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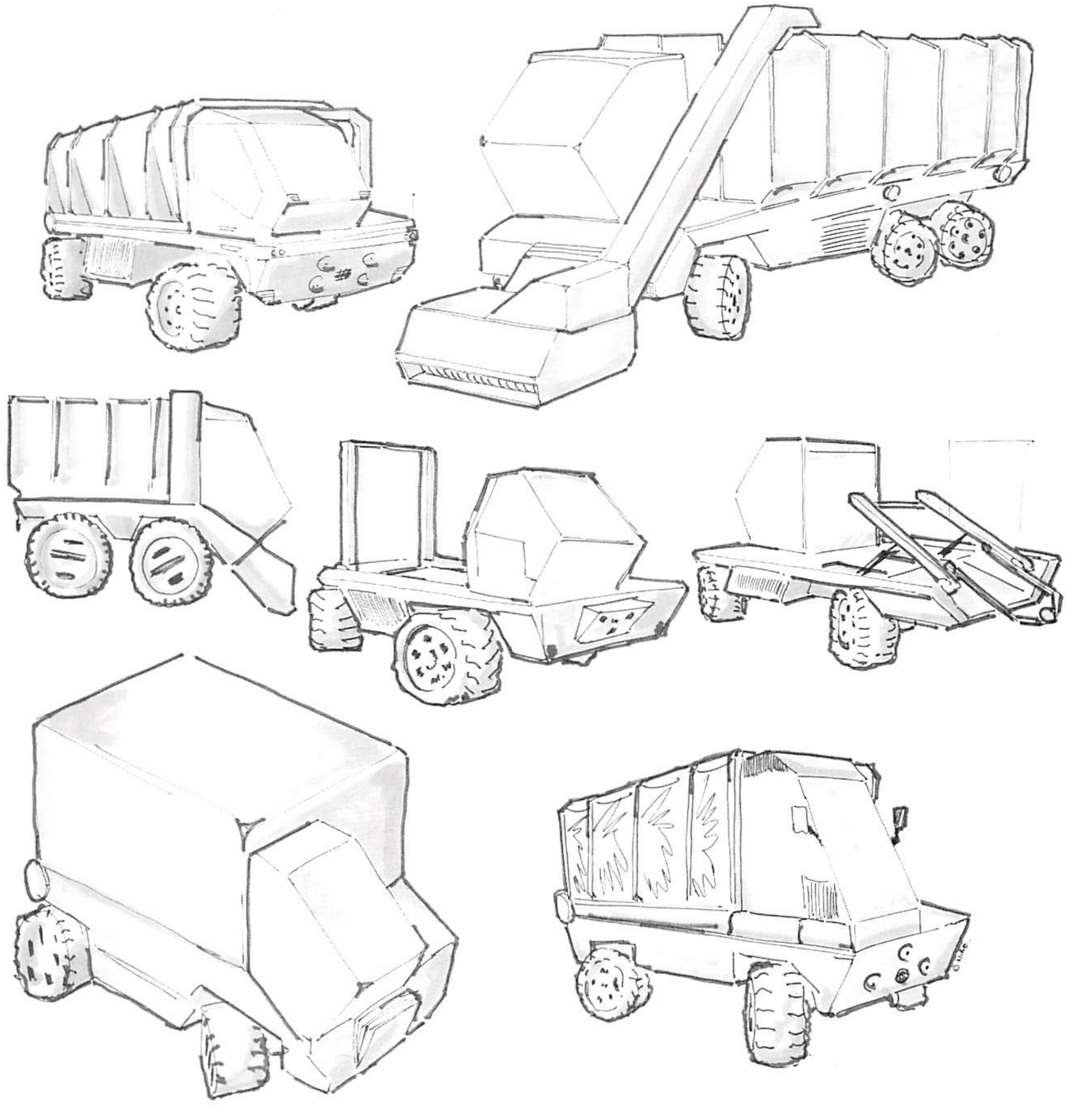

Off-highway/Self-propelled Vehicles

Proceedings of the Annual Conference

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Contents

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c) Mechanisation and review articles not normally appropriate for refereeing.

Front cover: Innovation in materials handling and fast farm transport

(NIAE sketches)

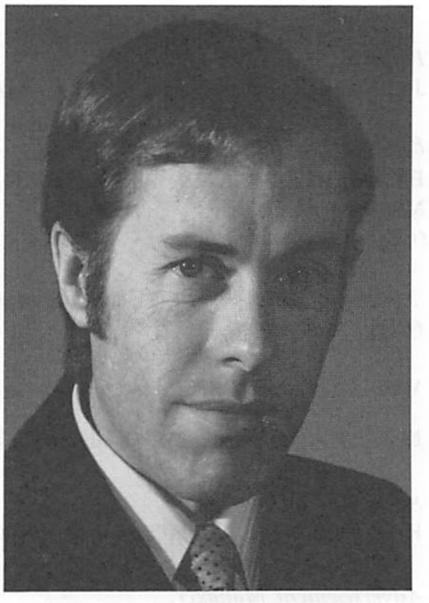
Soil dynamics and the problems of traction and compaction

M J Dwyer

Summary

THE main functions of a ground-drive system for an agricultural vehicle are to support the weight of the vehicle, to transmit propulsive, braking and steering forces and to provide some suspension. All agricultural vehicles should be designed to minimise soil compaction. Compaction of the top soil is mainly a function of ground pressure which, in the case of pneumatic tyres, is closely related to inflation pressure. Inflation pressures should not exceed 1.0 bar for general use and 0.5 bar for seedbed operations. Compaction of the subsoil is mainly a function of axle weight, which should not exceed 6 tonnes.

Tractive force is mainly determined by soil strength which is increased by vertical force. Tread or grouser design is less important than weight and tyre size. Maximum tractive force is mainly a function of weight but slip is also a function of the length of the ground contact area. To enable a self-propelled agricultural vehicle to operate at maximum efficiency, there must be a proper relationship between the weight on the driving wheels, the speed of operation and the power available.



1 Introduction

ALL too often, the choice of ground-drive system which usually means tyre size is left until the design of a vehicle is almost complete. Yet arguably this should be the first consideration, since, without adequate wheels or tracks, a vehicle can perform no useful function. This is true of all vehicles, but is especially so for agricultural vehicles which not only have to operate over difficult terrain but must do so without damage to the soil on which they run.

A ground-drive system for an agricultural vehicle firstly must be capable of supporting the maximum weight of the vehicle. It, therefore, must have adequate strength which, in the case of tyres, means that the sizes chosen must be such that the manufacturer's recommended maximum load will not be exceeded at the appropriate inflation pressure. It would seem good practice to estimate the likely maximum weight of a vehicle at an early stage in the design and consider the size of tyres which will be required, since this may impose important constraints on the rest of the design. However, there is evidence that this does not always happen.

The second major requirement of a ground-drive system is that it should be capable of transmitting the necessary propulsive, braking and steering forces. This again implies that there must be sufficient strength to withstand the maximum torques which will be applied in service. More importantly, however, as far as agricultural vehicles are concerned, since these forces must be reacted by the soil, the ground-drive system must be designed so as to make maximum use of the available strength of the soil, whilst still causing as little damage to it as possible.

The third major requirement, since most agricultural vehicles are not fitted with suspension systems, is to provide some isolation from ground-induced vibration. The need for this is clearly very dependent on the operating speed and, at the maximum legal road speed of 32 km/h, there seems to be no alternative to large low pressure pneumatic tyres. This duty, however, presents further constraints on the tyre manufacturer to build sufficient durability into tyres to withstand continual flexing at this speed. This is an important consideration in arriving at the recommended loads and inflation pressure for each size of tyre.

The performance of a ground-drive system for an agricultural vehicle is largely determined by the interaction between it and the soil. Considerable effort has gone into trying to understand this process sufficiently to be able to predict vehicle performance accurately at the drawing board stage. A full theoretical analysis is not yet available but vehicle designers cannot wait and many semi-empirical solutions have been used with varying degrees of success. This paper attempts to summarise the data and design techniques currently available to the designer, to identify their shortcomings and to point the way for further progress in the future.

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2 Soil compaction

The need to avoid soil compaction is a constraint which is almost peculiar to the design of agricultural vehicles but is one which is imposed on all such vehicles, whether towed or self-propelled (Soane *et al* 1981). It is a requirement, however, which is impossible to quantify. Numerous experiments have been carried out throughout the world to try and determine correlations between soil compaction and crop yield. The results do not provide a clear overall picture. They show variations from massive improvements in yield due to avoiding compaction to examples where compaction actually improved yield. Excessive soil compaction may have a direct effect on plant growth by impeding root development or an indirect effect by restricting the passage of air and water to and from the roots. Root crops such as potatoes and sugar beet are, therefore, always likely to be affected, whereas other crops such as cereals and grass may only be affected under adverse weather conditions. Some compaction of a seedbed is necessary, whereas other crops such as cereals and grass may only be affected under adverse weather conditions. Some compaction of a seedbed is necessary, however, especially in dry conditions, to maintain sufficient moisture close to the seed to encourage germination. Nevertheless, the most productive method of working overall must be to minimise compaction from vehicles as much as possible under all conditions and to rely on applying the most appropriate seedbed preparation techniques to suit the soil, crop and expected weather pattern. Another aspect of soil compaction is its effect on the power required for subsequent cultivations. This must always provide an advantage for reducing compaction.

It is possible to predict theoretically the distribution of pressure in a granular material such as soil caused by a point load applied at the surface (Soehne 1953). The solution becomes more difficult, however, when considering the pressure distribution under a finite area such as the contact area of a tyre or track in an inhomogeneous field soil. It then becomes necessary to introduce empirical corrections, but the basic theoretical concept is still useful. In particular, it shows the distinction between compaction in the soil close to the surface which is primarily a function of ground pressure and compaction at depth which is primarily a function of weight.

This distinction is important for agricultural vehicles. To minimise compaction of the top soil, it is important to keep ground pressure as low as possible by using tracks or low pressure tyres and weight is unimportant provided it is spread over a sufficient area. On the other hand, research in Sweden has shown that compaction of the subsoil which cannot easily be remedied by cultivation is dependent on weight alone and cannot be prevented by increasing track or tyre contact area (Hakansson 1981). This has resulted in a recommendation of 6 tonnes maximum axle weight for agricultural vehicles to avoid risk of subsoil compaction and this recommendation is currently being evaluated by a number of research institutes in North America and Europe, including the Scottish Institute of Agricultural Engineering.

