$ and $45 \cdot 10^{-6}$ m^3 and the standard deviation varied only between 0.4 - 0.75 m.

The standard deviation of the profile was used to present surface undulation in the analyses of this study because of smaller variation and clear classification. The standard deviation does not include any frequency information of the profile while a- and n-coefficients do. In these analyses it is not necessary to have frequency information. If profile coefficients a and n were used in analysis, longer test runs would have been needed. This would have caused changes in soil structure and specific resistance.

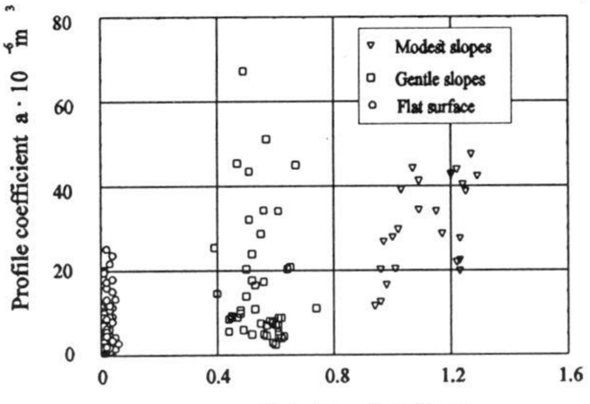


Fig. 29. Profile coefficient a as a function of profile standard deviation on three different fields.

4.1.4 Profile wavelengths

The wavelengths of the ground profile were calculated from the power spectral densities. The wavelengths were chosen according to the tractor wheelbase, L. The wavelengths were: over 2· wheelbase, (1 - 2) · wheelbase, (0.5 - 1) · wheelbase and (0.25 - 0.5)· wheelbase.

The profile wavelengths on three different fields are shown in Fig. 30. On every field the longest wavelengths (over 2·wheelbase) had the largest variances. Variance is related to the power of the signal and longer wavelengths have larger power. When the ground surface became rougher especially the variance of the long wavelengths increased.

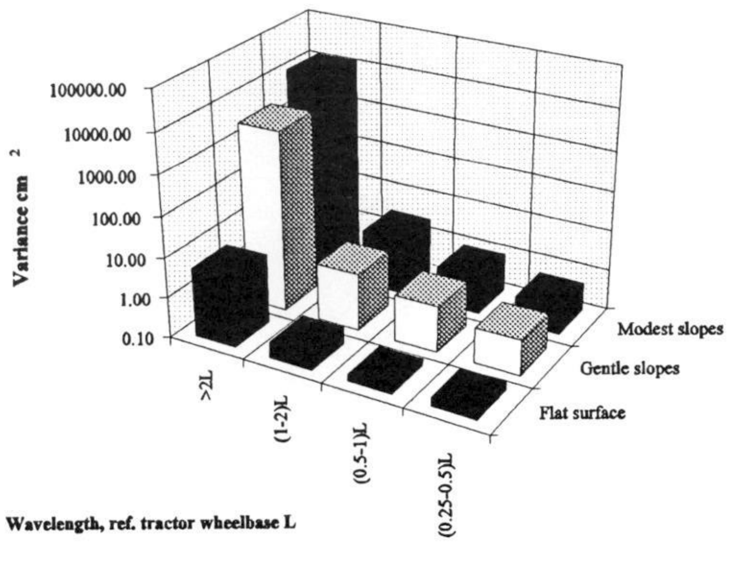


Fig. 30. Ground profile wavelengths as a function of tractor wheelbase L.

4.1.5 Changes in ploughing draught on undulating field

An example of the changes in cone-index pressure and specific resistance is shown in Fig. 31. Cone-index values were measured at three different places. They are presented in the upper part of the diagram. In the valley at 50 m travel the cone-index pressure up to 20 cm depth was lower than in two other places, surface was at this point slippery. The specific resistance changed with the profile, on the slopes and on the top of the field the specific resistance was greater than in the valleys. The rapid changes in specific resistance at 20 and 100 m travel are caused by changes in ploughing depth and difficulties in tractor and plough articulation. Specific resistance of a soil is a function of ploughing depth. So depth changes affected the specific resistance values.

When the test distance increases there are, especially on hilly soils, changes in soil moisture content and in soil types. This will affect the specific resistance and it will make the ploughing more difficult.

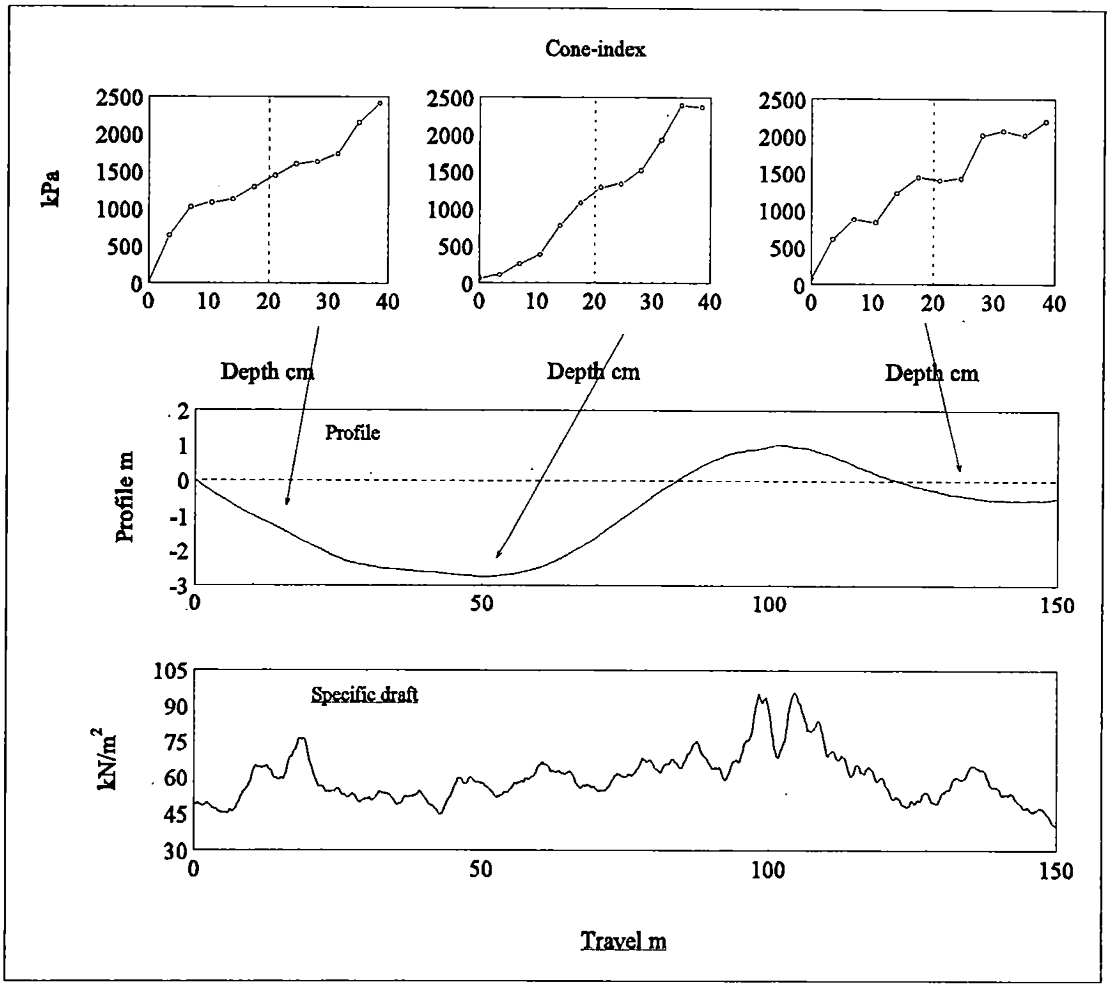


Fig. 31. Changes in specific resistance during a test, top: cone-index values at three points, middle: soil profile, bottom: specific resistance.

4.2 Ploughing depth

Ploughing depth was measured at both ends of the test plough. There is an example of a test run and the calculations in Fig. 32. In the upper left diagram the front and rear ploughing depths have been shown from the ground surface. In the lower right diagram the ploughing depths have been shown together with the ground profile. The distance between the front and the rear measuring point has been taken into account in Fig. 32 so that the depths are from the same point. The distributions of front and rear ploughing depths are in the upper right diagram. The power spectral density of the rear depth is shown in the lower left diagram.

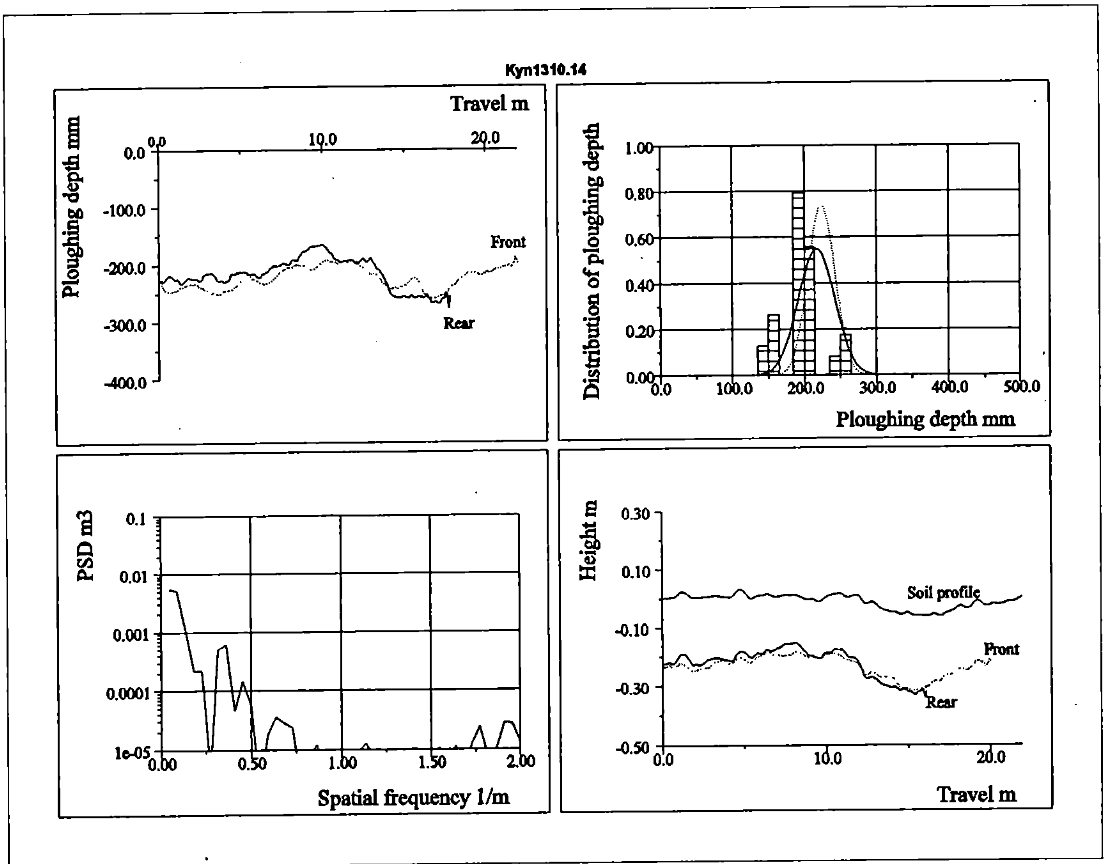
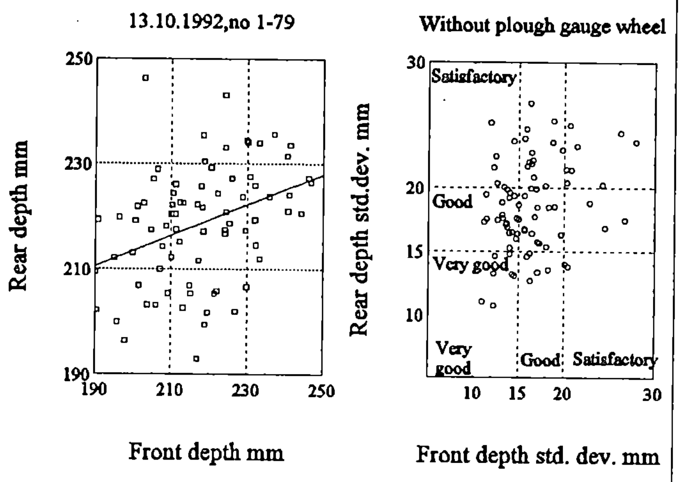


Fig. 32. Example of ploughing depth calculations, upper left: depth from ground surface, upper right: front and rear depth distribution, lower left: spectral density of rear depth, lower right: ground profile and depths.

4.2.1 Changes in ploughing depth

Examples of ploughing depths and their standard deviations are shown in Fig. 33 and Fig. 34. The results with the gauge wheel in use are shown in Fig. 33 and with the gauge wheel out of use in Fig. 34. The tests were performed on flat surface. During the test runs tractor lift control adjustments were varied between position control and pure draught control. All the test runs, regardless of lift adjustments, are shown in Fig. 33 and Fig. 34.



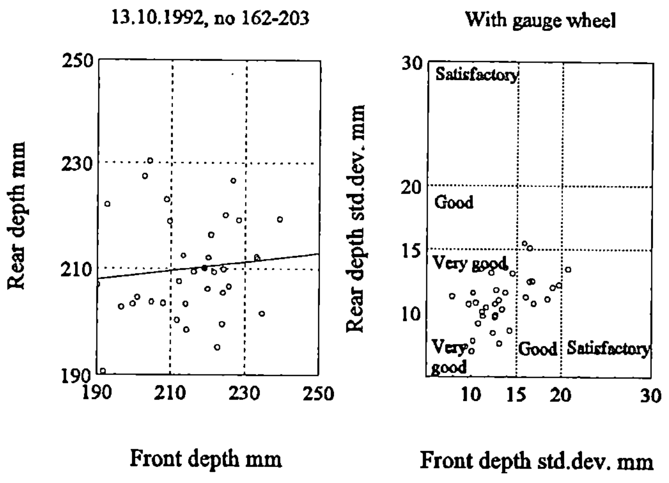
13.10.1992,no 1-79

Without plough gauge wheel

Fig. 33. Ploughing depths and their standard deviations at the rear and at the front of the test plough, gauge wheel out of use. Left: front and rear depths, right: standard deviation of front and rear depths.

The relation between the mean values of front and rear depth is shown in the left side of Fig. 33. Front and rear depths have the same value at 220 mm. If the front depth has changed from this value, the rear depth has also changed but not as much as the front depth. This depth relation is caused by the tractor lift geometry and the proper working depth in these tests was 220 mm.

The relation of depth deviation between the front and rear depth is shown in the right side of Fig. 33. The standard deviations of the ploughing depths were almost the same at both ends, the mean value of standard deviation was 18 mm at the rear and 16 mm at the front. According to the ploughing depth classification in chapter 2.1. Fig. 33 shows many cases where the front depth variation was less than 15 mm and the ploughing quality could be classified as 'very good'. Respectively there are fewer cases where the rear depth deviation can be classified as 'very good'.



13.10.1992, no 162-203

With gauge wheel

Fig. 34. Ploughing depths and their standard deviations with the gauge wheel in use. Left: front and rear depts, right: standard deviation of front and rear depths.

The test results with the gauge wheel of the plough in use are shown in Fig. 34. The rear depth of the plough has not changed as much as the front depth, Fig. 34, left side. Depth deviations shows a noticeably reduction compared to Fig. 33. Most of the results can be classified according to chapter 2.1. as 'very good'. Front depth had a wider deviation and the classification includes also 'good' and 'satisfactory' points.

Fig. 35 shows the results for depth variance at different wavelengths. Most of the total depth variance is in longer wavelengths. The use of the plough gauge wheel reduced variations, especially at long wavelengths, and the rear depth variation more than the front depth variation.