Compaction of the top soil is avoided by reducing ground pressure. The mean ground pressure for a tracklayer is usually defined as the weight of the vehicle divided by twice the product of the track width and the distance between the centres of the front idler and the driving sprocket. The maximum ground pressure under the rollers, however, depends on the soil conditions and may easily be twice the mean value. For many years, the military have used the term, *mean maximum pressure* (MMP) for predicting tracked vehicle mobility (Rowland 1972 & 1975). It is defined as:

$$MMP = \frac{1.26\,W}{2mcb\sqrt{p_t}\,d}$$

where W = vehicle weight,
m = number of rollers in one track,
c = rigid area of link/pb,
b = roller width,
p_t = track pitch,
d = roller diameter,

and probably provides a better value for comparison with wheeled vehicles.

On a hard surface, the mean ground pressure of pneumatic tyred vehicles is closely related to inflation pressure, provided this is within the normal recommended limits for the tyre size and load carried. There is a slight increase in ground pressure due to the tyre stiffness but, for low pressure agricultural tyres, this is small. On a soft surface the correlation between ground pressure and inflation pressure may not be so close, particularly if the inflation pressure is high, either in absolute terms or in relation to the load carried. In this case the tyre tends to behave like a rigid wheel whose ground pressure is obviously not infinite. A rigid wheel sinks until its area of contact is sufficient to support the weight carried. The amount of sinkage required depends on the width and diameter of the wheel and the strength of the soil.

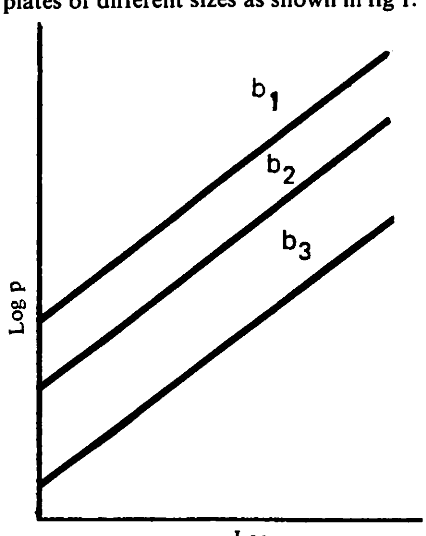
Rolling resistance is also closely related to sinkage since, on a soft surface, the major component of rolling resistance is due to the work done in compacting the soil. Typical values of rolling, resistance for an agricultural vehicle are 5–20% of the vehicle weight, depending on the soil conditions, whereas for a road vehicle, where the rolling resistance is only due to friction and tyre deflation, they would be only 1–2% of the vehicle weight.

Several attempts have been made to predict sinkage and rolling resistance from wheel and soil parameters. The best known of these is probably that of Bekker (1956 & 1960) who proposed a soil pressure-sinkage relationship of the form:

$$p = [k_c/b + k_\varnothing]\, z^n$$

where p = ground pressure,
b = the smaller dimension of the contact area eg wheel width,
z = sinkage,

and n, k_c and $k_\varnothing$ are constants for a particular soil condition and are measured by plate sinkage tests with plates of different sizes as shown in fig 1.



$p = (k_c/b + k_\varnothing)\, z^n$
Slope = n
Intercept = $k_c/b + k_\varnothing$

Fig 1 Pressure, p, plotted against sinkage, z, for plates of width, b

By equating the work done in overcoming rolling resistance to the work done in forming a rut, Bekker was able to show that the rolling resistance of a pneumatic tyre which deforms to produce a flat contact area is, as shown in fig 2, given by:

$$R = \frac{[W/\ell]^{(n+1)/n}}{[n+1]\,[k_c + bk_\varnothing]^{1/n}}$$

where R = rolling resistance,
W = weight on the wheel,
ℓ = length of the contact area.

This expression shows that the rolling resistance is only dependent on the weight, the dimensions of the contact area and the soil properties. The dimensions of the contact area are obviously in turn dependent on the inflation pressure. However, rolling resistance is independent of tyre diameter in this expression.

For a rigid wheel, such as a high pressure tyre on a soft soil (fig 3), a different expression is obtained:

$$R = \frac{[3\,W/\sqrt{d}]^{(2n+2)/(2n+1)}}{[3-n]^{(2n+2)/(2n+1)}\,[n+1)\,[k_c + bk_\varnothing]^{1/(2n+1)}}$$

where d = tyre diameter..

In this expression, the rolling resistance is dependent on the diameter of the wheel as well as its width, the weight on it and the soil properties.

Obviously to make use of these predictive equations it is necessary to know which applies in a given situation. Therefore, Bekker developed an expression for the critical inflation pressure, above which a tyre would behave as a rigid wheel

$$p_i = \frac{W\,[n+1]}{bk\,[d-k^2]^{1/2}} - p_c$$

where p_i = inflation pressure,
p_c = tyre carcass stiffness pressure,

$$\text{and } k = \left\{\frac{3W}{[3-n]\,b\,[k/b + k_\varnothing]\sqrt{d}}\right\}^{1/(2n+1)}$$

For typical agricultural field conditions, values of n, k_c and $k_\varnothing$ are such that the critical inflation pressure is in the range 0.5–1.0 bar. Therefore, to ensure that a tyre never behaves as a rigid wheel, inflation pressure must be kept below 0.5 bar. On the other hand, little is gained in reducing inflation pressure unless it can be reduced below 1.0 bar. If this is not possible, increasing diameter is then more important than reducing inflation pressure.

More recently Hetherington and Littleton (1978) have attempted a similar analysis but starting from the more fundamental bearing capacity theories used in the design of foundations in civil engineering. They developed the following equation for the rolling resistance of a rigid wheel in sand:

$$R = \left[\frac{2W^4}{b\,d^2\,\gamma\,N_q}\right]^{1/3}$$

where γ = soil density,

$$N_q = \frac{e^{(3\pi/2 - \varnothing)\tan\varnothing}}{2\cos^2[\pi/4 + \varnothing/2]},$$

and $\varnothing$ = soil friction angle.

Apart from a numerical constant, this

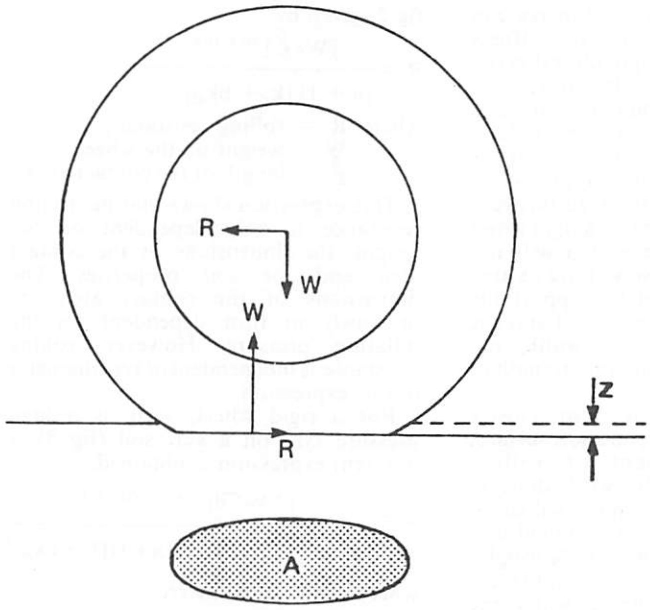


Fig 2 A low pressure tyre rolling on a relatively firm soil

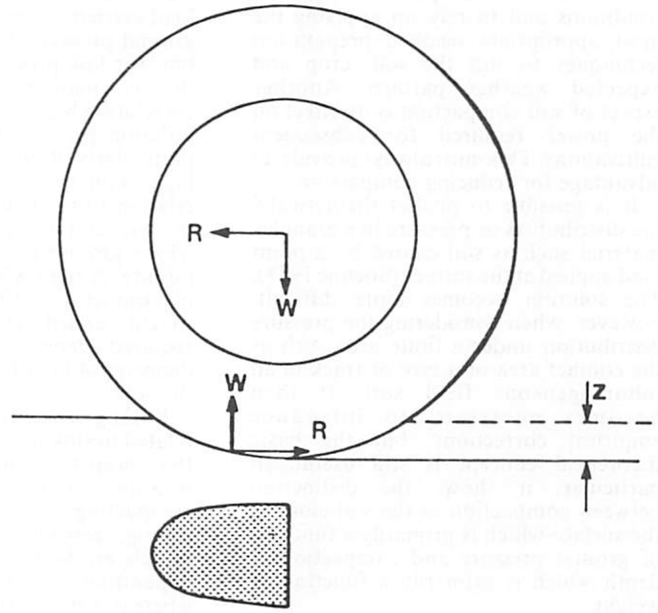


Fig 3 A high pressure tyre rolling on a relatively soft soil

expression is the same as Bekker's, with $n = 1$ and $[k_c/b + k_\phi] = N_q\gamma$.

This approach is attractive in that it uses more fundamental soil properties than Bekker's, but it needs further development to cope with cohesive soils and pneumatic tyres. The Bekker approach also has its limitations, however, although it has been invaluable in outlining the basic theoretical framework on which subsequent research has been built. It provides a good qualitative idea of the effect which changes in wheel or soil parameters will have on performance and, in a laboratory soil bin, where soil parameters can be accurately measured and maintained, good correlation between measured and predicted results can be obtained. It is less useful in the field, however, where soil conditions are more variable and it is very difficult to make meaningful measurements of the soil parameters. Consequently, no comprehensive bank of data for agricultural soil conditions exists.

An alternative approach which has been found more useful for interpreting results of field tests is to define soil strength by a single measurement of the resistance to penetration of a steel cone of 30° angle and 322 mm² (0.5 in²) base area (ASAE 1968). The average force required to push the cone into the soil at a steady speed of approximately 30.5 mm/s (72 in/min) is measured and averaged over the depth of interest, usually the top 25 cm. These measurements can be made quite quickly so that sufficient can be taken to give a good average value for a field. The average force is then divided by the cone base area to give the cone penetrometer resistance. This may be combined with the tyre parameters to give the mobility number:

$$M = \frac{Cbd}{W}\sqrt{\frac{\delta}{h}}\left[\frac{1}{1 + b/2d}\right]$$

where M = mobility number,
C = cone penetrometer resistance,
δ = tyre deflection,
and h = tyre section height.

A tractor mounted cone penetrometer is shown in fig 4.

Fig 4 Tractor mounted cone penetrometer

The mobility number concept was first derived by Freitag (1965) and later developed further by Turnage (1972) at the Waterways Experiment Station in the USA, using dimensional analysis and a series of performance measurements of tyres ranging from bicycle tyres to "Terra-Tires" in pure sand and pure clay soils. Freitag developed empirical relationships between tractive performance parameters and the above mobility numbers which were valid for all tyres in clay. He also developed another mobility number for sand, but this has been found less useful by subsequent workers. The clay mobility number, however, has been found both by Wismer and Luth (1973) in the USA and by the National Institute of Agricultural Engineering (Dwyer *et al* 1972) to be applicable to a wide range of agricultural soils, though with different empirical relationships from those derived by Freitag.

The inverse of the mobility number is approximately equal to the theoretical mean ground pressure divided by the cone penetrometer resistance. Therefore, we can define a ground pressure index, G, as follows:

$$G = \frac{W}{bd}\sqrt{\frac{h}{\delta}}\left[1 + \frac{b}{2d}\right]$$

and the higher the value of G, the worse the soil compaction is likely to be and the lower the tractive performance. The coefficient of rolling resistance, for example, which equals rolling resistance divided by weight, is related to ground pressure index and cone penetrometer resistance by the following empirical relationship:

$$\frac{R}{W} = 0.05 + 0.29\frac{G}{C}$$

Typical values of ground pressure index are shown in table 1, from which it can be seen that trailers and combines are likely to cause the worst soil compaction and even tractor front wheels are potentially more dangerous than the rear wheels.

Two other aspects which affect soil compaction but about which very little is known at present are the combined effect of vertical load and shearing and the effect of pressure variation within the contact area. A shearing force is added to vertical pressure under a traction tyre and must increase soil compaction but, since in a soft soil the horizontal force will be less than half the vertical force, the effect may be small.

Variations in pressure within the contact area may have different causes. With a deeply sunken tyre acting as a rigid wheel in soft soil, the pressure will increase from the front of the contact area to the point directly below the axle. Clearly in this situation, mean ground

Table 1 Ground pressure index

Vehicle	*Tyre size*	*Load, kg*	*Inflation pressure, bar*	*Ground pressure index*
Tractor (rear)	13.6–38	1500	1.4	83
	13.6–38 duals	1500	0.8	51
	16.9–34	1500	0.8	66
	600–38	1500	0.8	55
	66/43–25	1500	0.35	31
Tractor (front)	7.50–16	500	1.6	96
	400–17.5	500	0.8	54
	31/15.50–15	500	0.7	51
Combine	18.4–30	4500	1.9	146
	18.4–30 duals	4500	0.8	82
	24.5–32	4500	0.8	100
Trailer	16.0/70–20	3000	2.5	174
	16.0/70–20 tandem	3000	1.0	93

contact pressure has little meaning. The important criterion is then maximum pressure, since every point along the rut is subjected to this. Similarly, if a tyre has a relatively stiff sidewall, the pressure will be higher at the edges of the contact area than in the middle and two strips of more heavily compacted soil will be formed down each side of the rut. The least damaging type of pressure variation is that due to the lugs which, although they produce localised areas of high pressure, do not form a continuous strip of compacted soil and, therefore, roots are less likely to be affected. Lugs, however, may have a detrimental effect on a growing crop, during winter spraying for example, and more experience is needed before the optimum tread pattern for this application is established which will leave a slightly broken top surface without damaging the plants.

An alternative to either tracks or tyres are open lugged steel wheels, as shown in fig 5, which have been popular for many years in Asia for rice production and have recently been shown to be equally suitable for seedbed preparation and drilling in European conditions (Dickson *et al* 1981).

3 Traction

The way in which a vehicle develops traction forces is very similar to the way in which it develops steering and braking forces so that much of the following can equally well be applied to these other functions also. As with rolling resistance, it is the soil which largely determines the tractive forces which can be produced and the only function of tyres or tracks is to enable the best use to be made of the strength available in the soil. To this end. it is the weight on the driving elements and the size and shape of the contact area which are important. Grouser design, tread pattern and lug height are all of secondary importance (Dwyer 1975). Their only function is to ensure that the tyre or track grips the soil properly and does not allow slip to occur between it and any vegetation or slippery layer on the surface. In agricultural conditions, this only requires a penetration of about 20 mm. Any deeper penetration is only likely to cause an increase in rolling resistance due to unnecessary churning of the soil (Gee-Clough *et al* 1977).

For optimum traction, tyre tread patterns need to be such as to allow easy tread bar penetration. Lugs, therefore, should be thin and widely spaced. Unfortunately, however, this is exactly opposite to the requirement for good wear resistance, particularly on the road. The modern open centre chevron pattern adopted by all manufacturers represents a reasonable compromise and quite wide variations within this have no measurable effect on tractive performance. The importance of the open centre is that it allows the point of the lug to contact the ground first, on the tyre centreline, where the local pressure is highest, and it can penetrate most easily. Once the point has broken the surface, the rest of the lug can cut in behind it more easily.

The resistance of a soil to shearing and, therefore, the tractive force which it can transmit, depends on its cohesion, the tendency of particles to stick together, and its friction angle, the resistance of particles to stick together, and its friction angle, the resistance of particles to slide over one another. The force transmitted due to cohesion is proportional to the area of contact and the force transmitted due to friction is proportional to the weight. Therefore, the maximum tractive force which a vehicle can develop is given by Bekker, as shown in fig 6, as:

$$F = Ac + W \tan ø$$

where F = tractive force,
A = area of contact of driving wheels or tracks,
and c = soil cohesion.

If this equation is divided through by W, an expression for the coefficient of traction F/W, is obtained in terms of the mean ground pressure and the soil parameters:

$$\frac{F}{W} = \frac{c}{p} + \tan ø$$

The process of cultivating agricultural soil is designed to reduce its cohesion. Therefore, soils which have been regularly cultivated tend to derive much more of their strength from friction than from cohesion. Consequently, the weight on the driving wheels or tracks has a much greater influence on the maximum tractive force produced than does the area of contact.

Although the maximum tractive force is of interest, as far as vehicle

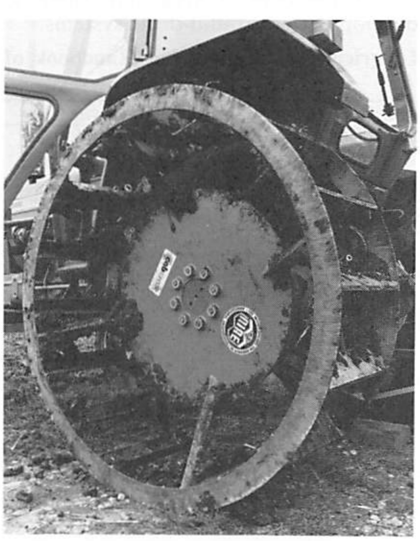


Fig 5 (left) Cab-craft Yieldwheel developed by the National Institute of Agricultural Engineering

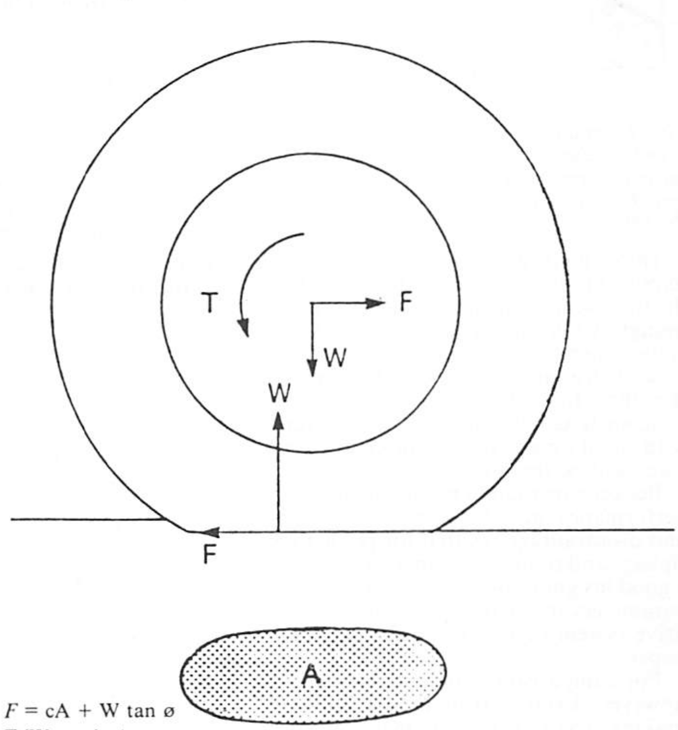


Fig 6 (right) A low pressure driving wheel tyre on a relatively firm surface

$F = cA + W \tan ø$
$F/W = c/p + \tan ø$

performance is concerned, the relationship between tractive force and slip is of even more importance. The strength of soil increases exponentially with displacement and the displacement of the soil increases linearly along the length of the contact area of a slipping tyre or track, as shown in fig 7. Therefore,

$$F = (Ac + W\tan\phi)(1 - e^{-j/K}),$$

where j = soil displacement
and K = a constant for a particular soil.
Also, $j = sx$
where s = slip
and x = distance from the front of the contact area.