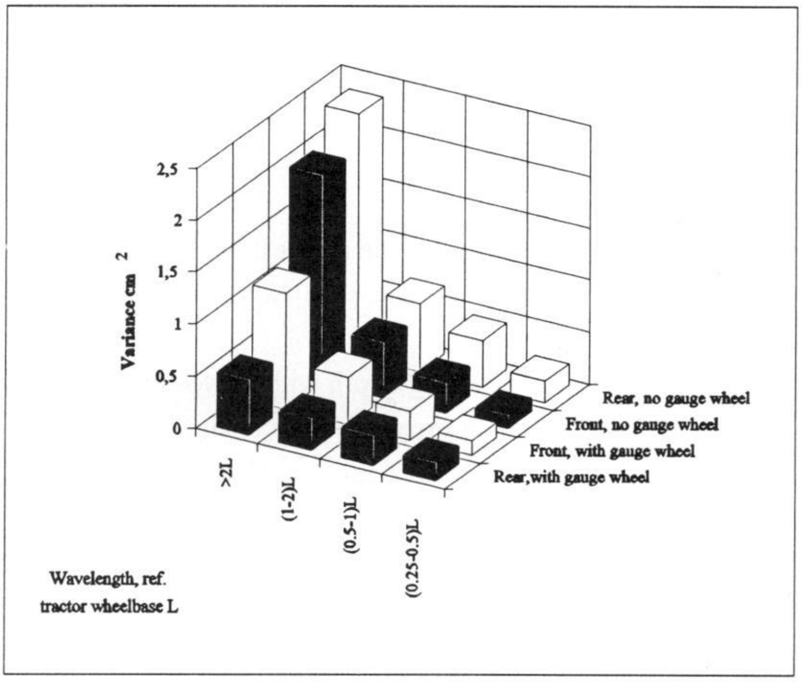


Fig. 35. Ploughing depth variance at different wavelenghts, L: tractor wheelbase.

Cowell & Len [10] and *Cowell & Herbert [35]* found in their tests that variation in depth of the front body was greater than in the rear body. In the present study the variations were different also when the ploughing depth was different from the depth where the plough was adjusted. When properly adjusted and when the ploughing depth was the same as adjustment depth, ploughing depths and their standard deviation were of the same size during the test runs.

Seifert [8] found that there were no significant differences in working depth or in working depth variances between the front and the rear body of a two-furrow plough. However the rear body followed more slowly changes in working depth than the front body. In the present study there was a short time lag in working depths. An example of front and rear depths is shown in Fig. 36, where the rear depth has 1 - 2 s time lag. The rear depth was measured about 1 m after the rear body. When this is taken into account, the time lag is reduced to about 0.5 s. The stiffness of the tractor links and the plough body, the free play in the connecting points, tractor inclination and tyre deflection contribute to this time lag.

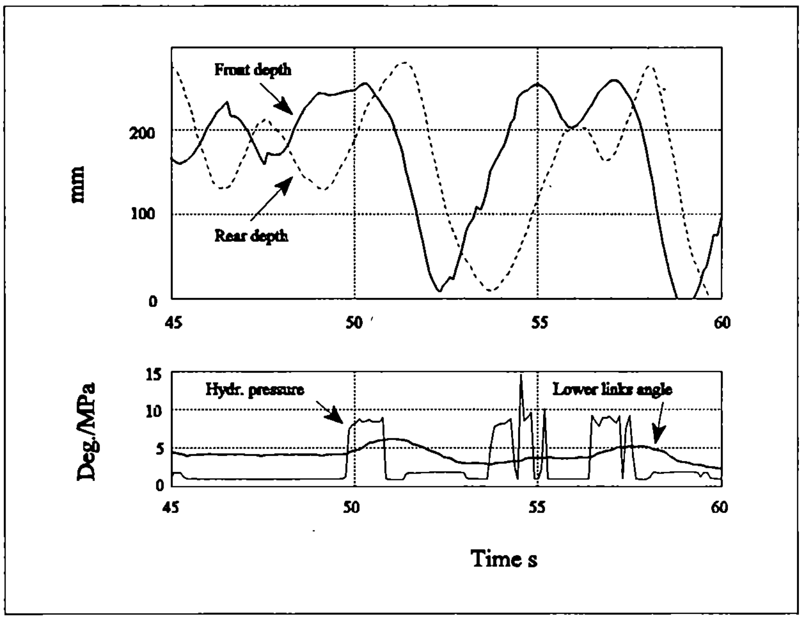


Fig. 36. Changes in ploughing depth at the front and at the rear of the plough, upper: front and rear depths, lower: position of lower links and hydraulic pressure.

According to *Bjerninger [6]* the greatest depth changes from mean value during tests were ± 12 % for towed plough, ± 15 % for position control and ± 24 % for draught control.

Seifert [8] measured working depth with a two-furrow plough and with three different lift control systems. The greatest depth changes were ± 19 % and the smallest were ± 4 %. The mean change was about ± 10 %. The surface of the test field was made even by hand.

Dwyer, Crolla & Pearson [9] made an investigation of the ploughing depth at farms. The operators tried to keep the working depth changes within ± 15 % limit. To achieve this they had to adjust the ploughing depth manually. When manual adjustments were not made the changes in working depth were ± 30 %.

In the present study the depth changed between 13 % and 33 % without the gauge wheel and between 9 and 20 % with it. This means that the gauge wheel improved the ploughing depth quality. The depth changes when the gauge wheel was in use were however somewhat worse than *Bjerninger's* result ± 12 % for towed ploughs.

Dwyer [36] measured draught control response on a field that had 15 cm amplitude and 7.3 m wavelength. The mean working depth was about 18 cm and the depth change was about ± 8 cm, over 40 % change in depth. In the present study when surface amplitude was of the same magnitude the working depth varied about ± 6 cm.

Cowell & Herbert [35] undertook ploughing tests on a field which surface had a sinusoid of approximately 10 m wavelength and 100 mm amplitude. In their tests the depth changes were remarkable larger, the standard deviation was from 26 mm to 36 mm when the mean depth varied from 148 to 167 mm. This means that depth changed about between 50 % and 70 %.

The ± 10 % change in working depth as recommended by many researchers seems to be too restrictive. In chapter 2.1 the working depth changes were divided into four different classes, ± 10 %, ± 20 %, ± 30 % and ± 40 %. The first class has a very good depth evenness and the last class will only keep the ploughing deeper than 10 cm.

Normally when ploughing with a mounted plough is measured, it is not necessary to have ploughing depth transducers at both ends. They will however make adjustment of the plough easier. If the plough is semi-mounted or the gauge wheel of the plough is in use, then both depth measurements are needed.

For good working quality it is advisable to use the plough gauge wheel.

4.2.2 Regression analysis of the ploughing depth

The regression analysis of the ploughing depth was performed for the rear depth values. The front depth measurements had at the time of last measurements interference due to potentiometer wear. The results of the regression analysis are in Appendix 3, in Eqn (17) and in Fig. 37.

$$t_{sd} = 21.48 - 0.06 H_{low} + 0.15 H_{sen} - 0.46 H_{mix} - 8.17 R_{at} + 18.92 P_{hs} \tag{17}$$

t_{sd} = standard deviation of the rear depth of the plough
H_{low} = setting value for the lowering speed of the hitch
H_{mix} = setting value for the mixing control of the hitch
H_{sen} = setting value for the sensitivity of the hitch
P_{sh} = standard deviation of the profile height
R_{at} = vertical force of the gauge wheel

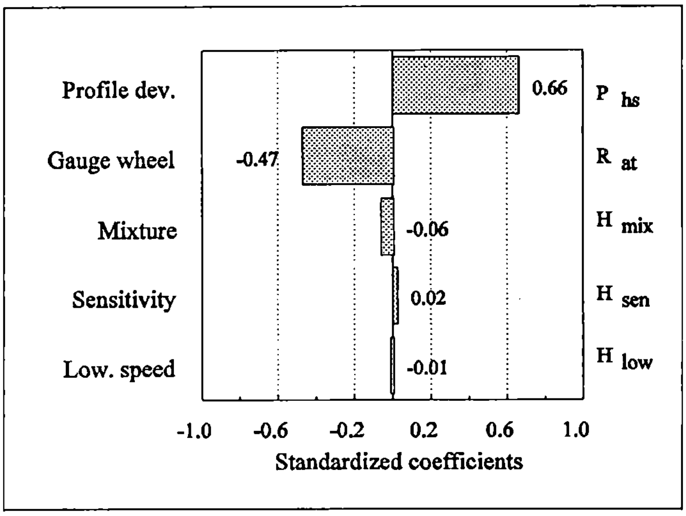


Fig. 37. Standardized coefficients of regression analysis, rear depth. ($R^2 = 0,76$)

Ground profile undulation had the greatest influence on working depth changes. When field slopes became steeper also the working depth changes increased, Fig. 38. On modest slopes and without the gauge wheel the standard deviation of depth was so great that the quality of ploughing could not even be regarded as 'fair'. The effect of the gauge wheel can also be seen from Fig. 38. On all grounds it reduced depth variations noticeably. The quality of the ploughing has been satisfactory or better almost in all tests.

According to the regression analysis the effect of the power lift settings was small compared to the effect of ground profile and use of the gauge wheel.

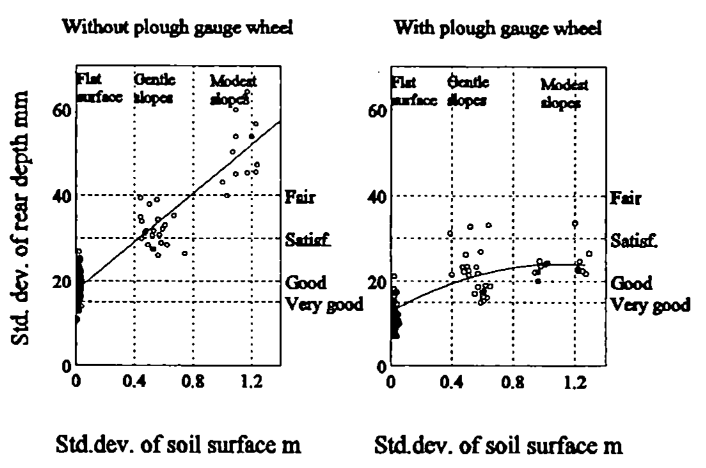


Fig. 38. The effect of the ground surface undulation on the standard deviation of the rear depth of the plough, left: plough gauge wheel out of use, right: plough gauge wheel in use.

Cowell & Len [10] made ploughing tests with two different tractors equipped with three-furrow ploughs. The surface was shaped by a tractor mounted blade so that it had a sine wave of wavelength 9.1 m and amplitude of 10 cm. The working depth was measured from the last furrow. The mean depth was between 10 and 13 cm. The minimum depth was between zero and 9 cm and the maximum between 18 and 25 cm. The tests showed a poor working depth quality. The tractor-plough combination could not follow the field undulation and the last plough share would often come totally or nearly out of the ground. When driving speed was increased the depth variation increased. The effect of the lowering speed of the hitch had only a small effect on depth control performance. The reason for poor depth control was explained by the lack of a control signal, by the hitch control delay and by the support forces at the heel of the rear body. The share points in the present study were long and curved downwards which kept the suction into the ground better. Also the working depth was deeper which kept the draught force more uniform.

4.2.3 Profile wavelengths and ploughing depth

The effect of profile wavelengths on the working depth variation is shown in Fig. 39. The profile wavelengths have been divided into two groups, wavelengths shorter than tractor wheelbase L and wavelengths longer than tractor wheelbase L. It can be seen from the charts that wavelengths which are shorter than the tractor wheelbase have the same effect on ploughing depth variation. When the gauge wheel is in use, the longer profile wavelengths have a much smaller effect on ploughing depth variation.

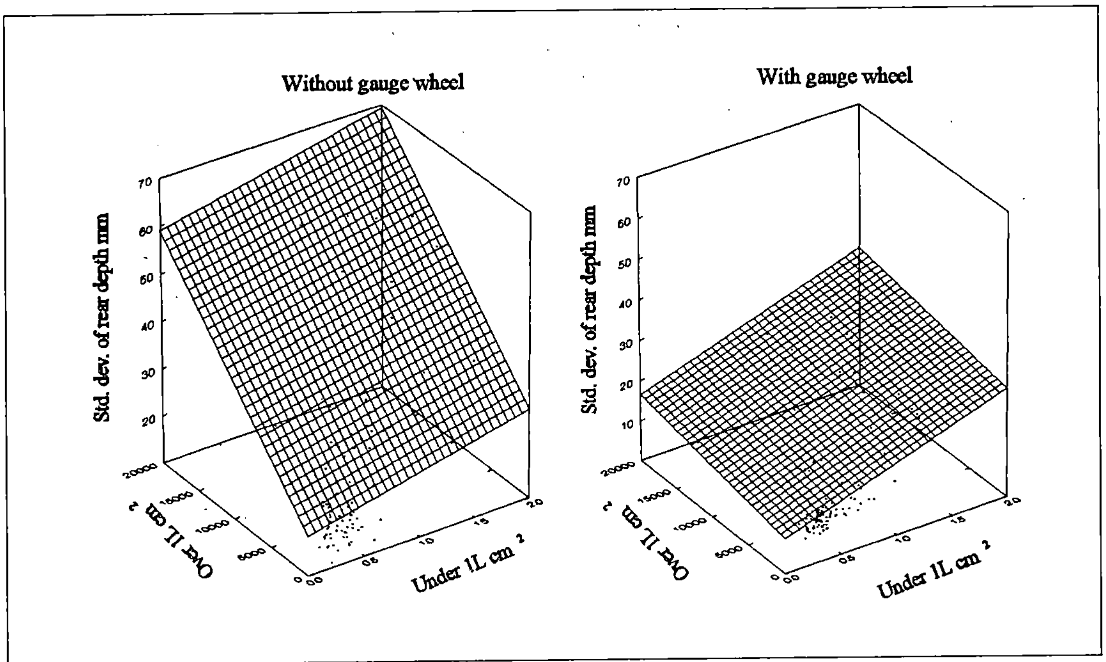


Fig. 39. Standard deviation of ploughing depth as a function of profile wavelengths, left: plough gauge wheel out of use, right: plough gauge wheel in use.Under 1L cm^2 : wavelengths shorter than tractor wheelbase, Over 1L cm^2: wavelengths longer than tractor wheelbase.

4.3 Ploughing width

An example of first furrow slice width change during a test run is shown in the upper part of Fig. 40. Interferences in measuring system mainly caused the width variations. Soil lumps between the furrow edge and the transducer and shallow working depths normally caused the changes. The transducer wing could not be adjusted to a lower working depth than 10 cm, because otherwise it would have touched the furrow bottom. When the working depth was lower the width measurement gave false values.

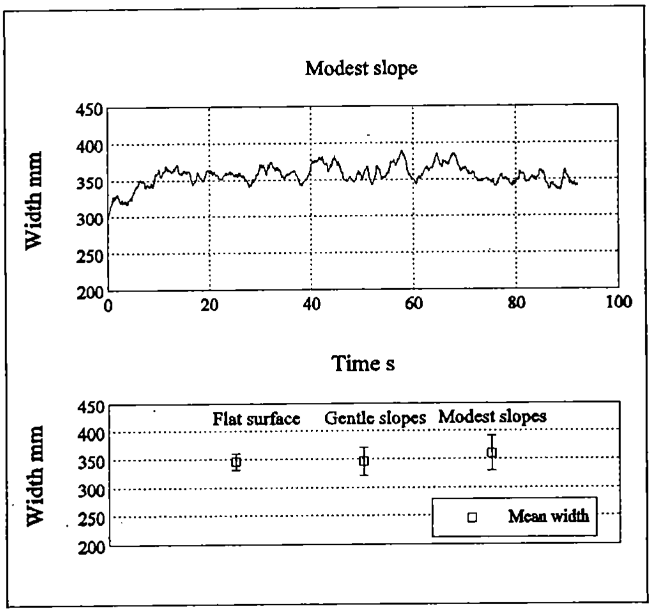


Fig. 40. Example of the first slice width (upper) and mean and standard deviation of width on three surfaces (lower).

The mean values and the standard deviations of ploughing width on three different fields are shown in the lower part of the Fig. 40. On flat surface the standard deviation was small, only 15 mm. On gentle and modest slopes the standard deviations were 29 and 36 mm. The greater variations were due to larger variation in ploughing depth.

There is little change in the first slice width when the plough is properly adjusted. The first slice width measurement can be best utilised during plough adjustment.

4.4 Support force of plough gauge wheel

The support force of the plough gauge wheel was changed by adjusting its height. Normally the gauge wheel is adjusted so that it 'touches the ground lightly'. To ascertain the effect of the support force a test series was performed with different force settings.