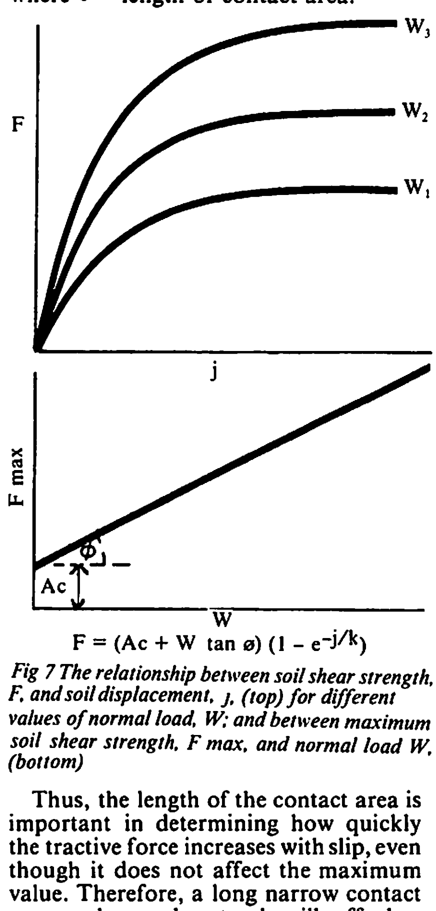
By integration along the contact area, the tractive force can be found as follows:

$$F = [Ac + W\tan\phi]\left[1 + \frac{K}{s\ell}e^{-s\ell/K} - \frac{K}{s\ell}\right]$$

and the coefficient of traction is:

$$\frac{F}{W} = \left[\frac{c}{p} + \tan\phi\right]\left[1 + \frac{K}{s\ell}e^{-s\ell/K} - \frac{K}{s\ell}\right]$$

where ℓ = length of contact area.



$F = (Ac + W\tan\phi)(1 - e^{-j/k})$

Fig 7 The relationship between soil shear strength, F, and soil displacement, j, (top) for different values of normal load, W; and between maximum soil shear strength, F max, and normal load W, (bottom)

Thus, the length of the contact area is important in determining how quickly the tractive force increases with slip, even though it does not affect the maximum value. Therefore, a long narrow contact area, such as under a track, will suffer less slip than the same short wide contact area, such as under a tyre, even though, with equal weight, the maximum tractive force will be the same.

Bekker's method of predicting tractive performance has the same advantages and disadvantages as that for predicting sinkage and rolling resistance. It provides a good insight into the effects of different parameters and enables different ground-drive system designs to be evaluated on paper.

For comparison of field performance, however, it suffers from the difficulty of making accurate measurements of the soil parameters. For this reason the cone penetrometer and mobility number approach has been developed for predicting the field performance of tyres. Work at the National Institute of Agricultural Engineering has established the following empirical relationships (Dwyer *et al* 1972, Gee-Clough *et al* 1978):

Maximum tractive efficiency = 78–55 G/C;

Coefficient of traction at 20% slip = 0.56–0.47 G/C;

Maximum coefficient of traction = 0.8–0.92 G/C.

Tractive efficiency is the power output, in terms of the tractive force multiplied by the forward speed, as a percentage of the power input, in terms of the axle torque multiplied by the rotational speed. Typical relationships with wheelslip and coefficients of traction are shown in fig 8.

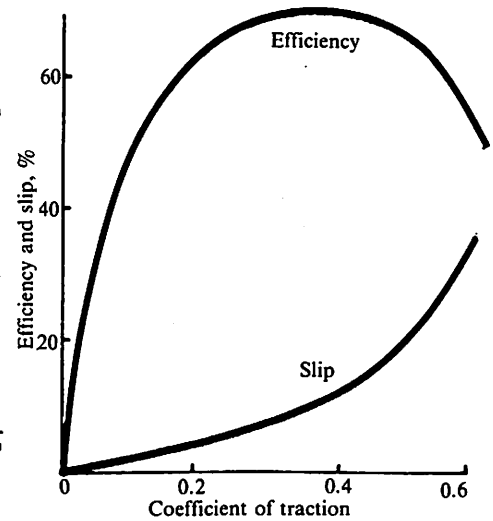


Fig 8 Typical relationships between tractive efficiency, wheelslip and coefficient of traction

Typical values of cone penetrometer resistance are as follows:

dry grassland	1500 kPa
dry stubble	1000 kPa
wet stubble	500 kPa
dry loose soil	400 kPa
wet loose soil	200 kPa

The National Institute of Agricultural Engineering Handbook of Agricultural Tyre Performance (Dwyer *et al* 1976) contains tabulated predicted values of tractive force, rolling resistance, maximum tractive efficiency, tractive force at maximum tractive efficiency and slip at maximum tractive efficiency, for the above field conditions, for a range of tyre sizes, with different loads and the appropriate recommended inflation pressures. Examples of some of the data are given in table 2.

These figures illustrate the effects on drawbar pull of the weight on the driving wheels and the size of the tyres in different soil conditions. For example, for a 47% increase in weight on a 12.4–36 tyre, there is a 44% increase in pull on dry stubble, even at a very high inflation pressure. On wet loose soil, on the other hand, although the pull still increases with weight, it does so by only 23%.

The effect of increasing tyre width can be seen by comparing the 12.4–36 tyre at 1730 kg load and the 16.9–30 tyre at 1750 kg load. The load and tyre diameter are nearly the same but the 16.9–30 tyre is 36% wider. The pull of the wider tyre on dry stubble is only 2% higher, yet in wet loose soil it is 15% higher.

Similarly, the effect of diameter can be seen by comparing the 18.4–30 tyre at 2898 kg load and the 18.4–38 tyre at 2860 kg load. In this case, the load and width are almost exactly the same but the diameter of the 18.4–38 tyre is 13% greater. There is no difference in pull on dry stubble but, in wet loose soil, the pull of the bigger tyre is 11% greater.

In good traction conditions, drawbar pull can be increased by adding weight to the driving wheels, provided the recommended maximum load for the tyres is not exceeded. The increase in inflation pressure required to accommodate the greater load will not reduce performance.

In poor traction conditions, on the other hand, although adding weight to the driving wheels still increases pull, it needs to be accompanied by an increase in tyre size to keep inflation pressure down if the full benefit is to be obtained.

Although this data is useful for comparing the performance of vehicles fitted with different types, it is limited in that the mobility number approach does not take adequate account of differences in contact area shape which Bekker shows is important. Further research is necessary, therefore, to gain a better understanding of the force distribution within the contact area and, thereby, develop better ground-drive systems.

Table 2 Data from the National Institute of Agricultural Engineering Handbook of Agricultural Tyre Performance.

Tyre size	*Load*	*Inflation pressure,*	*Pull at 20% slip*	
			Dry stubble	*Wet loose soil*
	kg	*bar*	*kN*	*kN*
12.4–36	1180	0.8	6.1	4.8
	1730	1.7	8.8	5.9
13.6–38	1370	0.8	7.1	5.6
	1990	1.6	10.1	6.8
16.9–30	1750	0.8	9.0	6.8
	2280	1.3	11.6	7.7
16.9–34	1850	0.8	9.6	7.2
	2420	1.3	12.3	8.2
18.4–30	2540	1.1	12.9	8.7
	2898	1.4	14.6	9.1
18.4–38	2860	1.1	14.6	10.1
	3260	1.4	16.4	10.6

4 Matching the ground-drive system to the vehicle

In the foregoing, the ground-drive system has been considered mainly in isolation from the rest of the vehicle. In designing a vehicle, however, it is essential to consider the ground-drive system from the outset. With regard to towed vehicles, it is only necessary to ensure that tyres are selected which are capable of carrying the maximum load at a reasonable inflation pressure for the ground conditions on which it will have to operate. For self-propelled vehicles, there are other considerations. The first decision must be whether to use tyres or tracks. Tracks are certainly more efficient, giving 20–30% more output for the same engine power. However, current designs are not suitable for high speeds or for operation on the road or in abrasive soils. For the present, therefore, it is likely that most agricultural vehicles will be wheeled.

The power output of a self-propelled agricultural vehicle may be limited either by the power available at the driving axles or by the tractive efficiency of its ground-driven system. To avoid over-design, they should clearly reach their limits under the same conditions. For a surprisingly wide range of tyres and soil conditions, it has been found that tractive efficiency reaches a maximum at a coefficient of traction of about 0.4. The highest tractive efficiency likely to be attained by a wheeled vehicle in most field conditions is about 70%. Therefore, we can calculate an optimum ratio for the power required at the driving wheels to the weight carried by them, related to speed, as follows (Dwyer 1975, Gee-Clough 1980):

$$0.7 \times \text{Power} = 0.4 \times \text{Weight on driving wheels} \times \text{Speed} \quad ;$$

$$\frac{\text{Power}}{\text{Weight on driving wheels}} = \frac{\text{Speed}}{1.75}$$

Having established from this relationship the required weight on the driving wheels, a tyre size can be chosen which will carry this weight at an acceptable recommended inflation pressure. For example, a tractor designed to carry out heavy draught operations at 6.5 km/h would need 100 kg/kW on the driving wheels. Suitable tyres for tractors of different power availability at the axles for this application are shown in table 3.

Table 3 Optimum tyre sizes for operation at 6.5 km/h

Power, kW	*Two-wheel drive*	*Four-wheel drive equal wheels*	*Four wheel drive (unequal size wheels)* Front	Rear	Front	Rear	Front	Rear
30	13.6–36	11.2–28	—	—	—	—	—	—
45	16.9–34	12.4–24	11.2–28	12.4–28	—	—	—	—
60	23.1–26	13.6–36	11.2–28	16.9–34	12.4–24	15.5–38	12.4–28	14.9–30
75	—	15.5–38	11.2–28	18.4–34	12.4–24	18.4–30	12.4–32	16.9–38
90	—	16.9–34	11.2–28	23.1–26	13.6–36	18.4–38	14.9–30	18.4–34
105	—	18.4–30	14.9–28	23.1–26	16.9–34	18.4–38	—	—
120	—	23.1–26	—	—	—	—	—	—

The first conclusion which can be drawn from table 3 is that, provided the correct tyre sizes are fitted, there should be no difference in tractive performance between two and four wheel drive tractors with either equal or unequal sized wheels. The differences which do occur in practice are because tractors other than four wheel drive tractors with equal-sized wheels are not normally fitted with tyres which are big enough to transmit the power available at 6.5 km/h. The second point to note is that, with tyres sizes readily available in the UK, 60 kW is the most power that can be transmitted efficiently through a single axle at 6.5 km/h. Thirdly, again with tyre sizes readily available in the UK, above 105 kW, four wheel drive tractors need equal-sized wheels to transmit their power efficiently at 6.5 km/h.