An example of gauge wheel force during a test on modest slope is shown in the upper part of Fig. 41. The support force changed during the test quite rapidly and over a wide range. This was due to changes in ground profile. This happened for instance at the 60 s point. The smaller variation in the support force was produced by varying ground top surface.

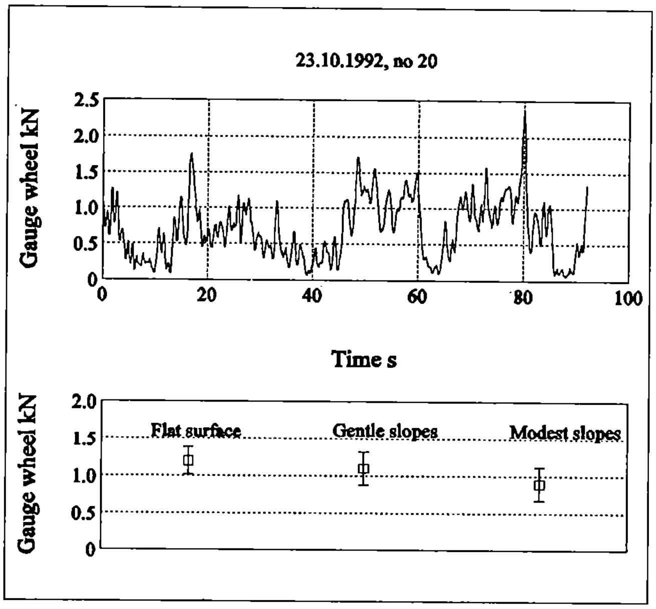


Fig. 41. Example of the gauge wheel support force during a test run (upper) and support force mean value and standard deviation on three surfaces (lower).

The mean values of the gauge wheel force together with standard deviations are shown in the lower part of Fig. 41. The tests were done on three different fields. As the field profile became rougher, the standard deviation increased somewhat. Changes in mean value are caused by differences in lift and gauge wheel settings.

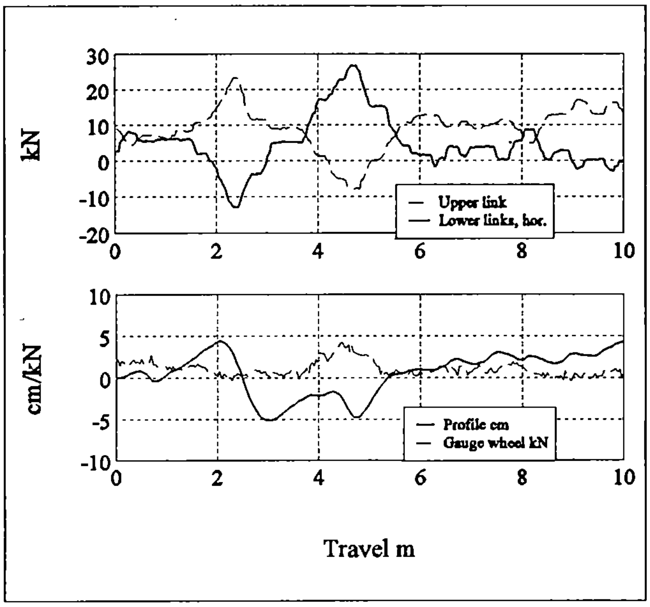


Fig. 42. Tractor hitch and plough gauge wheel forces during rut crossing. Plough gauge wheel in use, upper: upper and lower link forces, lower: ground profile and gauge wheel force.

An example of the three point hitch and plough gauge wheel forces during rut crossing (Fig. 25) is shown in Fig. 42. The front wheels of the tractor went into the rut after 2 m travel and the rear wheels at about 5 m travel. When the front wheels went into the rut the pulling force at the upper link increased and the horizontal force of the lower links reduced. When the rear wheels went into the rut the upper link force reduced and the lower links force increased. The forces changed when there was a new inclination of the tractor. Upper and lower link forces are mirror images from each other when the tractor is crossing the rut.

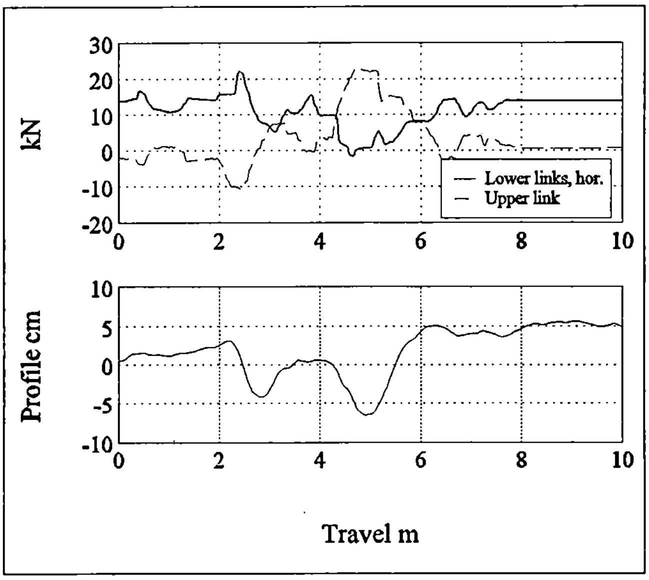


Fig. 43. Tractor hitch forces during rut crossing. Plough gauge wheel was not in use, upper: upper and lower link forces, lower: ground profile.

An example of rut crossing when the gauge wheel was not in use is shown in Fig. 43. The force changes are smaller and they occurred later than when using the gauge wheel. With the plough gauge wheel there is the added bonus of the amplified sensing forces which predict articulation changes between tractor and plough.

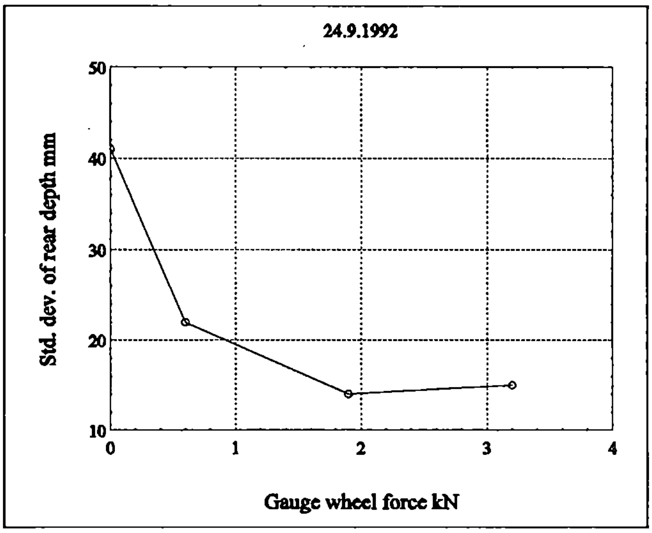


Fig. 44. Standard deviation of the rear depth as a function of gauge wheel force. Mean values of the test results.

The effect of the gauge wheel force on the standard deviation of the ploughing depth is presented in Fig. 44. When the gauge wheel was in use it reduced depth variation. This occurred already with light support forces because the gauge wheel prevented excess ploughing depths. When the support force exceeded 1 kN, the variation was no more reduced which meant that for good working quality it is enough that the gauge wheel only 'lightly' touched the ground.

An example of ploughing depth changes during two tests is shown in Fig. 45. When the plough gauge wheel was in use it prevented excess working depths which occurred when the ground profile changed, for example at 40, 60 and 100 m travels (the ground profiles are shown in Fig. 48).

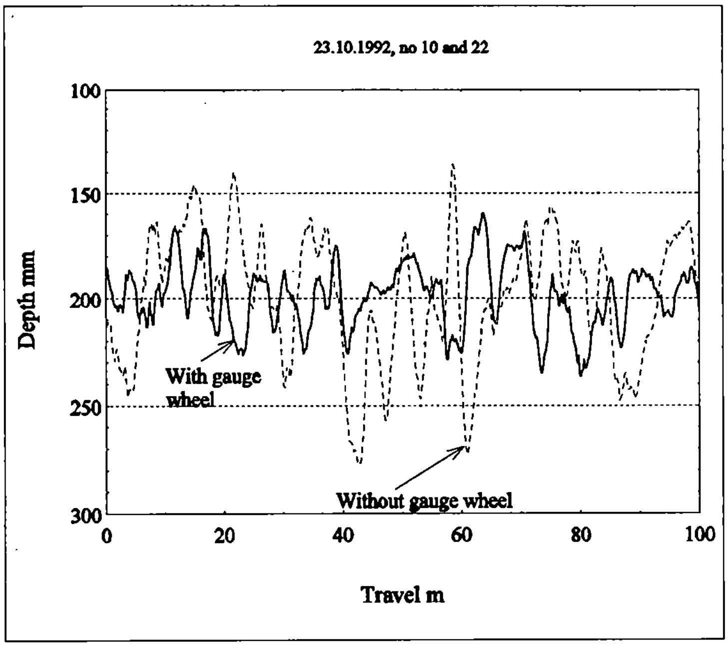


Fig. 45. Changes in ploughing depth during two tests

Hesse and Möller [37] measured the gauge wheel force of a four-furrow 622 kg plough. Depending on the settings the mean value of the force was from 1 to 2.5 kN. In their tests they wanted to increase the rear axle force of the tractor to increase mobility. They performed the tests with different top link forces.

Skalweit [38] measured link forces and gauge wheel force with a two furrow plough. He found that the gauge wheel made the ploughing depth more uniform on undulating fields. *Dwyer, Crolla & Pearson [9]* experimented with pure draught control and simulated top link control. They reported that pure draught control gave worse results than top link control. When the top link was in use also the vertical plough forces contributed to the power lift control. When the ploughing depth varied, the vertical ploughing force changed and this caused the power lift control to work although the draught force did not change much. When the gauge wheel of the plough is in use this phenomena increases. The experiments were continued by *Crolla & Pearson [39]* and they noted that the vertical force component also sensed tractor pitches immediately.

4.5 Lower link sensing force variation

The ploughing draught, the vertical ploughing force and the support force of the gauge wheel all have an effect on the sensing force of the power lift (chapter 2.2.2). The results of regression analysis for the varition of the sensing force of the power lift are in Appendix 3, in Eqn (18) and in Fig. 46. The tests were undertaken on 'flat surface', on 'gentle slopes' and 'modest slopes'.

$$F_{ls} = 6.40 + 0.02\,H_{low} - 0.28\,H_{sen} - 0.42\,H_{mix} - 0.33\,R_{at} + 1.87\,P_{sh} \qquad (18)$$

F_{ls} = standard deviation of lower links sensing force

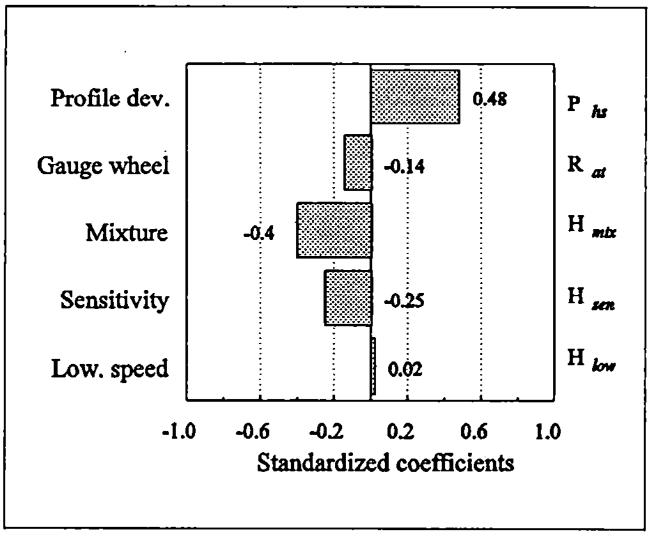


Fig. 46. Standardized coefficients of regression analysis, standard deviation of lower links sensing force. (R^2 = 0,69)

Standard deviation of the ground profile had the greatest influence on the sensing force deviation. When the severity of a slope increased, changes in the horizontal force also increased. Increasing sensitivity of the lift and using the lift more on draught control decreased this force change. The gauge wheel also decreased force changes. Power lift lowering speed did not have much effect on the sensing force.

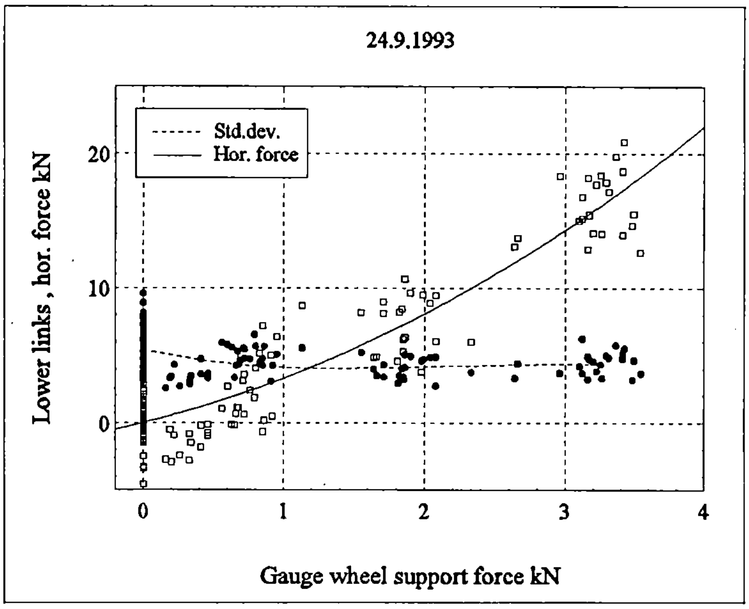


Fig. 47. Lower links sensing force and its standard deviation when the gauge wheel support force changes.

The effect of the gauge wheel on the sensing force is shown in Fig. 47. Without the gauge wheel the sensing force of the lower links was near zero. When the gauge wheel force increased the sensing force increased and the standard deviation of the sensing force was reduced somewhat.

There is an example of lower links sensing forces on undulating field in Fig. 48. The two tests were performed on the same field at about 15 m distance from each other. In both tests the power lift settings were the same. When the gauge wheel was in use, the sensing force changes were smaller. This made the power lift function smoother and the working depth variation was smaller and ploughing quality was better. The reason for better operation was the fact that the gauge wheel gained the lower links sensing force. A small depth change caused a sufficient force change for power lift. Without the gauge wheel the same force change required a larger change in ploughing depth. This can be seen from the lower links angle in Fig. 48. Without the gauge wheel it has varied much more. During a distance of 40 and 60 m the front of the tractor lifted up (left side of Fig. 48). The soil was heavy and the power lift movement did not raise the plough but raised the tractor front. This has led to interference where ploughing depth varied between 13 and 28 cm.

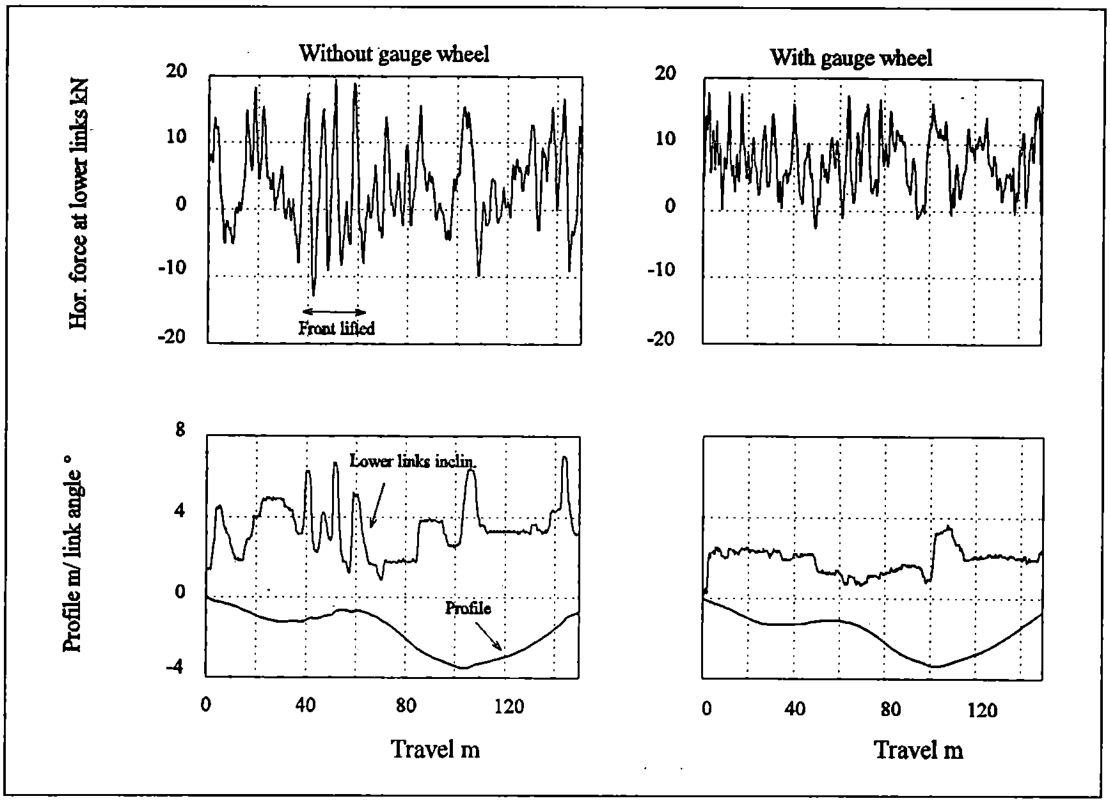


Fig. 48. Functioning of power lift during two tests, modest slopes. Left: gauge wheel out of use, right: gauge wheel in use, lower: lower links position and ground profile, upper: horizontal force at lower links.