A study has been made of how critical it is to have the correct weight on the driving wheels (Dwyer 1978), Gee-Clough *et al* 1982) and it has been found that up to 20% variation does not usually cause too much loss in performance but any wider variation rapidly causes maximum tractive efficiency to fall to 50 or 60%. This is confirmed by comparison of two and four wheel drive tractors on standard tyres, where the two wheel drive tractor could not be ballasted to the optimum weight because of the inadequacy of the standard tyres, as shown in figures 9 and 10.

5 Conclusions

To minimise rolling resistance and compaction of the top soil, agricultural vehicles should be fitted with tracks or tyres which are large enough to carry the maximum weight at inflation pressures no higher than 1.0 bar for operation on firm soils such as stubble or grassland and 0.5 bar for operation on soft soils such as seedbeds. To avoid compaction of the sub-soil, maximum axle weight should not exceed 6 tonnes. Further research is necessary to confirm these figures, particularly to investigate the effect of variations in pressure within the contact area and to quantify the effects of soil compaction on crop yield. There is a requirement for tyres capable of carrying up to 3 tonnes at 0.5 bar inflation pressure at speeds of up to 30 km/h on and off the road, at an economic cost, and with adequate life.

To optimise the tractive performance of wheeled agricultural vehicles, the weight on the driving wheels must be correctly related to the power available and the speed of operation. The size of tyres fitted must be adequate to carry this weight at an inflation pressure which is low enough for the proposed application. This will result in a maximum tractive efficiency of about 70% in most field conditions. To increase this value, it is necessary to use a ground-drive system such as a track with a longer ground contact area. Such a track must also be capable of travelling at speeds of up to 30 km/h on and off the road and must be manufactured at an economic cost and have adequate life. Further research is necessary to produce such a track and to investigate the importance of pressure variations within the contact area.

6 References

ASAE (1968). Soil penetrometer. Am Soc agric Engng recommendation R313.

Fig 9 Drawbar power obtainable from a vehicle having 100 kW available at the driving axles which carry a mass of 6500 kg on firm soil conditions

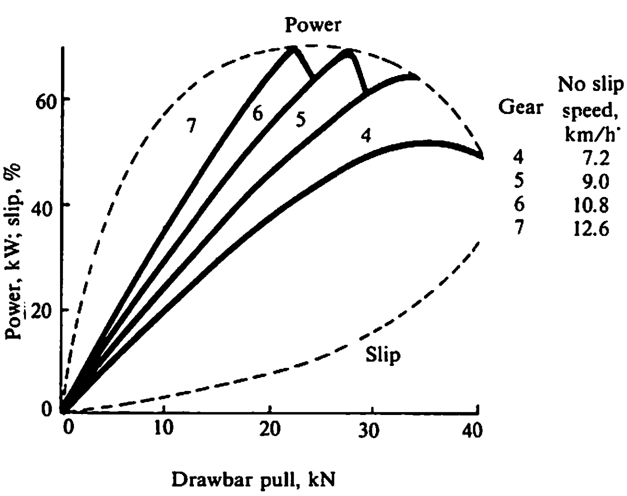
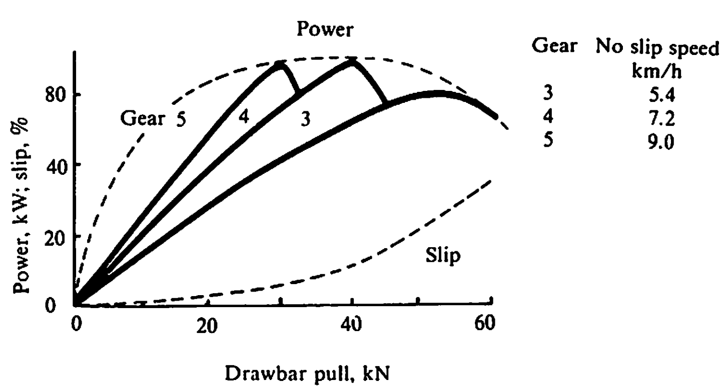


Fig 10 Drawbar power obtainable from a vehicle having 100 kW available at the driving axles which carry a mass of 10,000 kg on firm soil conditions



Bekker M G (1956). *Theory of Land Locomotion.* University of Michigan Press, Ann Arbor.

Bekker M G (1960). *Off-the-Road Locomotion.* University of Michigan Press, Ann Arbor.

Dickson J W, Gee-Clough D, Henshall J K (1981). The tractive performance and compaction produced in agricultural soils by open flat-lugged wheels mounted alone. Proc 7th Int Conf, Int Soc Terrain-Vehicle Systems, Calgary, 551-583.

Dwyer M J, Comely D R, Evernden D W (1975). Development of the NIAE Handbook of Agricultural Tyre Performance. Proc 5th Int Conf, Int Soc Terrain-Vehicle Systems, Detroit, 679-699.

Dwyer M J (1975). Some aspects of tyre design and their effect on agricultural tractor performance. Proc Instn Mech Engrs Conf on Off-Highway Vehicles, Tractors and Equipment, London, 73-79.

Dwyer M J, Evernden D W, McAllister M (1976). Handbok of Agricultural Tyre Performance (Second edition). Nat Inst Agric Engng Report No 18.

Dwyer M J (1978). Maximising agricultural tractor performance by matching weight, tyre size and speed to the power available. Proc 6th Int Conf, Int Soc Terrain-Vehicle Systems, Vienna, 479-499.

Freitag D R (1965). A dimensional analysis of the performance of pneumatic tyres on soft soils. Technical Report No 3-688, US Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Gee-Clough D, McAllister M, Evernden D W (1977). The effect of lug height on the tractive performance of tractor drive wheel tyres. *J agric Engng Res,* 22, 373-384.

Gee-Clough D, McAllister M, Pearson G, Evernden D W (1978). The empirical prediction of tractor-implement field performance. *J Terramechanics,* 15, 81-94.

Gee-Clough D (1980). Selection of tyre sizes for agricultural vehicles. *J agric Engng Res,* 25, 261-278.

Gee-Clough D, Pearson G, McAllister M (1982). Ballasting wheeled tractors to achieve maximum power output in frictional-cohesive soils. *J agric Engng Res,* 27, 1-19.

Hakansson I (1981). Effects of heavy traffic on soil conditions and crop growth. Proc 7th Int Conf, Int Soc Terrain-Vehicle Systems, Calgary, 239-253.

Hetherington J, Littleton I (1978). The rolling resistance of towed rigid wheels in sand. *J Terramechanics,* 15, 95-105.

Rowland D (1972). Tracked vehicle ground pressure and its effect on soft ground performance. Proc 4th Int Conf, Int Soc Terrain-Vehicle Systems, Stockholm, 353-384.

Rowland D (1975). A review of vehicle design for soft ground operation. Proc 5th Int Conf, Int Soc Terrain-Vehicle Systems, Detroit, 179-219.

Soane B D, Blackwell P S, Dickson J W, Painter D J (1981-82). Compaction by agricultural vehicles: a review, I, II and III. *Soil and Tillage Research,* 1, 207-237; 1, 373-400; 2, 3-36.

Soehne W (1953). Druckverteilung im Boden und Boderverformung unter Schlepperreifen (Pressure and deformation in the soil under tractor tyres) *Grundlagen der Landtechnik* No 5, 49-63.

Turnage G W (1972). Tire selection and performance prediction for off-road wheeled vehicle operations. Proc 4th Int Conf, Int Soc Terrain-Vehicle Systems, Stockholm, 61-82.

Wismer R D, Luth H J (1973). Off-Road traction prediction for wheeled vehicles. *J Terramechanics,* 10, 49-61.

The suspension and steering of off-road vehicles

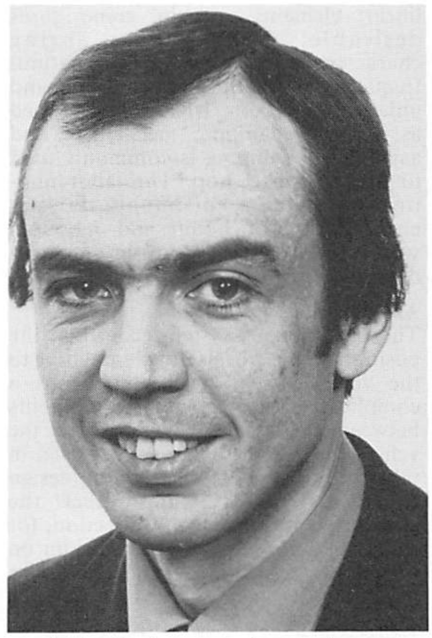
D A Crolla

Summary

The state of the art of suspension and steering design of off-road vehicles is reviewed.

Recent developments in semi- and fully active suspensions have taken place and, although these systems are still costly, they offer clear technical advantages. For passive suspensions, relatively simple computer models are now well enough established to be used more widely for the optimisation of existing designs.

Steering system designs present few problems but, again, computer models are being used successfully to predict handling and stability of off-road vehicles.



Introduction

The technology associated with suspension and steering systems, to date, has been derived mainly from road vehicle applications. Off-road vehicles, however, pose their own special problems and so the design requirements of steering and suspension components may be dramatically different from their road vehicle counterparts.

There is a unique combination of three operating characteristics of off-road vehicles that influences suspension and steering requirements, namely:

1) good traction and mobility;
2) travel over rough surfaces;
3) good manoeuvrability.

To the experienced vehicle designer, these immediately imply a set of desirable properties of the suspension and steering, eg good tyre/ground contact, multi-wheel drive, long suspension travel, large steering angles. However, further analysis of the design problem is warranted. Therefore, the objects of this paper are:

a) to present a view of the current state of the art of off-road suspension and steering design for a wide range of applications;
b) to review more recent developments that may lead to better designs or improved analysis techniques for off-road vehicle suspensions and steering.