When the gauge wheel was in use, it prevented deep working and in this way it prevented occasional high draughts. It predicted changes in the ground profile. When the tractor inclination changed the support force of the gauge wheel also changed. When the gauge wheel was not in use, the working depth must first change enough to change the sensing force.

4.6 Ploughing draught variation

The sensing force of the power lift includes horizontal and vertical draught forces and gauge wheel force. Ploughing draught includes only the horizontal draught force. If ploughing draught is uniform, then also wheel slip and ploughing power are uniform. The results of regression analysis are in Appendix 3, in Fig. 49 and in Eqn (19).

$$F_{xs} = 2.69 + 0.02 H_{low} - 0.07 H_{sen} - 0.14 H_{mix} - 0.23 R_{ats} + 1.39 P_{hs} \qquad (19)$$

F_{xs} = standard deviation of ploughing draught

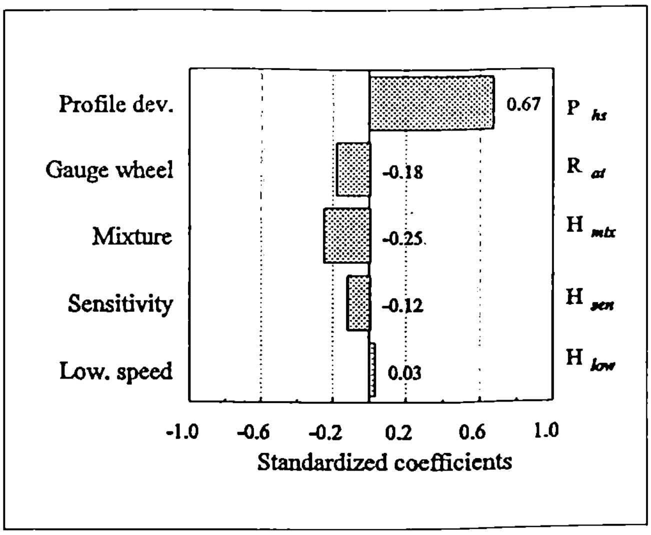


Fig. 49. Standardized coefficients of regression analysis, standard deviation of ploughing draught. ($R^2 = 0,76$)

The effect of ground profile undulation and the gauge wheel is shown in Fig. 50. Variation in ploughing draught increased when slopes became steeper. This is partly due to changes in ploughing depth. Ground surface undulation increased changes in ploughing depth and then also in draught. The gauge wheel decreased draught changes because it decreased depth variation.

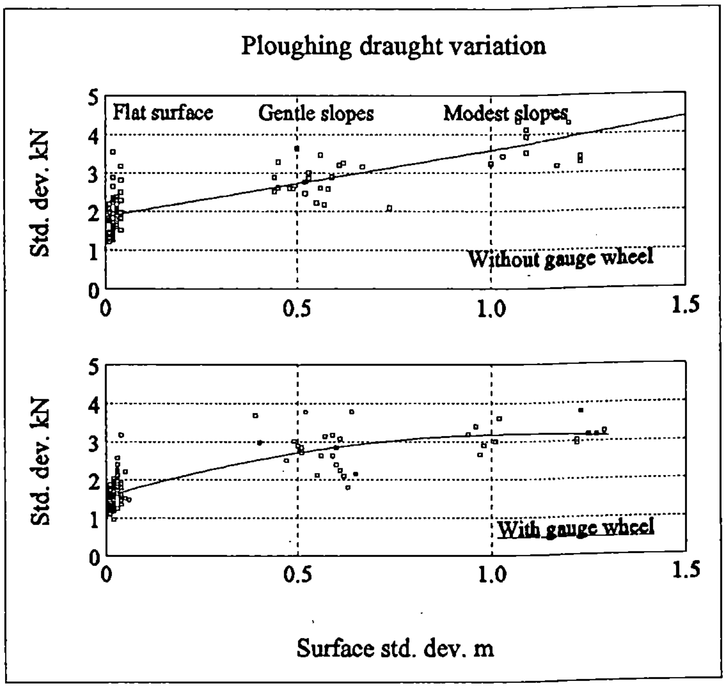


Fig. 50. The effect of ground surface undulation on draught variation of the plough, upper: gauge wheel out of use, lower: gauge wheel in use.

Within power lift settings mixture control had the greatest effect on draught deviation. It was slightly greater than effect of the gauge wheel. Sensitivity control had slightly smaller effect than the gauge wheel. The trend for control settings is shown in Fig. 51 which was calculated from tests without the gauge wheel. In tests with the gauge wheel the trend was similar.

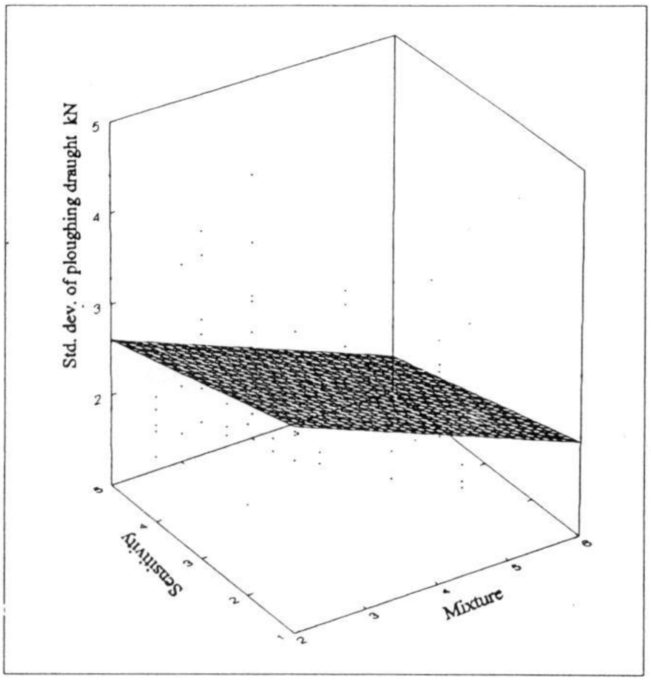


Fig. 51. Effect of mixture and sensitivity control on standard deviation of ploughing draught, gauge wheel out of use.

The effect of the gauge wheel on mean ploughing draught and its standard deviation is shown in Fig. 52. When the gauge wheel is in use, both mean ploughing draught and its variation was somewhat reduced. This is due to the fact that the gauge wheel prevented deep working. Specific ploughing resistance usually increases with working depth. An increase in depth deviation results in an increase in mean draught. This can be seen from a calculation for 200 mm mean depth which results are shown in Fig. 53. When standard deviation of the depth increases, the mean ploughing draught also increases.

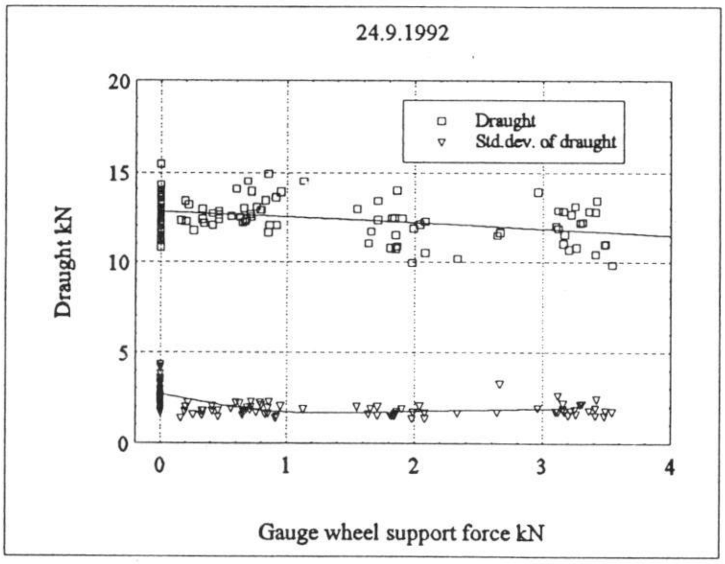


Fig. 52. Gauge wheel support force and ploughing draught.

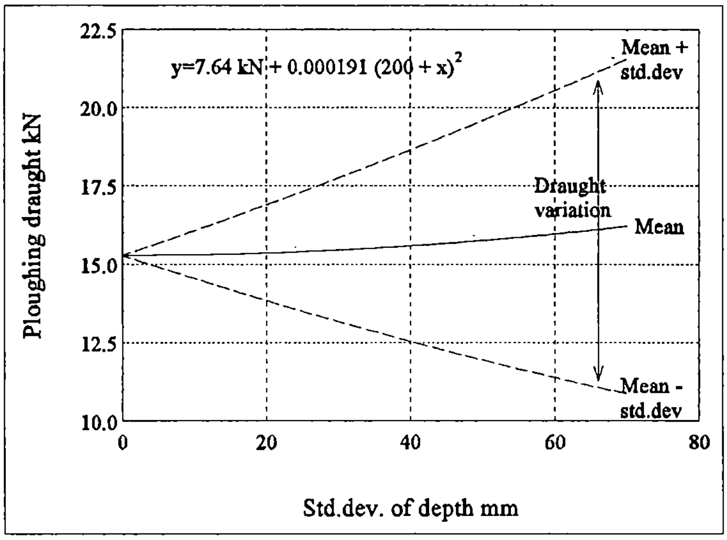


Fig. 53. Ploughing draught as a function of standard deviation of ploughing depth (mean depth = 200mm).

The draught force deviations on flat surface were about 12 %, on gentle slopes about 18 % and on modest slopes about 20 %. If regression Eqn (19) is used, ploughing draught deviation can be reduced by about 43 % when the best power lift setting combination is compared to position control. This is not a practical setting because it would give uneven working depth. With a practical setting the draught variation can be reduced by about 20 %.

Aho [40] measured the clutch axle torque of a 29 kW tractor during ploughing with a two-furrow plough where the standard deviation of torque was between 9 and 15 %. The clutch axle torque includes also rolling resistance forces, but their share is small compared to pulling force.

Dwyer [36] measured draught forces on a field with 15 cm amplitude and 7.3 m wavelength. He used two different tractors with two-furrow ploughs. The mean draught force was about 13 kN and standard deviation about 1.7 kN. This means 13 % standard deviation.

Dwyer, Crolla & Pearson [9] conducted tests on five different fields with a three-furrow plough. The field undulation was simulated by setting the tractor driving wheels eccentric so that 9 cm amplitude was achieved. They studied the effect of driving speed, dead-band of the control system, rate of lift and force sensing system. The draught variation was from 19 % upwards. They found that draught variation increased with driving speed and decreased when the dead-band was reduced or rate of lift was increased. *Crolla & Pearson [39]* continued these experiments. When they used position control, the deviation was 14 - 17 % and when draught control was in use the variation was 10-30 % lower than with position control. There was a noticeable increase in variation with increased driving speed.

The results of tests in the present study support the data as found in the literature reviewed: the standard deviation of ploughing draught is normally between 10 and 20 %.

It depends on the soil, plough and tractor function. This variation means that the maximum ploughing draught is about 30 - 60 % higher than the mean value. The torque back-up characteristics of tractor engines range from 10 to 30 %. The recommended torque back-up ratio on level ground is from 15 to 20 % *[1]*. The requirements for the back-up ratio cannot be directly compared with the ploughing draught changes. Usually the highest values of standard deviation have short duration time and they can be overcome by the kinetic energy of the tractor. When engine speed decreases because of higher draught, driving speed and therefore also draught decreases. It is however easier to keep up high ploughing power if the ploughing draught changes are small.

4.7 Ploughing power variation

The results of regression analysis are in Appendix 3, in Fig. 54 and in Eqn (20).

$$P_{sp} = 3.53 - 0.03\,H_{sen} - 0.14\,H_{mix} - 0.29\,R_{at} + 1.92\,P_{sh} \qquad (20)$$

P_{sp} = standard deviation of ploughing power, kW

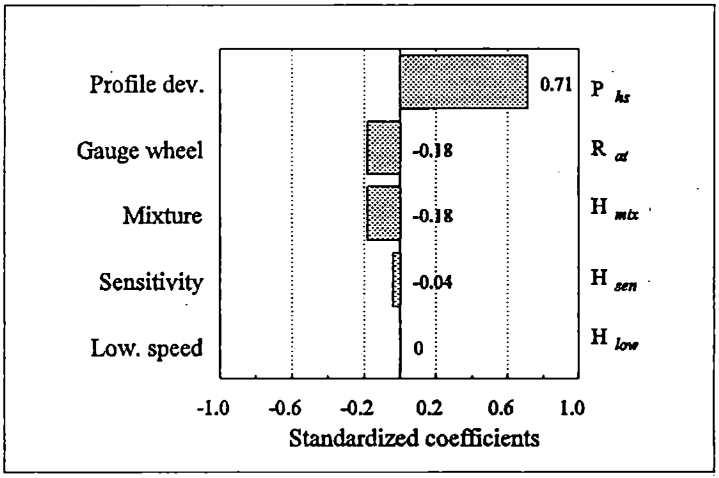


Fig. 54. Standardized coefficients of regression analysis, standard deviation of ploughing power. ($R^2 = 0.71$)

Ploughing power changes because draught changes and driving speed changes, steeper slopes increased power changes and the gauge wheel decreased it. When the mixture control of the power lift was towards draught control, power changes also decreased. The other settings did not influence power changes. The standard deviation of power on flat surface was 11 %, on gentle slopes 15 % and on modest slopes 19 %. According to regression Eqn (20) the power deviation can be reduced in maximum by about 25 % when compared to position control. The normal reduction is about 10 % when the ploughing quality is also considered. Power variation depends also on tractor engine characteristics, low torque back-up ratio causes a large power variation.

4.8 Weight transfer

Decreases in weight transfer cause worse mobility because wheel slip increases. Weight transfer depends on ploughing forces, on gauge wheel force and on power link support system (chapter 2.4). For good tractor mobility weight transfer should be strong and constant and wheel slip should be low and constant.

The power lift acted during the tests as a rigid system supporting the plough all the time. Only in some difficult interferences the support force disappeared and the system acted as a free link system. The reason for the rigid system behaviour was the lowering speed regulation, the plough mass, the plough share design and the functioning of the power lift regulation system. The lowering speed regulation prevented fast lowering and thus the vertical support force was better maintained. The share points of the plough were long and curved downwards which kept the suction into the ground better. The heavy weight of the plough emphasized this phenomena. The power lift regulation system allowed only small lowering changes and thus also maintained the vertical support force better.

Results of regression analysis are shown in Appendix 3, in Fig. 55 and in Eqn (21). Tractor lift settings did not have much affect on the total weight transfer or on the standard deviation of weight transfer. Field undulation increased changes in weight transfer. The total weight transfer was also increased but this was due to a higher specific ploughing resistance. With the gauge wheel in use the total weight transfer was reduced but did not have any effect on its changes.

$$
\begin{aligned}
\Delta R_{tr} &= 8.68 - 0.01 H_{low} + 0.04 H_{sen} + 0.04 H_{mix} - 1.08 R_{at} + 1.57 P_{sh} + 0.05 F_{x} \\
\Delta R_{trs} &= 0.80 - 0.01 H_{low} - 0.03 H_{mix} + 0.07 R_{at} + 0.63 P_{sh}
\end{aligned}
\tag{21}
$$

ΔR_{tr} = total weight transfer of the tractor

ΔR_{trs} = standard deviation of the total weight transfer of the tractor

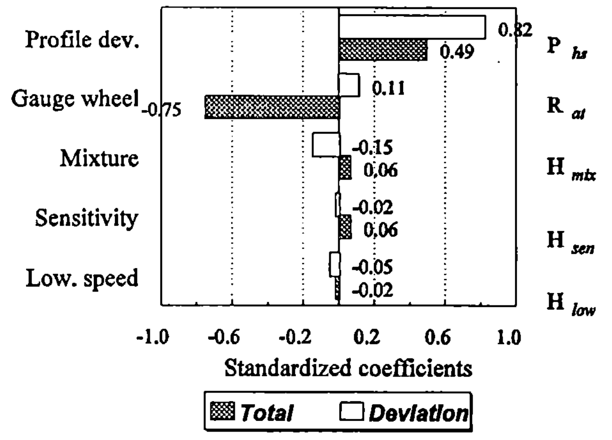


Fig. 55. Standardized coefficients of regression analysis, weight transfer. (Total: $R^2 = 0.71$, Std. dev.: $R^2 = 0.82$)

Krause *[41]* made a test with a four furrow plough and found that there were no clear differences in weigth transfer when using draught, position or depth control on the tractor.

The inclination of the tractor on slopes and changing soil properties increase variation in weight transfer, Fig. 56. The standard deviation on modest slopes was almost three times that on flat surface.

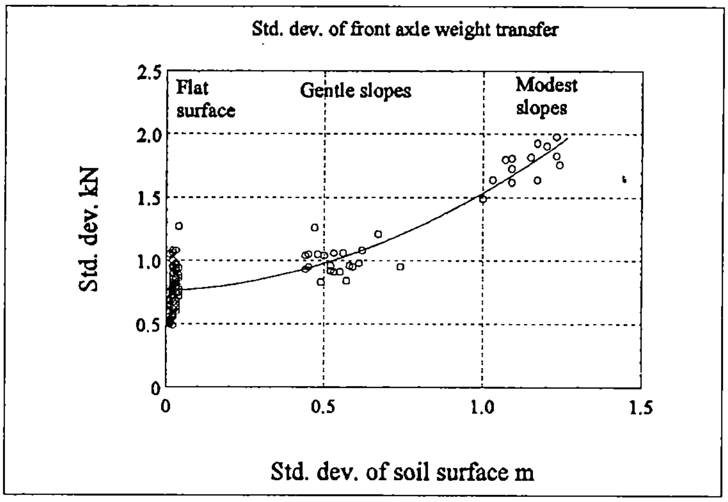


Fig. 56. Effect of ground surface undulation on front axle weight tranfer changes

The effect of the gauge wheel support force on total weight transfer and on transfer changes of the tractor is shown in Fig. 57. When the gauge wheel was in use, the total weight transfer was reduced, the rear axle weight transfer decreased and the front axle weight transfer increased. The gauge wheel force did not have any affect on the standard deviation of weight transfer at the present study.

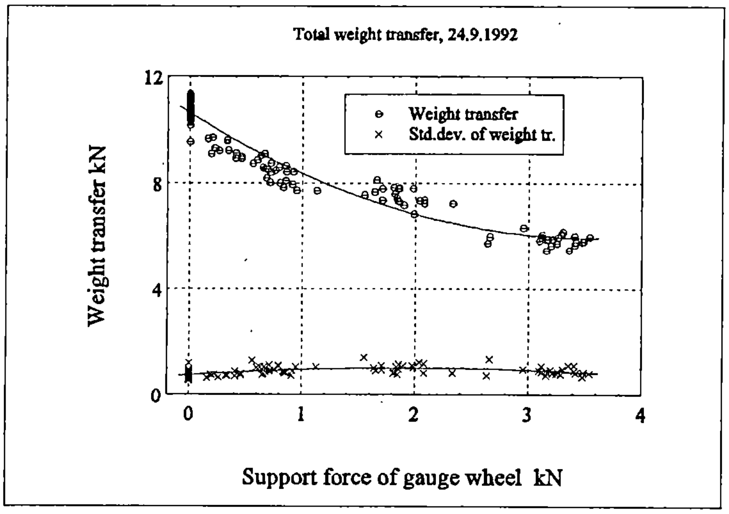


Fig. 57. Gauge wheel support force and weight transfer.

Interferences in ploughing have an affect on weight transfer. There is is an example in the left side of Fig. 58, that is measured on modest slopes. Between a distance of 40 and 80 m there are strong interferences in ploughing. Ploughing depth was occasionally deep and also ploughing draught has been high. This has caused the front of the tractor to lift up.

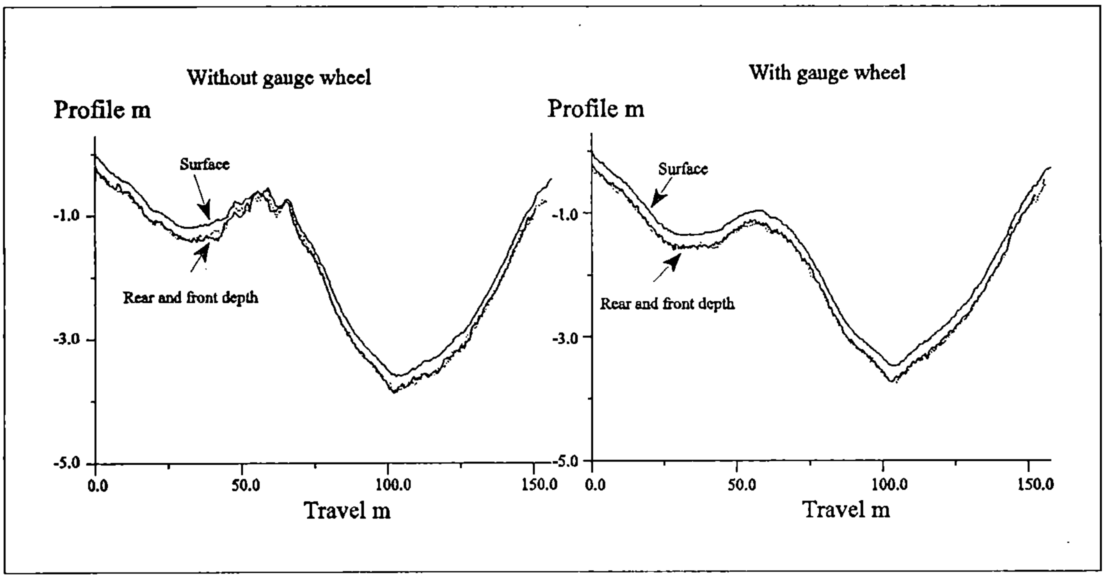


Fig. 58. Example of field profile and ploughing depths on modest slope. Left: plough gauge wheel out of use, right: plough gauge wheel in use.

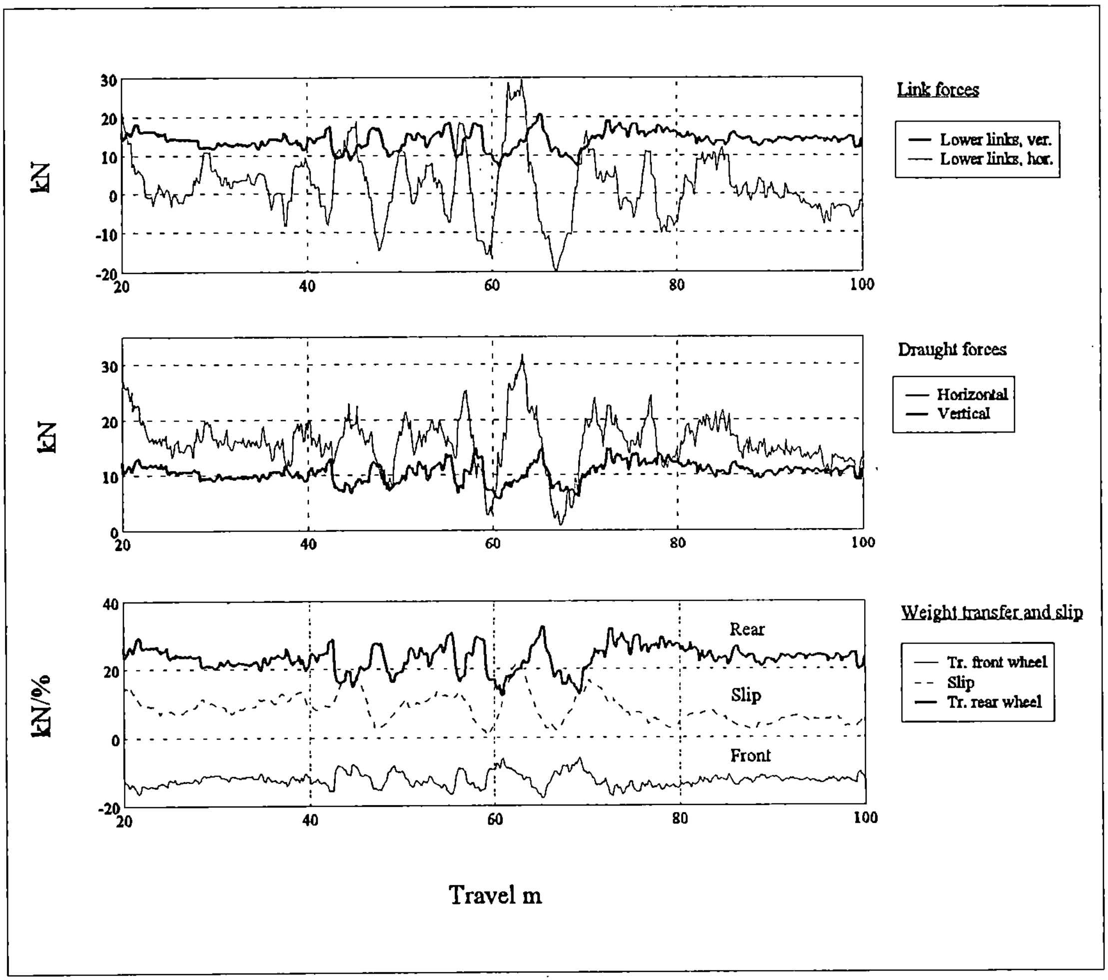


Fig. 59. Ploughing forces, weight transfer and wheel slip during a test, top: forces at lower links, middle: ploughing draughts, bottom: weight transfer and wheel slip. Plough gauge wheel was out of use.

The forces during the test of the left side of Fig. 58 can be seen in Fig. 59. Between a distance of 40 and 80 m the lower links forces and the ploughing draught changed noticeably. When the front of the tractor lifts up it is possible that the vertical ploughing force reduces. This weakens the weight transfer from the plough to the tractor. At about a distance of 60 m in Fig. 59 the vertical draught force has been low and the horizontal draught force has begun to increase. This resulted in increased wheel slip because of higher draught and poor weight transfer.

When the gauge wheel of the plough was in use the interference did not occur. The gauge wheel prevented large working depths and it also prevented the tractor from lifting up.

An example of a test run with the plough gauge wheel is shown in the right side of Fig. 58 which was undertaken in close proximity to the test featured in the left side of Fig. 58. Ploughing during the test was quite uniform and there were no interferences.

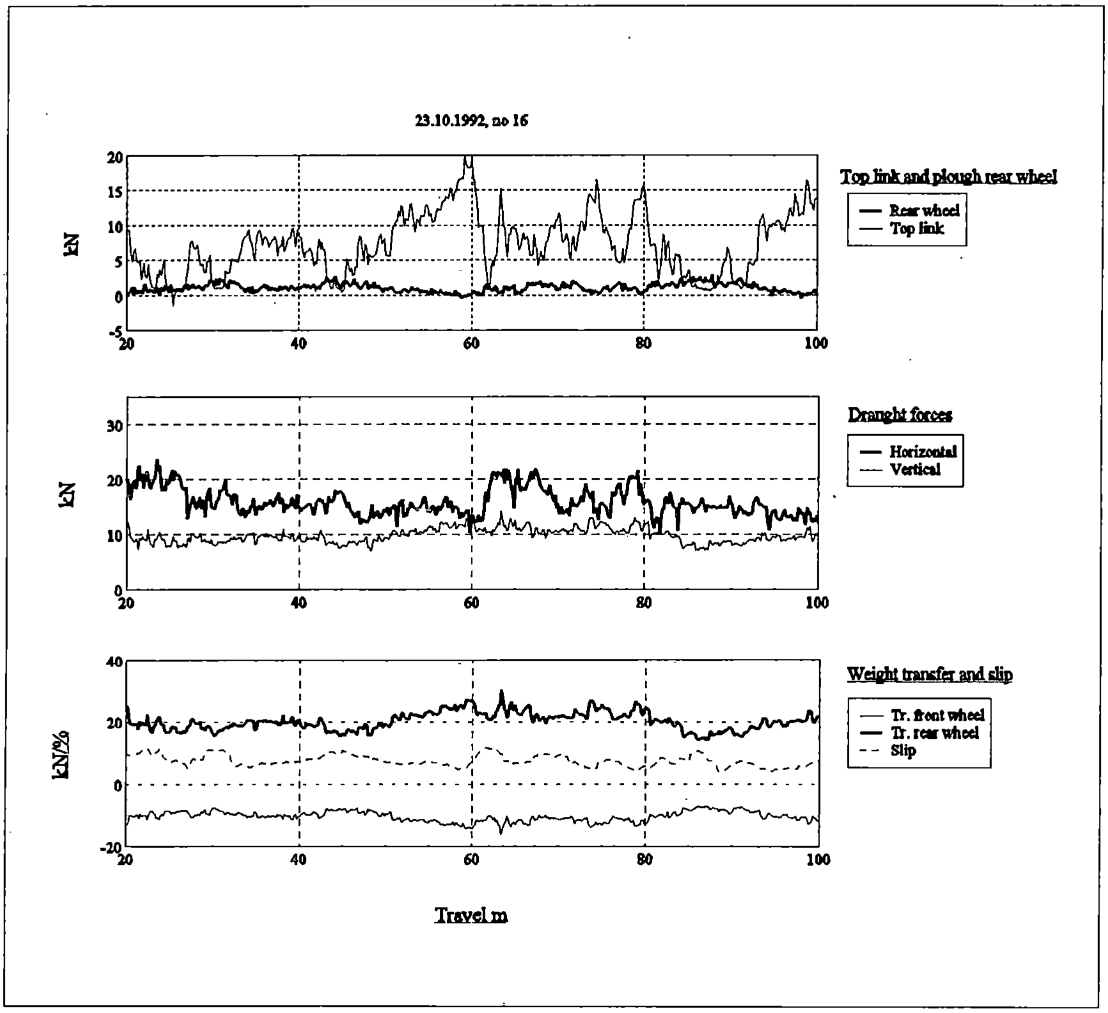


Fig. 60. Weight transfer, ploughing draft and wheel slip during a test, top: top link and plough gauge wheel forces, middle: ploughing draughts, bottom: weight transfer and wheel slip. The plough gauge wheel was in use.

An example of ploughing forces when the gauge wheel was in use is shown in Fig. 60. With the gauge wheel in use the ploughing depth has been more uniform and there are no interferences in the ploughing.