Suspension

The vehicle suspension system must perform two separate tasks:

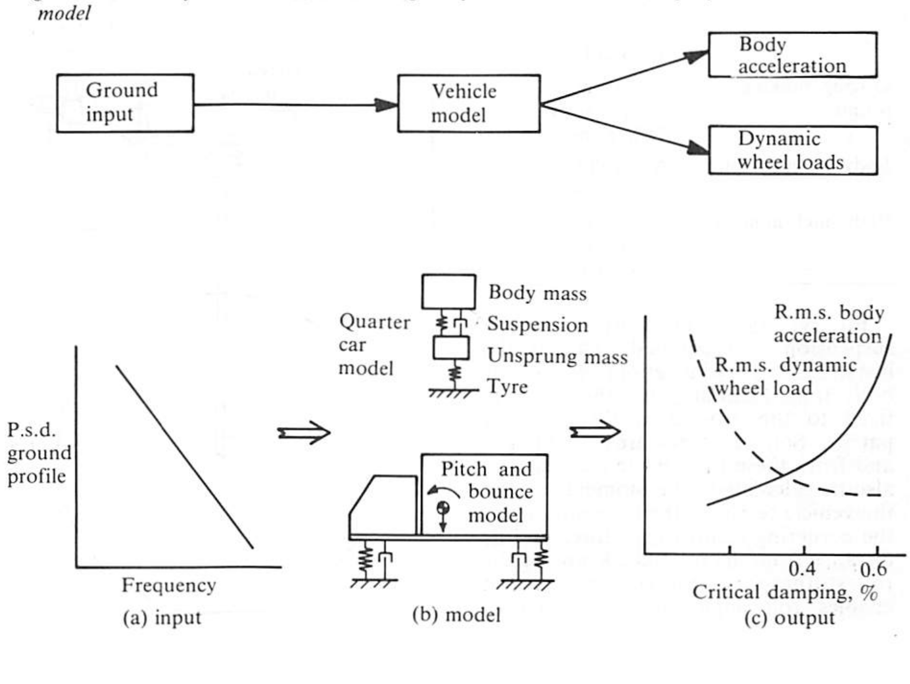
1) ride isolation;
2) axle location.

Ride isolation

The technique for analysing the ride isolation characteristics of a vehicle suspension is summarised in fig 1. Although more sophisticated vehicle models are currently being studied at various research centres, the simple models shown reveal some interesting results. In a practical vehicle design, the masses and tyre sizes will usually be decided based on other operating constraints and so the problem reduces to one of selecting the optimum spring and damper values. The best high frequency attenuation is achieved with the lowest natural frequency, so the lowest possible spring stiffness should be selected. This clearly implies large wheel travel and this will limit the minimum spring stiffness value for conventional, passive suspensions. Much of the advantage obtained with active or self-levelling suspensions arises from the lower spring stiffness compared to the limiting value for a passive suspension. The damping value, as indicated in fig 1(c), is then a compromise between controlling the variation in dynamic wheel loads and minimising the body acceleration level. The optimum value clearly depends on the weighting given to each of these criteria. Low values of damping tend to give the best ride whereas higher values result in the best tyre/ground contact. For vehicles which must travel on dramatically different surfaces, eg on and off-road, then a semi-active control system which varies the damper settings according to an input signal proportional to ground roughness may have considerable potential. This technique has been tried in prototype form on road vehicles with some success.

Considering the whole vehicle rather than just a single suspension unit, it is clear the pitch motion must be considered as well as bounce, because

Fig 1 Calculation of ride characteristics using the quarter car model or simple pitch/bounce vehicle model



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pitch results in both vertical and longitudinal motion of driver. Should the designer have freedom to choose the cab and driver position, then the simple model illustrated can be used to select the optimum driver position and the optimum front/rear balance of spring stiffness.

Whilst simple analyses are adequate for defining the general design strategy, more accurate analyses are complicated by non-linear elements in the suspension. Some examples are shown in fig 2. Non-linear elements are in some cases desirable; a non-linear spring characteristic can be used to keep natural frequency constant between laden and unladen conditions, friction can be used as a crude damping mechanism and asymmetric damping is commonly used to control wheel hop. The latter non-linearity, ie a different damper characteristic of bump and rebound, would merit careful study in an active damper control system.

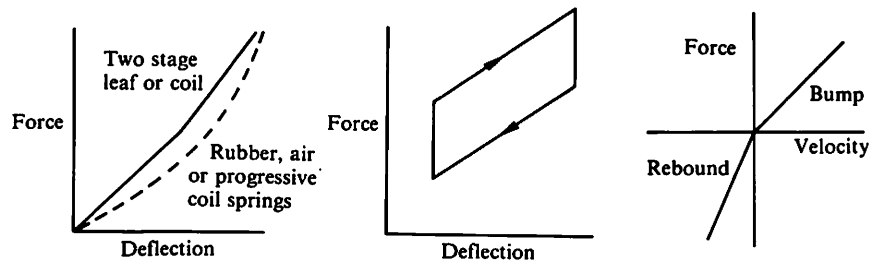
Axle location

The suspension system controls the position of the wheels or axles relative to the vehicle body. It also transmits a complicated set of forces and moments between the axles or wheels and the vehicle body. These are summarised in table 1. One of the main design considerations is what effect the suspension has in the roll direction, for example, during cornering or working on side-slopes. Again, the merits of a particular vehicle suspension can be analysed fairly simply.

Table 1 Summary of main forces and moment involved in axle and wheel location

Force or moment	*Suspension element to react to the force or moment*
Driving/braking forces	Leading/trailing arms Leaf springs, wishbones
Lateral, cornering forces	Panhard rod "A" frame Watt linkage
Vertical, bounce forces	Coil Leaf Air Rubber Torsion bar
Driving/braking torques	Leaf springs Torque arms Twin arms
Body roll moment	Anti-roll bar Active control
Body pitch moment	Anti-dive/ squat geometry Active control

Firstly, the roll centre of the suspension is calculated. This is the instantaneous point about which the body rolls, assuming that the tyres are fixed to the ground at their contact patches. Some examples are given in fig 3, and from these the vehicle roll axis can also be calculated. The moment causing the vehicle to roll is then the product of the cornering (centrifugal) force and its distance from the roll axis. Knowing the roll stiffnesses of the suspensions also enables roll angles to be calculated.



a) Non-linear spring characteristic

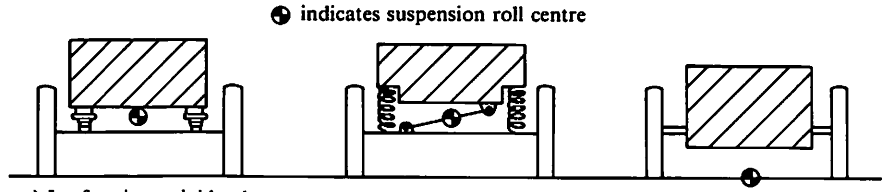
b) Spring characteristic with friction present

c) Asymmetric damper characteristic

Fig 2 Typical non-linear elements in suspension systems

Fig 3 Calculation of suspension roll centres, vehicle roll axis and total roll moment

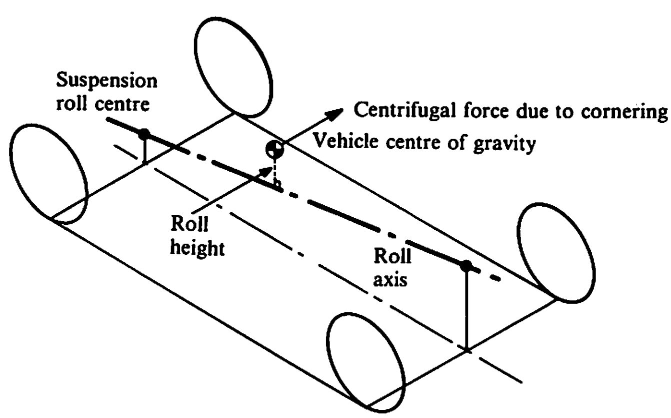
⊕ indicates suspension roll centre



a) Leaf springs, rigid axle

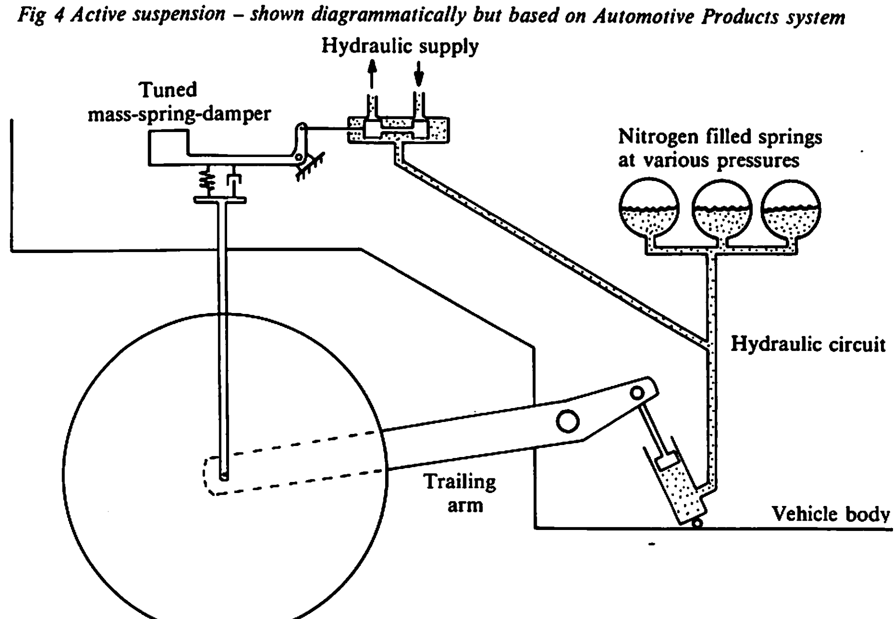
b) Coil springs, trailing arms, panhard rod, rigid axle

c) Trailing arms, independent suspension



Hence the designer can decide how the lateral weight transfer due to roll is distributed between front and rear suspension, and whether additional stiffness, eg anti-roll bar, is required. The lateral weight transfer significantly affects vehicle handling under severe cornering conditions.

Fig 4 Active suspension – shown diagrammatically but based on Automotive Products system



Review of current practice

A comprehensive review of every off-road suspension is neither very practical nor instructive because, if one includes military vehicles, the options tried out over the years are too numerous to list. However, a summary of the more common types which have commercial significance is presented in table 2.