4.9 Wheel slip

Wheel slip and its variation depends on ploughing draught, traction and rolling resistance. Because soil conditions were different in different test fields, analysis was done separately for each test field, for flat surface and for modest slopes. Results of regression analysis are shown in Appendix 3, in Eqns (22) -(25) and standardized coefficients on modest slopes are in Fig. 61.

$$s_f = 2.80 - 0.13\,H_{low} - 0.37\,H_{sen} - 0.43\,H_{mix} + 1.23\,R_{at} + 4.17\,P_{sh} + 0.72\,F_x \qquad (22)$$

$$s_m = -1.12 - 0.05\,H_{low} - 0.10\,H_{sen} - 0.05\,H_{mix} - 0.57\,R_{at} + 5.34\,P_{sh} + 0.34\,F_x \qquad (23)$$

$$s_{fs} = 3.36 + 0.07\,H_{low} - 0.16\,H_{sen} - 0.16\,H_{mix} - 0.71\,R_{at} + 10.32\,P_{sh} + 0.01\,F_x \qquad (24)$$

$$s_{ms} = 4.83 - 0.03\,H_{low} - 0.04\,H_{sen} - 0.31\,H_{mix} - 0.51\,R_{at} + 1.89\,P_{sh} + 0.11\,F_x. \qquad (25)$$

s_f = tractor wheel slip, flat surface

s_m = tractor wheel slip, modest slope

s_{fs} = standard deviation of tractor wheel slip, flat surface

s_{ms} = standard deviation of tractor wheel slip, modest slope

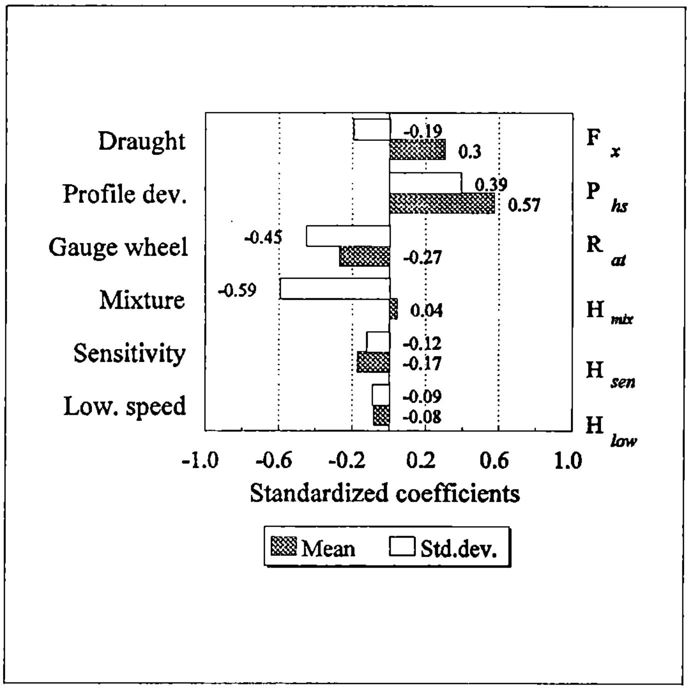


Fig. 61. Standardized coefficients of regression analysis, mean wheel slip and standard deviation of wheel slip on modest slopes. (Mean: $R^2 = 0.80$, Std. dev.: $R^2 = 0.59$)

On flat surface the plough gauge wheel had the greatest influence on mean slip. When the gauge wheel was in use, the mean slip was reduced, although the gauge wheel reduced weight transfer and consequently should have increased wheel slip. Draught force had almost as great an influence on mean wheel slip as the gauge wheel. This indicates changing specific resistance and traction. From power lift settings greater sensitivity and draught control reduced mean slip.

On modest slopes the profile standard deviation increased the mean slip. On slopes rolling resistance was increased and soil was harder resulting in increased slip. Power lift settings had a smaller influence on modest slopes than on flat surface. On both soils the gauge wheel reduced slip variation, draught control also reduced it.

The effect of the gauge wheel on flat surface is shown in Fig. 62. Tractor wheel slip and its standard deviation were reduced when the gauge wheel was in use. This is due to the fact that total ploughing draught and changes in ploughing depth were reduced. The effect of the gauge wheel force on slip was small, it was sufficient that the gauge wheel was in use.

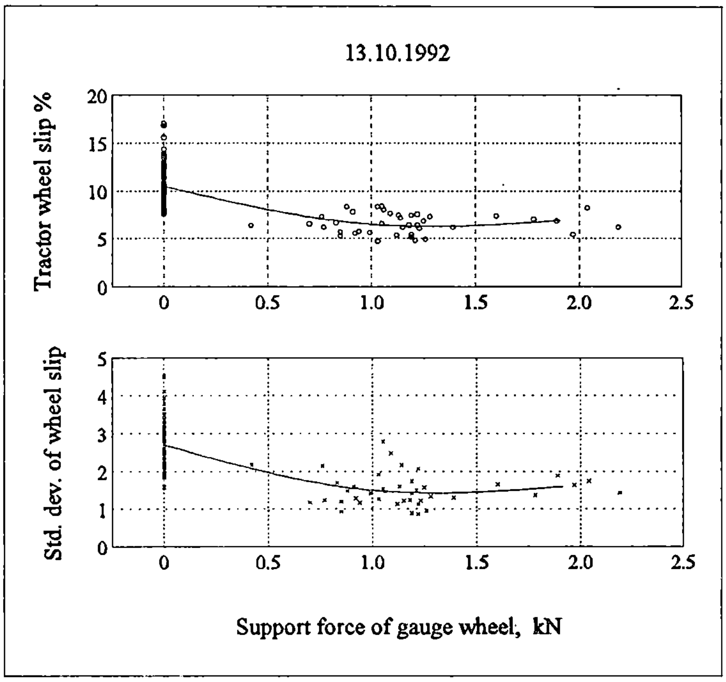


Fig. 62. Wheel slip and plough gauge wheel support force on flat surface, upper: wheel slip, lower: standard deviation of wheel slip.

The slip variation as a function of mean slip is shown in Fig. 63. The plough gauge wheel reduced mean slip and slip variation especially on flat surface. The use of the plough gauge wheel on modest slopes also reduced total slip and slip variation, but there are not enough test points that the phenomena could be better seen.

Tractor wheel slip variation during a test run on a modest slope is shown in Fig. 64. With the gauge wheel out of use tractor wheel slip has varied in a wider range. This can be seen from the two hollows at 40 m and 110 m. Without the plough gauge wheel in use the plough and the tractor did not articulate enough and this led to ploughing to a deep depth, to high draught and wheel slip. Traversing the valley at 100 m without using the gauge wheel caused tractor wheel slip of over 20 % resulting in the tractor wheel tracks being seen on the field. If tractor wheel slip continues at this level for a long period the tyre treads become packed with soil resulting in even more pronounced wheel slip and in markedly reduced traction.

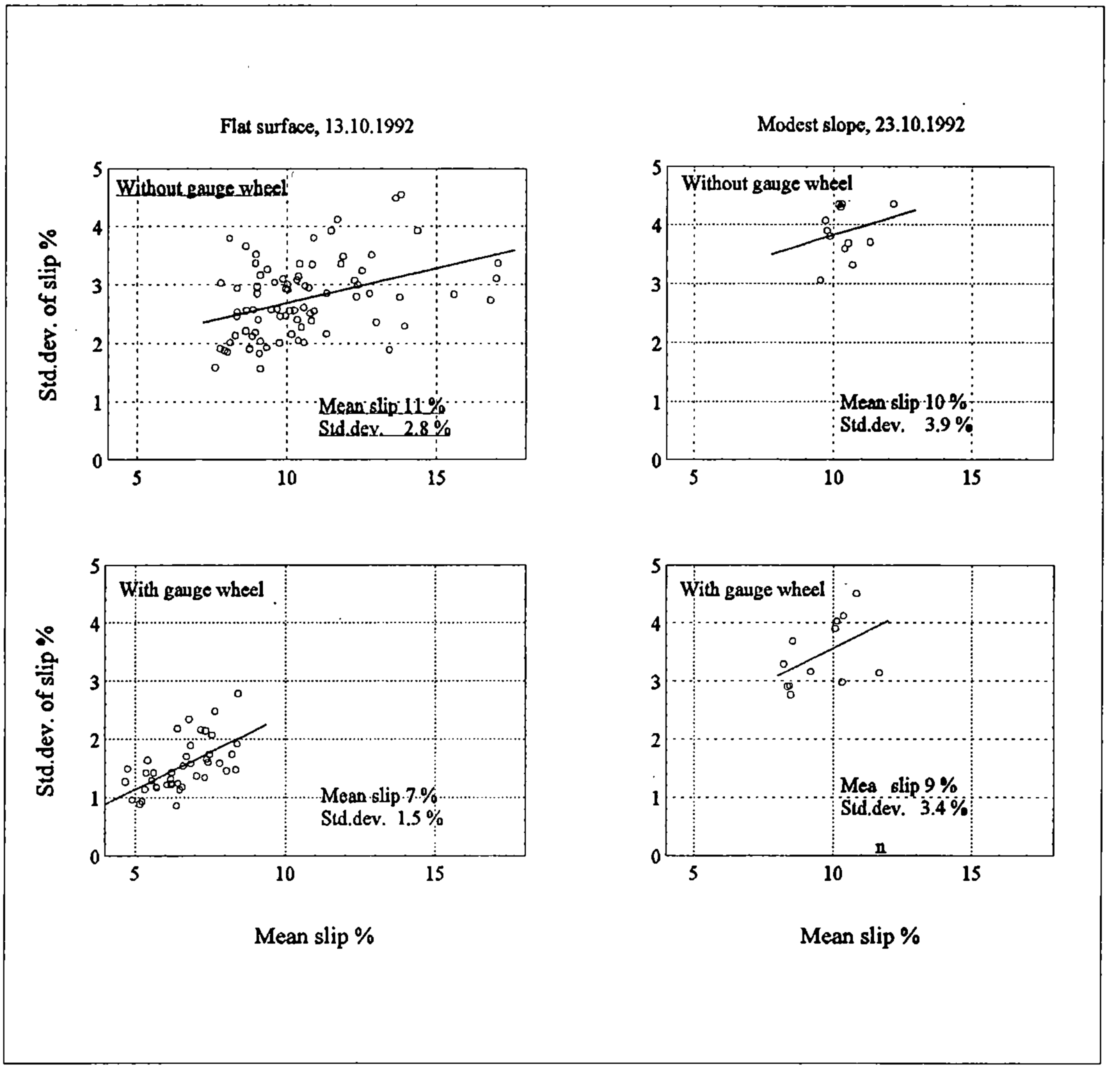


Fig. 63. Standard deviation of tractor wheel slip on flat surface and on modest slopes, left: flat soil, right: modest slopes, upper: plough gauge wheel out of use, lower: plough gauge wheel in use.

An example of tractor wheel slip during rut crossing is shown in Fig. 65 (rut profile, see Fig. 25). Wheel slip increased when the tractor rear wheels climbed from the rut at 7 m travel. Again, with the gauge wheel in use the highest slip value was significantly lower than without it being used.

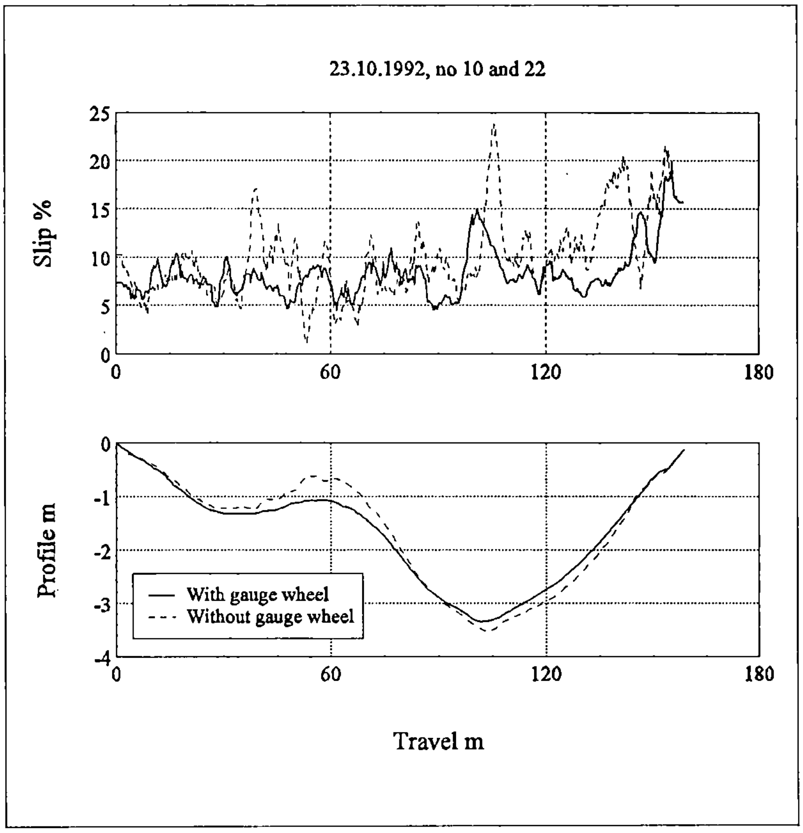


Fig. 64. Wheel slip during two test runs, upper: wheel slips, lower: ground profiles.

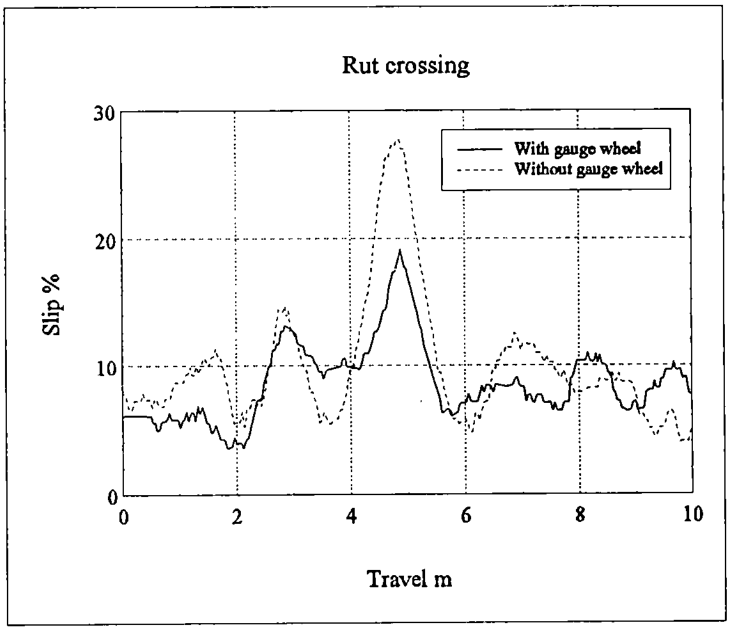


Fig. 65. Wheel slip during rut crossing

5. DISCUSSION

5.1 Field profile

The field profile was measured with an inclination and a travel transducer. The inclination transducer was mounted in the tractor cabin. It did not measure the true ground profile but the measured value was the mean value of the four tractor tyres. Also tractor movements during hard pulling could be seen in the measured values. Because the transducer was mounted on the tractor it was easy to use and it measured the profile simultaneously with other measurements.

The standard deviation of the field profile was used in ploughing analysis and its effect on ploughing quality was significant. When the ground became rougher, there were changes in soil conditions and there were difficulties in the articulation of the tractor-plough combination. This produced changes in the ploughing depth and poor ploughing quality. These are normal situations in ploughing and the drivers have to adjust the power lift during ploughing to get good ploughing quality.

The standard deviation of the ground profile was used in this study to represent ground roughness. In on-road and in off-road measurements the profile coefficients are normally calculated. Standardizing work is going on this calculation method. The ISO/DIS 8608 draft standard uses a smoothing method, which reduces measuring errors. The procedure, however, needs long measuring distances. A study would be needed to clarify how the ISO/DIS 8608 method could be used in ploughing measurements. This would include the required test length and the smoothing method. In this study the profile coefficients were also calculated, but no smoothing method was used, because the test distances were often too short. The calculated profile coefficients could not be used in analysis because of large variation. The standard deviation of the profile gave a better result.

5.2 Ploughing depth and width

Many researchers have suggested that the working depth should be kept in ± 10 % tolerance. This is hard to achieve with mounted ploughs and there are no strong agronomic reasons for this. The suggestion will give good appearance to the ploughing. In this study the working depth has been classified into four groups: the first class gives good ploughing appearance and the last class will, in normal ploughing depths, only keep the depth under 10 cm. If the depth is shallower harrowing will be difficult.

Both field undulation and the gauge wheel of the plough had great influence on depth changes. When undulation increased, the ploughing depth quality worsened. There was a marked increase in quality with the gauge wheel in use. The use of the gauge wheel reduced especially longer changes (long wavelengths) in ploughing depth.

The effect of power lift settings was small when compared to the effects of field undulation or the gauge wheel.

In the tests the ploughing depth was measured both at the front and at the rear of the plough. Normally when a fully mounted plough is used, it is not necessary to have ploughing depth transducers at both ends but they make adjustment of the plough easier. If the plough is semi-mounted or the gauge wheel of the plough is in use, then both depth measurements are needed.

The ploughing width was measured from the first furrow slice. Ploughing width did not change much during the measurements. Most of the variation was caused by interferences, such as soil blocks and shallow working depths. The width measuring system was useful during plough adjustments.