There are several interesting trends highlighted here: i) designs incorporating leading/trailing arms and rigid axles tend to predominante; ii) relatively crude suspensions are now common on large, earthmoving equipment; iii) experience is being gained with active suspensions, which, although too expensive at present, are clearly in many cases the best technical solution to off-road suspension.

Future trends

For vehicles which are currently not suspended but which are widely recognised as having unacceptable levels of ride comfort — the obvious example being the agricultural tractor — the question arises of how industry will seek to improve their performance. There are two alternatives; the adoption of crude axle suspensions following the practice of large, earthmoving machines or fitting cab suspensions derived, to some extent, from road vehicle truck cab designs. Both these alternatives are based on experience gained in other areas and are, therefore, more attractive economically than completely new designs. Whichever alternative is favoured by industry, it is almost certain that the first improvements will appear on the largest tractors for economic reasons although, conversely, the ride problem is more acute on the smaller tractors.

For vehicles which are already suspended, the way forward is fairly clear. Optimisation of existing designs using computer models and increased use of semi- and fully active systems will be the main developments. Current thinking in semi-active systems centres around active damping control using mechanical or possibly electro-rheological means of controlling the damper. An example of a fully active system developed by Automotive Products is shown in fig 4. The subsidiary spring-mass-damper system is carefully tuned so that the suspension behaves as a passive, low frequency system until inertial forces — due to body pitch or roll accelerations — occur, when the hydraulic circuit responds to level the vehicle.

Future research topics

There are several areas in which further analysis is necessary to provide design information relating to new or optimised suspensions.

a) *Improved tyre/ground model*

The point contact, single spring model is a dramatic over-simplification. A better model of the complex nature of a flexible tyre on a deformable surface is required, perhaps based on empirical frequency response functions because, from a purely analytical viewpoint, the problems appears daunting.

b) *Active suspensions*

There is a range of possible developments here, varying from inexpensive self-levelling systems, through active damper control to fully active systems. Further analysis, particularly on optimal control strategies, is required because not all the technical problems have yet been solved.

c) *Effect of external forces*

The effect of trailers, or mounted implements in the case of agricultural tractors, on vehicle ride requires further analysis. Of particular importance is the case in which the vehicle frame is used as a reference to control height or depth of an attachment, eg plough or scraper blade.

Steering

There are two main areas of interest to the vehicle designer:

a) steering system and geometry;
b) vehicle handling behaviour.

Steering system and geometry

The important design parameters of a conventional, front steering wheel and stub axle are shown in fig 5. Considerable experience already exists in the design of the geometry and, in general, few

Table 2 Summary of off-road vehicle suspension systems

Type of suspension		Duty: / Speed: / Example:	Heavy / Low / Earthmoving, Agricultural	Medium / Medium off-road, High on-road / General purpose On/off-road use	Light / High off-road / Military
1)	No suspension		tractors, bulldozers, small dump trucks		
2)	Leaf spring, rigid axles			Land Rover, Stonefield, Renolds-Boughton, Bedford CF, Ford Transit and other American/Japanese pick-up trucks Military 4, 6, & 8 WD lorries, eg Bedford, Foden, Scammel	
3)	Leading/trailing arm, with nitrogen + oil combined suspension and damping units, rigid axles		Large dumptrucks (25–100t) eg Aveling Barford, DJB, Haulamatic Tractor-scraper units, eg Caterpillar, Terex, Clark-Michigan		
4)	Leading/trailing arms, coil springs, torque tube axle, panhard rod, anti-roll bar, rigid axles		MB trac (front axle only)	Unimog	
5)	Leading/trailing arms coil or leaf springs, rigid axles			Trantor (twin trailing arms rear), MB Personnel Wagen (+ anti-roll bars), M A N light military truck	
6)	Double wishbone, coil spring and damper				Alvis Saracen and Stalwart Daimler Ferret
7)	Trailing arm, transverse torsion bar				Various military vehicles
8)	Arm type suspension, hydrogas units, active pitch/roll control			Prototype farm transport vehicle (NIAE)	Prototype military vehicle (MVEF)
9)	Twin 'traction' beam, leading arms, coil or leaf spring			American Ford 4WD light-weight truck (front only)	

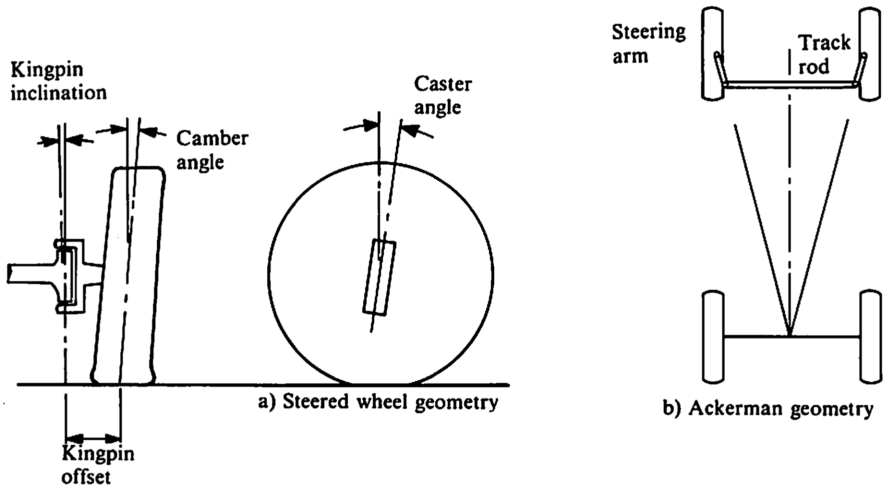
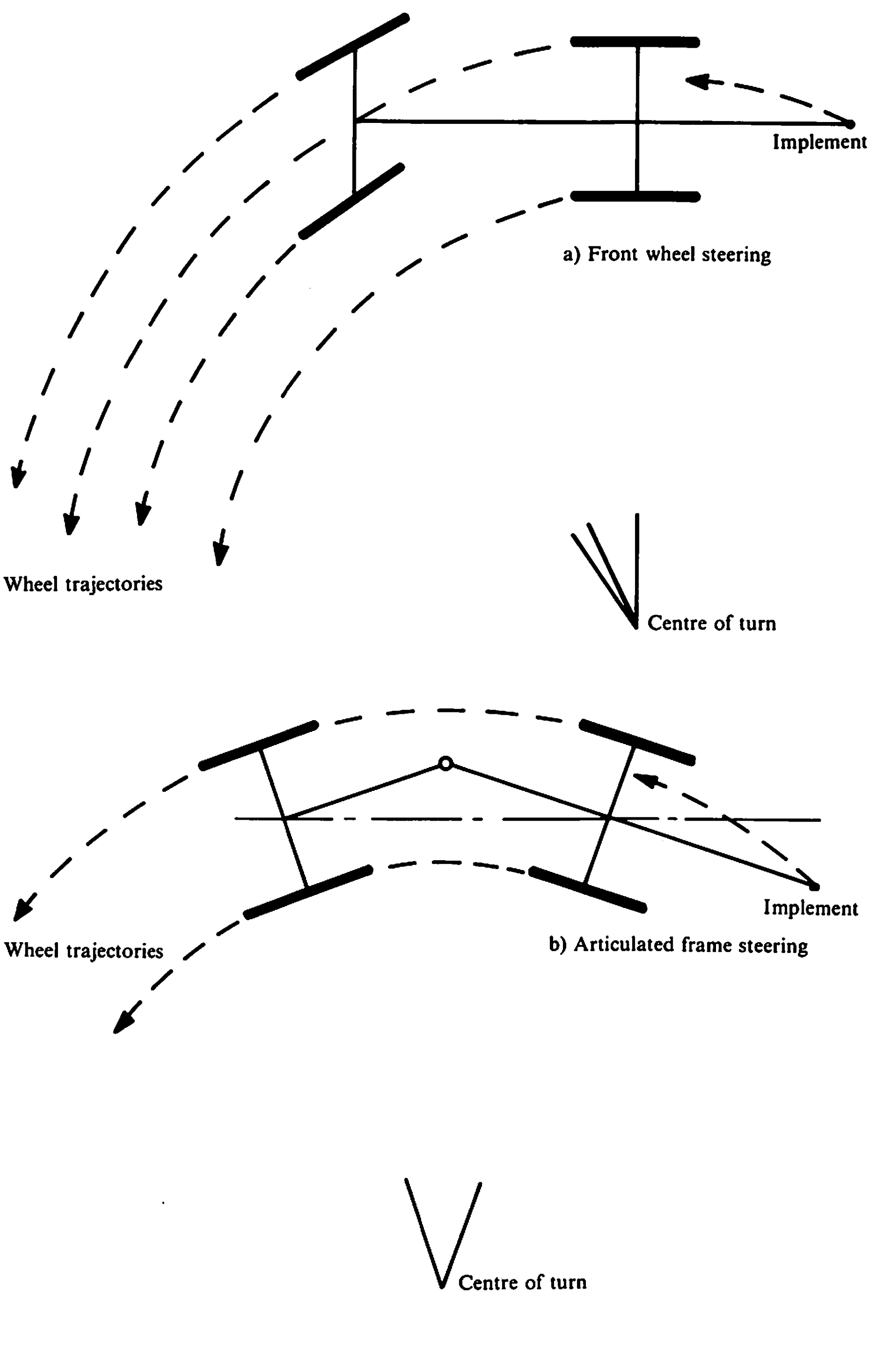


Fig 5 Steering geometry

Fig 6 Vehicle paths assuming ideal rolling conditions



operating problems exist. The importance of the parameters shown is in controlling tyre wear, avoiding wheel shimmy and providing the appropriate self-centering and feel to the system at the steering wheel.

The only novel feature recently introduced in this area is the adoption of a 12° caster angle by John Deere in order to increase the maximum steering angle of their four wheel drive tractors. The principles behind Ackerman steering are well understood suffice to say that, because of space restrictions, many off-road vehicle steering systems deviate substantially from Ackerman at high steer angles. The result is that the outer front wheel generates nearly all the cornering force and the inner front wheel is almost ineffective. This is undesirable for several reasons; it tends to increase understeer, it increases wheel and axle loadings and it accelerates tyre wear.