5.3 Gauge wheel

The gauge wheel of the plough had a great influence on ploughing quality. When it was used depth evenness and tractor mobility were significantly increased. When the gauge wheel was in use the changes in ploughing depth were smaller, especially so on undulating fields. In this study the depth changed without the gauge wheel from 13 to 33 % and with it from 9 to 20 %. Also tractor wheel slip decreased because ploughing draught and its changes decreased.

Many researchers have neglected the gauge wheel because it is seen to upset the lift control. Farmers, however, have been using the gauge wheel for years because it improves ploughing.

The use of the gauge wheel causes wider changes in the sensing force of the power lift than changing draught alone would do. This helps the lift to function better. Changes in ground inclinations affect immediately on the gauge wheel force. This change is transmitted to the power lift and the corrective lift movement occurs earlier than what the draught force indicates.

Gauge wheels should be used because they improve ploughing quality and function of the tractor hitch controls. The gauge wheel should be situated as far to the rear as possible so that its effect on weight transfer is smaller. It is enough that the gauge wheel only 'lightly' touches the ground. This will prevent deep ploughing depths and gain power lift functioning.

5.4 Ploughing draught and power

The standard deviation of ploughing draught was normally between 10 and 20 %, depending on the soil, plough and tractor function. From power lift settings mixture control had the greatest effect on draught deviation. It was slightly greater than the effect of the plough gauge wheel. Sensitivity control had slightly weaker effect. With the draught control draught deviation could be reduced in maximum by over 40 %. The setting for the minimum draught deviation produced a poor ploughing quality. If good ploughing quality was considered, then the deviation was reduced by some 20 %. With proper power lift settings and with the gauge wheel in use ploughing draught changes were decreased and tractor mobility and power usage were increased.

5.5 Weight transfer

For good mobility weight transfer should be strong and it should stay as constant as possible. Linkage geometry, plough shares and tractor ballasting have an influence on the total weight transfer. In this study the connection geometry was the same throughout the tests. The share points of the plough were curved down and this kept the vertical ploughing force good in most cases. With straight share points the situation would have been different. These facts can greatly affect weight transfer and for good mobility this subject requires further studies.

The deviation of weight transfer was normally near 10 %. In this study field undulation caused the greatest deviations in weight transfer due to changing soil types and difficulties in tractor-plough articulation. Power lift settings did not have much effect on weight transfer changes.

Weight transfer can change notably when there are difficulties in ploughing. Momentary weight transfer can be lost almost completely and tractor mobility will be affected. The rear gauge wheel of the plough reduced these interferences and thus improved quality and mobility.

5.6 Tractor wheel slip

Wheel slip depends on traction, ploughing draught and weight transfer. In this study the mean slip was about 9 % and the mean deviation was some 3 %. Power lift reduced both total wheel slip and its standard deviation. The gauge wheel of the plough reduced wheel slip noticeably. For instance on level ground the mean slip was reduced from 11 % to 7 % and the deviation was reduced from 2.8 % to 1.5 %. The use of the gauge wheel prevented deep ploughing depths and thus reduced high draught forces and high slip.

6 CONCLUSIONS

The present study has been undertaken to find the effect of the plough gauge wheel and how ground undulation can be measured and taken into account in ploughing analysis. These are normally excluded from ploughing analysis. Usually their influences were much stronger than for instance the influence of the tractor power lift settings. This means that they must be included when ploughing tests are done. Tests which are done on level and even surfaces are special cases where one very important variable is excluded by making it constant. Also if the gauge wheel of the plough is not used during tests the normal usage of the plough is not taken into account.

1. Ground undulation

The standard deviation of the profile height was used in the analysis. This made possible to have the field profile as one variable in the analysis. As a result ploughing measurements can be done on normal fields in normal conditions. This makes possible to improve the functioning of the power lift control system because comparable tests can be done in different kinds of fields. From the measured profile values power spectral density of the ground profile could be calculated. The required measuring length was however much longer than what is normal in ploughing tests. When only the standard deviation of the profile was used the frequency information of the field profile was lost. That was not a necessary information in this study but if it is needed then a study should be made to establish the relationship between the demands in test lengths in ploughing and field profile tests.

2. Plough gauge wheel

When the gauge wheel is in use the quality of the ploughing and the mobility of the tractor is improved significantly. With the gauge wheel the tractor power lift functions better because it foresees changes in the ploughing depth and in the field profile. A small change in gauge wheel support force will introduce a much larger force change in the three point links. The lift control system responds to this change much earlier than what the changing draught alone would introduce.

3. Recommendations for future research and development

The control systems of tractor power lifts are not functioning satisfactorily in all situations. Especially when the soil conditions or the ground profile is varying then the ploughing quality is poor. To achieve a good quality the driver has to adjust the power lift during ploughing. The power lift controls should be developed further so that they could manage also the difficult situations. It could be possible to use the gauge wheel for lift control system by measuring the support force, ploughing depth or driving speed. When this information is included in the normal power lift information, a better power lift control could be made.

7. SUMMARY

Normally ploughing tests are undertaken on level ground and without the use of the plough gauge wheel. In practise ploughing is often done in changing soil conditions and with the gauge wheel in use. The present study has been undertaken to find the effect of the gauge wheel and how ground undulation can be measured and taken into account in ploughing analysis. The criteria have been good ploughing quality, good mobility and effective usage of tractor power.

A Valmet 805-4 tractor with a mounted Överum CI 487 plough was used in the measurements. The ploughing forces were measured with force transducers at the links of the power lift. The gauge wheel supporting force of the plough was measured with a force transducer.Travel, driving speed and tractor wheel slip were measured with a Peiseler-wheel and with a speed transducer on the tractor engine. Ploughing depths were measured at both ends of the plough and also the cutting width of the first share was measured. The ground inclination was measured with an inclination transducer mounted in the tractor cabin. From inclination and travel values the ground profile could be calculated. The system measured the profile of the ground 'as seen by the tractor'. The functioning of the power lift was measured with an angle transducer at the lower links and with a pressure transducer at the hydraulic pump. A portable computer with a data acquisition card was used for measurements.

The measuring system was used in different soil conditions and in different ground undulations. The tests were run with and without the gauge wheel. During the tests the power lift settings of the tractor were varied between the minimum and maximum limits. The functioning of the lift was tested also in artificially made ruts. In this study about 400 test runs were used. Each test included 12 channels and from 500 to 1500 measuring points in each channel.

The ploughing quality was judged by uniform ploughing depth. Many researchers have proposed that changes in ploughing depth should be kept within ± 10 % tolerance. This requirement results in a good appearance but there are no obvious agronomic reasons for this, so in the present study, the ploughing quality is divided into four classes. The first class is the ± 10 % requirement and the fourth class just keeps the ploughing in normal situations deep enough so that harrowing is not made difficult. The second class has a depth tolerance of ± 20 % and it is named good ploughing depth evenness. The third class has a ± 30 % tolerance and it is named satisfactory ploughing depth evenness.

Tractor mobility and use of engine power were judged by wheel slip, weight transfer and horizontal pulling force. When wheel slip was moderate and uniform and weight transfer was strong and uniform and pull force was moderate and uniform, then also mobility was good and power usage was effective.

The use of the gauge wheel at the end of the plough had many benefits. It reduced tractor wheel slip and made better ploughing quality. When the gauge wheel was in use the changes in ploughing depth or in ground inclination produced an immediate change in the power lift sensing element force. The power lift of the tractor made a correction movement at the right time. When the gauge wheel was not in use the ploughing draught had to change before the correction movement was done. This lead to larger changes in depth, draught and tractor wheel slip.

The profile measuring system did not measure a true profile, but the accuracy was sufficient. Both power spectral density and standard deviation of the profile height were calculated. The standard deviation was used in analysis because it gave better classification of the slope type and the required measuring distance was shorter. The test results showed that field undulation had a significant influence on ploughing quality. This was due to changes in soil condition and difficulties in articulation of the tractor-plough combination. This surface profile measuring method can be used when ploughing tests are conducted on undulating fields.

8. TIIVISTELMÄ

Kyntömittaukset tehdään usein tasaisilla, tasalaatuisilla ja vaakasuorilla pelloilla. Kokeissa ei useinkaan käytetä auran tukipyörää, vaan aura on kokonaan traktorin nostolaitteen kannattelemana. Normaalissa kynnössä maan ominaisuudet ja pinnan muoto voivat vaihdella samallakin pellolla huomattavasti ja auran tukipyörän käyttö on hyvin yleistä. Tämän tutkimuksen aiheena on ollut miten auran tukipyörän käytön sekä pellon pinnan muodon vaikutus voidaan mitata ja ottaa huomioon kyntökokeissa. Arvosteluperusteina ovat olleet hyvä kynnön laatu, traktorin hyvä liikkumiskyky ja traktorin moottoritehon tehokas käyttö. Saatujen tulosten mukaan pellon pinnan muodon ja tukipyörän käytön vaikutukset olivat lähes aina huomattavasti merkittävämmät kuin esimerkiksi traktorin nostolaitehydrauliikan säädön vaikutukset. Kyntö- ja nostolaitekokeita tehtäessä sekä pellon pinnan muoto että tukipyörän käyttö pitäisi ottaa huomioon, muutoin tarkasteluista jätetään pois vaikutukseltaan merkittävät tekijät.

Mittauksissa käytettiin Valmet 805-4 traktoria ja nelisiipistä Överum CI 487 nostolaiteauraa. Kyntövoimat mitattiin traktorin nostolaitteen varsiin asennetuilla voima-antureilla. Auran tukipyörän voima mitattiin tukipyörään asennetulla anturilla. Ajonopeus, ajomatka ja pyörien luisto mitattiin seuraajapyörän ja traktorin moottorin pyörimisnopeuksien avulla. Kyntösyvyys mitattiin sekä auran alku- että loppupäästä ja työleveys mitattiin ensimmäisen viilun leveydestä. Pellon kaltevuus mitattiin traktorin ohjaamoon asennetun kallistuma-anturin avulla. Kallistuman ja kuljetun matkan avulla laskettiin pellon pinnan muoto. Tämä oli 'traktorin näkemä' muoto, koska kallistumaan vaikutti traktorin pyörien korkeuserot ja renkaiden joustot. Nostolaitteen toiminta mitattiin vetovarsien asentoanturin ja hydraulipumpun lähtövirtauksen paineanturin avulla. Asentoanturi ilmaisi vetovarsien asennon traktorin runkoon nähden ja paineanturi ilmaisi nostolaitehydrauliikan korjausliikkeet. Mittauksissa käytettiin kannettavaa tietokonetta, johon oli asennettu tiedonkeruukortti.

Mittaukset tehtiin erilaisilla maalajeilla ja muodoltaan vaihtelevilla pelloilla sekä ilman tukipyörää että tukipyörää käyttämällä. Traktorin nostolaitteen säätöjä muutettiin järjestelmällisesti pienimmän ja suurimman säätöarvon väliltä. Mittauksia oli kaikkiaan n 400 kpl ja jokaisessa mittauksessa oli 12 kanavaa ja kanavaa kohti oli 500 - 1500 mittauspistettä.

Kyntösyvyyden laatua arvosteltiin syvyyden tasaisuuden avulla. Useat tutkijat ovat ehdottaneet, että kyntösyvyyden pitäisi pysyä ±10 % rajoissa. Tämä vaatimus aikaansaa ulkönäöltään hyvän kynnön, mutta vaatimukselle ei ole olemassa mitään selviä viljelyksellisiä perusteita. Tämän takia arvostelussa on käytetty neljää laatuluokkaa. Kun keskimääräinen kyntösyvyys on 20 ja 25 cm väliltä, näiden laatuluokkien vaatimukset ovat seuraavat. Ensimmäisen laatuluokan vatimukset vastaavat edellä olevaa ±10 % rajaa, jolloin kyntösyvyys vaihtelee ±2,5 cm keskiarvostaan. Laatuluokasta on käytetty nimeä 'erittäin hyvä' kyntösyvyyden tasaisuus. Toisessa laatuluokassa vaihtelu saa olla ±20 %, jolloin työsyvyys vaihtelee ± 5 cm keskiarvostaan. Laatuluokasta on käytetty nimeä 'hyvä' kyntösyvyyden tasaisuus. Kolmannessa laatuluokassa vaihtelu saa olla ±30 %, jolloin kyntösyvyys vaihtelee ±7,5 cm keskiarvostaan. Laatuluokasta on käytetty nimeä 'tyydyttävä' kyntösyvyyden tasaisuus. Neljännessä laatuluokassa vaihtelu saa olla ±40 %, jolloin kyntösyvyys vaihtelee ±10 cm keskiarvostaan. Neljännen laatuluokan nimenä on 'välttävä' kyntösyvyyden tasaisuus, kyntösyvyys pysyy 10 cm syvempänä, jolloin se on äestyssyvyyttä hieman syvempi ja kylvö- ja äestystöissä ei vielä pitäisi olla ongelmia. Kun auran tukipyörä ei ollut käytössä, kynnön laatu oli tasaisilla pelloilla keskimäärin hyvä, loivissa rinteissä tyydyttävä ja jyrkissä rinteissä monasti huonompi kuin välttävä. Kun auran tukipyörä oli käytössä, kynnön tasaisuus oli tasaisilla pelloilla erittäin hyvä, loivissa rinteissä hyvä ja jyrkissä rinteissä tyydyttävä.

Traktorin liikkumiskykyä ja moottoritehon hyödyntämistä on arvosteltu pyörien luiston, painonsiirron ja vetovoiman avulla. Kun luisto oli kohtuullinen ja painonsiirto oli voimakasta, tällöin tasainen luisto, painonsiirto ja vetovoima aikaansaivat hyvän liikkumiskyvyn ja tehon käytön.

Auran tukipyörän käytöstä oli hyötyä. Sen käyttö vähensi traktorin pyörien luistoa ja paransi kynnön laatua. Kun tukipyörä oli käytössä, pienikin tukipyörän tukivoiman muutos aikaansai riittävän voimamuutoksen traktorin nostolaitteessa, jolloin nostalaitteen korjausliike tapahtui ajoissa. Kun tukipyörä ei ollut käytössä, vastuksen oli muututtava riittävästi, jotta nostolaite reagoi. Tällöin korjausliike tapahtui myöhemmin kuin tukipyörää käytettäessä ja kyntösyvyyden, vetovastuksen ja traktorin pyörien luiston muutokset olivat suurempia.

Pellon pinnan muodon mittausjärjestelmä ei mitannut pellon todellista muotoa, vaan traktorin 'näkemää' pinnan muotoa. Tämä oli kuitenkin pellon pinnan arvosteluun riittävän tarkka. Pellon pinnan muodon tuloksista laskettiin sekä tehospektritiheydet että pinnan korkeuden hajonnat. Tulosten tarkastelussa käytettiin pinnan korkeuden hajontaa, koska se luokitteli paremmin pinnan muodon ja koska mittausmatkalle ei ollut pituusvaatimusta kuten tehospektrimittauksissa on. Toisaalta tehospektritiheyden käyttö sisältää myös pinnan taajuusominaisuudet, joka tieto pinnan hajontaa käytettäessä menetetään. Tässä tutkimuksessa pinnan taajuusominaisuuksia ei tarvittu, jolloin hajontatiedot riittivät arvosteluun. Tulokset osoittivat, että pellon pinnan epätasaisuudet vaikuttivat voimakkaasti kynnön laatuun. Kun pinnan vaihtelu lisääntyi, maan ominaisuudet muuttuivat enemmän ja traktori-aurayhdistelmän niveltyvyys kumpareissa ja notkoissa vaikeutui.

Traktorin nostolaitehydrauliikat eivät toimi kaikissa tilanteissa tyydyttävästi. Jos kyntöolosuhteet ovat vaihtelevat tai pellon pinnan muoto vaihtelee, kynnön laatu on huono. Tälläisissä tilanteissa kuljettajan täytyy säätää hydrauliikka ajon aikana. Nostolaitehydrauliikkaa pitäisi kehittää edelleen niin, että kynnön automatiikka selviytyisi myös vaikeissa olosuhteissa. Tähän voitaisiin käyttää avuksi auran tukipyörää mittaamalla sen tukivoimaa tai mittamalla sen avulla työsyvyyttä ja traktorin pyörien luistoa. Yhdistämällä nämä tiedot traktorin nostolaitteen säätöjärjestelmään saataisiin paremmin toimiva nostolaitteen kyntösäätö.

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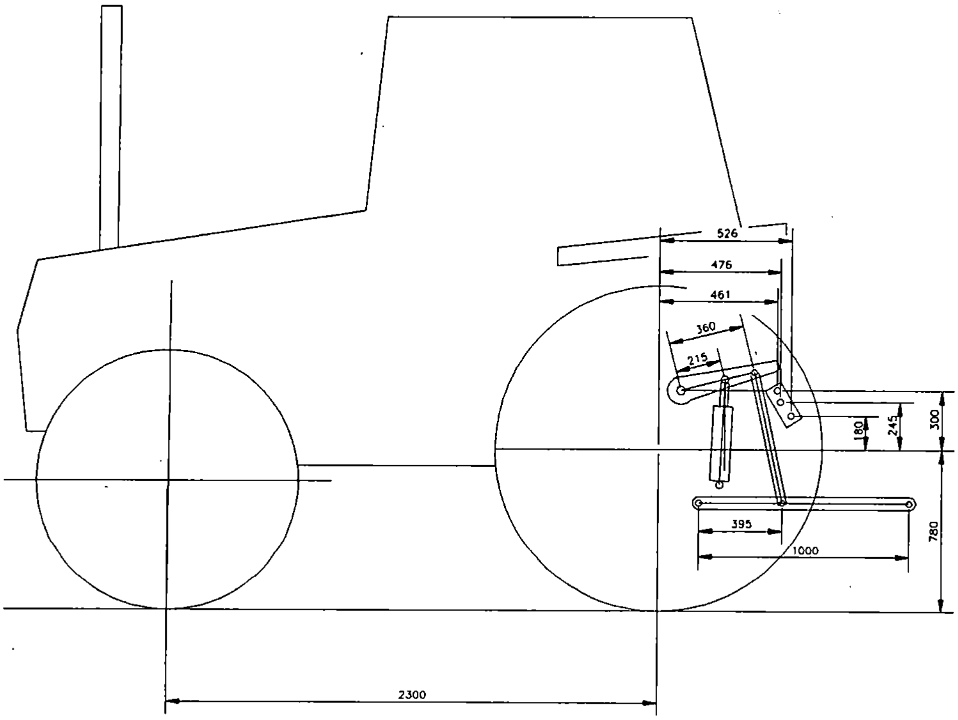
Appendix 1.

Valmet 805-4, technical specifications:

Nominal Power-Take-Off power	66.6 kW
Tractor mass:	
Front	1660 kg
Rear	2180 kg
Toatal	3840 kg
Wheels:	
Front	13.6 R 28
Rear	16.9 R 38
Nominal driving speeds between 5 and 10 km/h:	
L2H	5.6 km/h
L3L	6.3 km/h
L3H	8.0 km/h
L4L	8.0 km/h
L4H	10.0 km/h

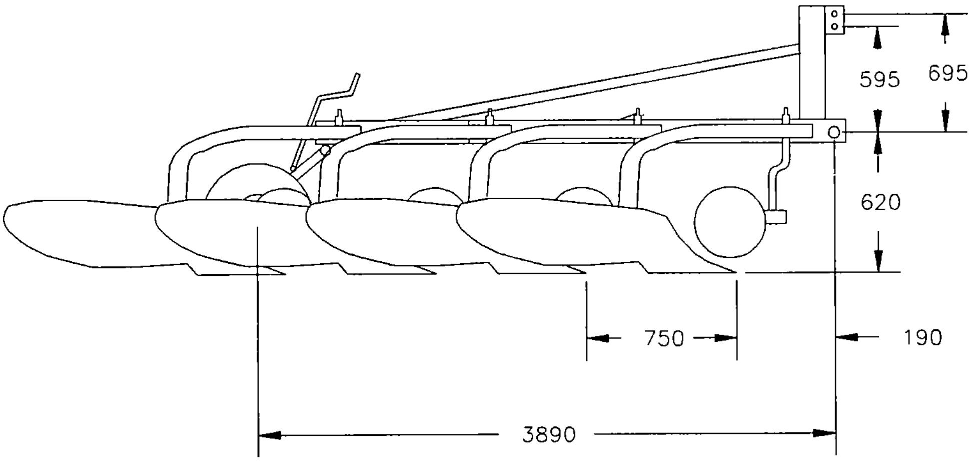


Dimensions of Valmet 805-4 tractor, mm

Appendix 2.

The technical specifications of the test plough

Plough	**Överum CI 487**
Total mass	850 mm
Ploughing width	250 - 400 mm, stepwise adjustable
Number of furrows	4



Dimensions of Överum CI 487 - plough, mm

Results of regression analysis

Appendix 3

Lowering speed, sensitivity and mixing setting: 1 - 6
Plough wheel support force and draught force: kN
Profile deviation: m

```
DEP VAR:     Standard deviation of slip, 13.10.1992
N:      147  MULTIPLE R: 0.765  SQUARED MULTIPLE R: 0.585
ADJUSTED SQUARED MULTIPLE R:  .567     STANDARD ERROR OF ESTIMATE:          0.51

VARIABLE       COEFFICIENT    STD ERROR      STD COEF TOLERANCE    T    P(2 TAIL)

CONSTANT               3.36         0.80         0.00        .      4.20      0.00
LOW. SPEED             0.07         0.04         0.11      0.97     1.93      0.06
SENSITIV.             -0.16         0.04        -0.22      0.88    -3.78      0.00
MIX.                  -0.16         0.04        -0.28      0.76    -4.55      0.00
PLOUGH WHEEL          -0.71         0.07        -0.59      0.86   -10.11      0.00
PROF. DEV.            10.32         4.13         0.14      0.94     2.50      0.01
DRAUGHT FORCE          0.01         0.04         0.02      0.60     0.27      0.79
```

```
DEP VAR:  Standard deviation of slip, 23.10.1992
N:       24  MULTIPLE R: 0.768  SQUARED MULTIPLE R: 0.590
ADJUSTED SQUARED MULTIPLE R:  .445     STANDARD ERROR OF ESTIMATE:          0.40

VARIABLE       COEFFICIENT    STD ERROR      STD COEF TOLERANCE    T    P(2 TAIL)

CONSTANT               4.83         2.36         0.00               2.04      0.06
LOW. SPEED            -0.03         0.06        -0.09      1.00    -0.59      0.56
SENSITIV.             -0.04         0.07        -0.12      0.58    -0.61      0.55
MIX.                  -0.31         0.09        -0.59      0.92    -3.64      0.00
PLOUGH WHEEL          -0.51         0.20        -0.45      0.75    -2.51      0.02
PROF. DEV.             1.89         0.89         0.39      0.72     2.12      0.05
DRAUGHT FORCE         -0.11         0.15        -0.19      0.40    -0.78      0.44
```

```
DEP VAR:  Slip, 13.10.1992
N:      147  MULTIPLE R: 0.776  SQUARED MULTIPLE R: 0.602
ADJUSTED SQUARED MULTIPLE R:  .585     STANDARD ERROR OF ESTIMATE:          1.47

VARIABLE          COEFFICIENT    STD ERROR      STD COEF TOLERANCE    T    P(2 TAIL)

CONSTANT                  2.80         2.34         0.00        .      1.20      0.23
LOW. SPEED               -0.13         0.10        -0.07      0.97    -1.29      0.20
SENSITIV.                -0.37         0.13        -0.17      0.88    -2.95      0.00
MIX.                     -0.43         0.10        -0.25      0.76    -4.09      0.00
PLOUGH WHEEL             -1.23         0.21        -0.34      0.86    -5.97      0.00
PROF. DEV.                4.17        12.03         0.02      0.94     0.35      0.73
DRAUGHT FORCE             0.72         0.13         0.39      0.60     5.63      0.00
```

```
DEP VAR:  Slip, 23.10.1992
N:      24  MULTIPLE R: 0.894  SQUARED MULTIPLE R: 0.798
ADJUSTED SQUARED MULTIPLE R:  .727    STANDARD ERROR OF ESTIMATE:        0.54

VARIABLE       COEFFICIENT      STD ERROR      STD COEF TOLERANCE     T    P(2 TAIL)

CONSTANT             -1.12           3.18          0.00         .     -0.35      0.73
LOW. SPEED           -0.05           0.07         -0.08      1.00     -0.71      0.48
SENSITIV.            -0.10           0.09         -0.17      0.58     -1.16      0.26
MIX.                  0.05           0.12          0.04      0.92      0.39      0.70
PLOUGH WHEEL         -0.57           0.27         -0.27      0.75     -2.11      0.05
PROF. DEV.            5.34           1.20          0.57      0.72      4.44      0.00
DRAUGHT FORCE         0.34           0.20          0.30      0.40      1.72      0.10
```

```
DEP VAR:       Standard deviation of depth at the rear of the plough, 13.10.1992,
               22.10.1992 and 23.10.1992
N:      213  MULTIPLE R: 0.874  SQUARED MULTIPLE R: 0.763
ADJUSTED SQUARED MULTIPLE R:  .757    STANDARD ERROR OF ESTIMATE:        5.34

VARIABLE       COEFFICIENT      STD ERROR      STD COEF TOLERANCE     T    P(2 TAIL)

CONSTANT             21.48           1.86          0.00         .     11.57      0.00
LOW. SPEED           -0.06           0.28         -0.01      0.99     -0.23      0.82
SENSITIV.             0.15           0.29          0.02      0.93      0.50      0.62
MIX.                 -0.46           0.28         -0.06      0.92     -1.66      0.10
PLOUGH WHEEL         -8.17           0.60         -0.47      0.97    -13.58      0.00
PROF. DEV.           18.92           1.06          0.66      0.85     17.91      0.00
```

```
DEP VAR:        Standard deviation of the sensing force of lower links, 13.10.1992,
                22.10.1992 and 23.10.1992
N:      213  MULTIPLE R: 0.832  SQUARED MULTIPLE R: 0.692
ADJUSTED SQUARED MULTIPLE R:  .685    STANDARD ERROR OF ESTIMATE:        0.82

VARIABLE       COEFFICIENT      STD ERROR      STD COEF TOLERANCE     T    P(2 TAIL)

CONSTANT              6.40           0.29          0.00         .     22.38      0.00
LOW. SPEED            0.02           0.04          0.02      0.99      0.57      0.57
SENSITIV.            -0.28           0.05         -0.25      0.93     -6.27      0.00
MIX.                 -0.42           0.04         -0.40      0.92     -9.89      0.00
PLOUGH WHEEL         -0.33           0.09         -0.14      0.97     -3.54      0.00
PROF. DEV.            1.87           0.16          0.48      0.85     11.50      0.00
```

```
DEP VAR:        Standard deviation of the draught force of the plough, 13.10.1992,
                22.10.1992 and 23.10.1992
N:      213  MULTIPLE R: 0.871  SQUARED MULTIPLE R: 0.758
ADJUSTED SQUARED MULTIPLE R:  .752    STANDARD ERROR OF ESTIMATE:        0.39

VARIABLE       COEFFICIENT      STD ERROR      STD COEF TOLERANCE     T    P(2 TAIL)

CONSTANT              2.69           0.13          0.00         .     20.00      0.00
LOW. SPEED            0.02           0.02          0.03      0.99      0.94      0.35
SENSITIV.            -0.07           0.02         -0.12      0.93     -3.40      0.00
MIX.                 -0.14           0.02         -0.25      0.92     -7.02      0.00
PLOUGH WHEEL         -0.23           0.04         -0.18      0.97     -5.23      0.00
PROF. DEV.            1.39           0.08          0.67      0.85     18.22      0.00
```

```
DEP VAR:        Standard deviation of ploughing power, 13.10.1992, 22.10.1992 and
                23.10.1992
N:      213  MULTIPLE R: 0.840  SQUARED MULTIPLE R: 0.705
ADJUSTED SQUARED MULTIPLE R:  .698    STANDARD ERROR OF ESTIMATE:        0.56

VARIABLE       COEFFICIENT      STD ERROR      STD COEF TOLERANCE     T    P(2 TAIL)

CONSTANT              3.53           0.19          0.00         .     18.17      0.00
LOW. SPEED            0.00           0.03          0.00      0.99      0.06      0.95
SENSITIV.            -0.03           0.03         -0.04      0.93     -0.97      0.33
MIX.                 -0.14           0.03         -0.18      0.92     -4.67      0.00
PLOUGH WHEEL         -0.29           0.06         -0.18      0.97     -4.61      0.00
PROF. DEV.            1.92           0.11          0.71      0.85     17.41      0.00
```

```
DEP VAR:      Standard deviation of weight transfer at the front axle of
              the tractor, 13.10.1992, 22.10.1992 and 23.10.1992
N:      213  MULTIPLE R: 0.874  SQUARED MULTIPLE R: 0.763
ADJUSTED SQUARED MULTIPLE R:  .758    STANDARD ERROR OF ESTIMATE:         0.18

VARIABLE      COEFFICIENT     STD ERROR     STD COEF TOLERANCE    T    P(2 TAIL)

CONSTANT            0.94          0.06          0.00       .     14.76      0.00
LOW. SPEED         -0.01          0.01         -0.02     0.99    -0.71      0.48
SENSITIV.          -0.01          0.01         -0.05     0.93    -1.39      0.17
MIX.               -0.03          0.01         -0.13     0.92    -3.67      0.00
PLOUGH WHEEL        0.12          0.02          0.19     0.97     5.65      0.00
PROF. DEV.          0.82          0.04          0.83     0.85    22.54      0.00
```

```
DEP VAR:      Standard deviation of weight transfer at rear axle of
              the tractor, 13.10.1992, 22.10.1992 and 23.10.1992
N:      213  MULTIPLE R: 0.884  SQUARED MULTIPLE R: 0.781
ADJUSTED SQUARED MULTIPLE R:  .775    STANDARD ERROR OF ESTIMATE:         0.32

VARIABLE      COEFFICIENT     STD ERROR     STD COEF TOLERANCE    T    P(2 TAIL)

CONSTANT            1.63          0.11          0.00       .     14.81      0.00
LOW. SPEED         -0.02          0.02         -0.03     0.99    -0.92      0.36
SENSITIV.          -0.03          0.02         -0.05     0.93    -1.59      0.11
MIX.               -0.06          0.02         -0.13     0.92    -3.93      0.00
PLOUGH WHEEL        0.17          0.04          0.16     0.97     4.82      0.00
PROF. DEV.          1.48          0.06          0.83     0.85    23.67      0.00
```

```
DEP VAR:      Standard deviation of total weight transfer of the tractor,
 13.10.1992 and 22.10.1992
N:      157  MULTIPLE R: 0.903  SQUARED MULTIPLE R: 0.815
ADJUSTED SQUARED MULTIPLE R:  .809    STANDARD ERROR OF ESTIMATE:         0.14

VARIABLE       COEFFICIENT     STD ERROR      STD COEF TOLERANCE    T    P(2 TAIL)

CONSTANT              0.80          0.05          0.00        .     14.98       0.00
LOW. SPEED           -0.01          0.01         -0.05      0.99    -1.43       0.16
SENSITIV.            -0.00          0.01         -0.02      0.93    -0.54       0.59
MIX.                 -0.03          0.01         -0.15      0.90    -4.10       0.00
PLOUGH WHEEL          0.07          0.02          0.11      0.98     3.20       0.00
PROF. DEV.            0.63          0.03          0.82      0.84    21.63       0.00
```

```
DEP VAR:      Total weight transfer of the tractor,
              13.10.1992 and 22.10.1992
N:      133  MULTIPLE R: 0.843  SQUARED MULTIPLE R: 0.711
ADJUSTED SQUARED MULTIPLE R:  .698    STANDARD ERROR OF ESTIMATE:         0.44

VARIABLE       COEFFICIENT     STD ERROR      STD COEF TOLERANCE    T    P(2 TAIL)

CONSTANT              8.68          0.60          0.00        .     14.42       0.00
LOW. SPEED           -0.01          0.03         -0.02      0.96    -0.45       0.65
SENSITIV.             0.04          0.03          0.06      0.87     1.21       0.23
MIX.                  0.04          0.03          0.06      0.80     1.16       0.25
PLOUGH WHEEL         -1.08          0.07         -0.75      0.92   -15.06       0.00
PROF. DEV.            1.57          0.17          0.49      0.84     9.38       0.00
PLOUGH Draught        0.05            0.03          0.08      0.74      1.52      0.13
```

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