Hydrostatic steering is used extensively on off-road vehicles and the specialist manufacturers of such equipment have amassed much operating experience. However, steering wander on conventionally steered vehicles and weave of articulated body steer vehicles still remain problems. Both are related to the finite deadband required in hydraulic systems.

Vehicle handling behaviour

The overall handling behaviour of the vehicle is a far less well understood, but equally important, aspect of performance. Several types of steering configuration are currently used on off-road vehicles:

a) front, rear or four wheel steer (Ackerman type);
b) centre pivoted front and rear axle;
c) articulated body steer;
d) articulated body + pivoting rear axle:
e) skid steer.

Needless to say, the characteristics of these systems vary dramatically. A design study might start by assuming the case of cornering under ideal rolling conditions. In this case, the wheel trajectories are trivial to draw out but nevertheless revealing, particularly in the special case of a rear-mounted implement (see fig 6). The articulated body steer vehicle in this case demonstrates the advantages of front and rear wheel tracking, reduced wheel ruts and less outswing of the attached implement.

Under actual cornering conditions the situation is more complicated (fig 7). Each tyre operates at a slip angle and the resultant forces combine to make the vehicle take up a curved path. There are several methods of analysing and expressing the transient behaviour; much of this work being based on the extensive previous work on road vehicles. Computer models for the range of steering types have been developed at Leeds University and work is continuing on steering types c) and d). From a designer's point of view, important information on vehicle dynamic behaviour, eg high speed response, sliding/overturning stability, understeer/oversteer characteristics, etc, can be predicted, The important feature to note, however, is that such

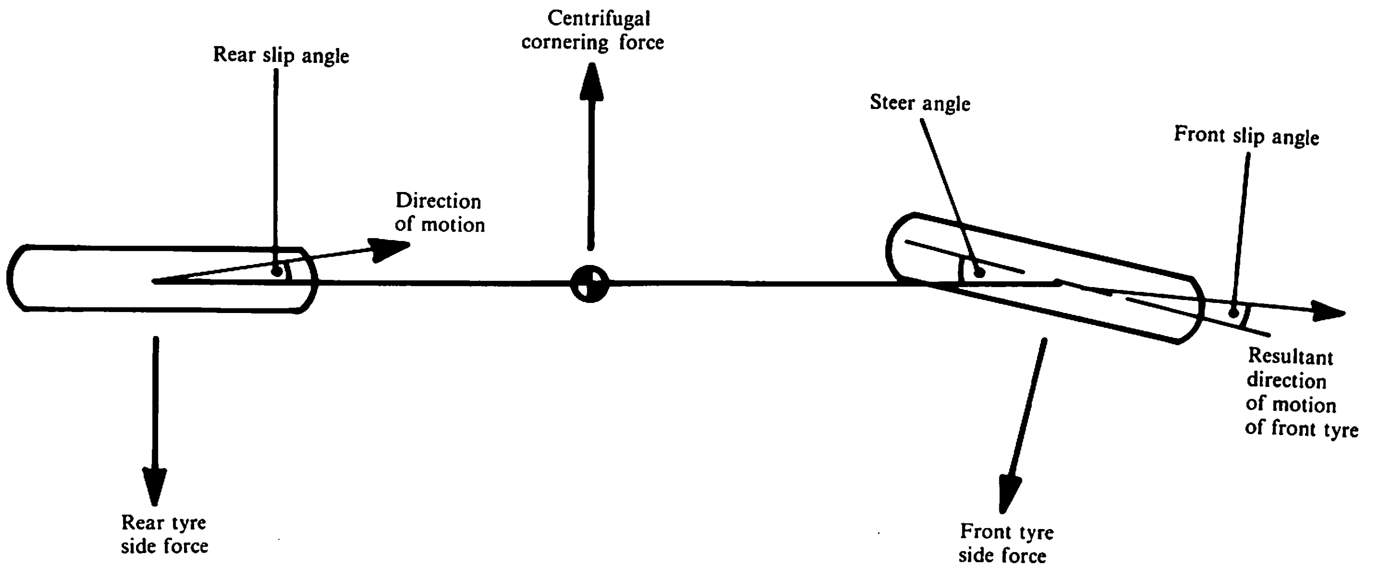


Fig 7 Tyre forces and slip angles occurring during practical cornering manoeuvres

calculations can be done at the concept stage rather than waiting until a prototype vehicle is built.

Future research topics

a) *Dynamic response of hydrostatic steering systems*

A mathematical model of the steering system coupled with the vehicle model will lead to a better understanding of wander and weave problems with conventional and articulated body steer vehicles respectively.

b) *Handling models*

Further development of simulation models of off-road vehicle handling will be necessary, particularly as more data on the crucial aspect of lateral tyre force characteristics are obtained.

Conclusions

1 Using existing knowledge of off-road vehicle design, it is possible to piece together a design strategy for a particular section of the vehicle. An example is given below for a typical off-road suspension which could apply for instance to a prototype design for a currently unsuspended vehicle, eg tractor.

* Cab and seat location — optimise using simple ride model.
* Suspension natural frequency — as low as possible.
* Damper settings — optimise using simple ride model.
* Wheel travel — as much as possible.
* Unsprung mass — as low as possible.
* Arm suspension — cheap and robust.
* Rigid axles — cheap and robust whereas independent suspension not usually cost-effective.
* Large tyres — attenuate high frequency ground inputs.

2 Computer models of the ride and handling behaviour of off-road vehicles have been developed. Though the models typically contain many simplifying assumptions, they are already starting to be used as a valuable design for suspension and steering systems.

3 Further research into the analysis of off-road vehicle ride and handling should include the following topics, tyre-ground model, suspension non-linearities, effect of implements/trailers, hydrostatic steering responses, articulated body steer vehicles.

The Institution of Agricultural Engineers

1983/84 Conferences

Scottish Branch

9 November 1983 at 10 00 hours "Irrigation" East of Scotland College of Agriculture, West Mains Road, Edinburgh 9.
Registrations: Dr M E Parkes MSc T Eng(CEI) MI Agr E, East of Scotland College of Agriculture, West Mains Road, Edinburgh 9. Tel: O. 031 667 1041, H. 031 445 5206.

East Midlands

17 November 1983 at 10 15 hours "High Quality Maincrop Potatoes, Production, Handling and Storage" Lincolnshire College of Agriculture, Riseholme.
Registrations: J N Davis Tech(CEI) AIAgrE, "Stonewall", Heath Lane, Normanton, Grantham, Lincs. Tel: O. 0400 72521, H. 0400 50504.

East Anglia

24 November 1983 at 09 45–16 00 hours "Soil Compaction — It's Causes, Effects, Remedies & Avoidance" Norfolk College of Agriculture, Easton, Norwich.
Registrations: T J Rivers MI Agr E, 8 Ebbisham Drive, Norwich, Norfolk NR4 6HN. Tel: H. 0603 52386.

Northern Ireland

30 November 1983 at 13 30–17 00 hours "Soil Compaction" Dunadry Hotel, Co Antrim.
Registrations: J W Duff B Agr MSc(AgrEng) T Eng(CEI), MI Agr E Ultimo House, 70 Urbal Road, Coagh, Cookstown, Co Tyrone, N Ireland. Tel: O. 02318 2601, H. 06487 37467.

Visitors are most welcome; for details of charges and any other information please contact the member responsible for registrations.

The past, present and future of the agricultural tractor

J Withers

Introduction

IT is the tractor of the future to which I wish to devote the main emphasis of this paper, primarily with the hope that it will stimulate ideas that will make a positive contribution to the future product but first a brief look at the past.

Early development with steam

The invention and development of the steam engine preceeded the internal combustion engine by more than 100 years and, consequently, the earliest tractors were of the steam type. In England, during 1810, Major Pratt attempted to use steam power for ploughing but many years passed before significant progress was made in the practical application of steam power to agriculture. The "steam plough", or traction engine, was the first step of importance in mechanical power farming.

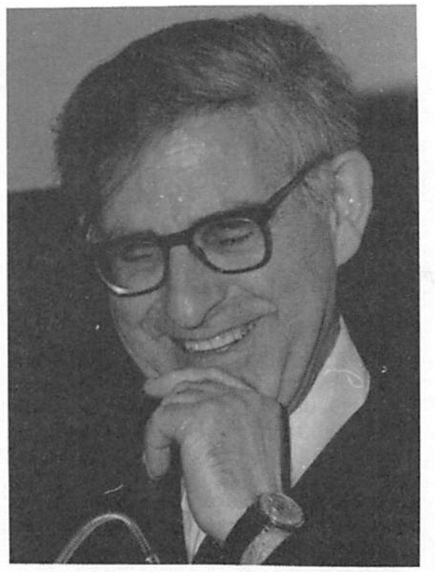
In addition to the demand for steam ploughing, new farm machines invented in the first half of the 19th century stimulated the need for mechanical power. First used for operation of threshers, the development cycle was from stationary units to portable steam engines and then, finally, to self-propelled machines.

In 1859, the Fowler cable machine was awarded the Royal Society of Agriculture prize for steam ploughs at a trial held just a mile or two from here, at Warwick.

Manufacture of farm machines was greatly accelerated with the opening of the USA western prairie land (homesteading era) and, by 1870, the farming industry was demanding more and more power. Probably the first attempt to use rubber tyres on tractor wheels was 'Thompsons Rubber Tired Steamer'. Built in England, it was entered in tests in England and France, fitted with pneumatic tyres, but they performed unsuccessfully. Its first appearance in the USA was in 1871, with wheels fitted with rubber cleats.

By about 1886, companies were offering steam-lifts for the multiple-bottom steam tractor ploughs.

Both horizontal-tube and vertical-tube boilers were employed on these early steam tractor engines; they were usually single or two-cylinder engines, coal and wood-burners, or straw burners. Their heavy weight led to the development of



very wide wheels to provide adequate traction in soft land and inspired the idea of substituting tracks for wheels. Heavy weight, slow travel speed and bulky fuel requirements limited the progress of steam.

Early internal combustion engines and tractors

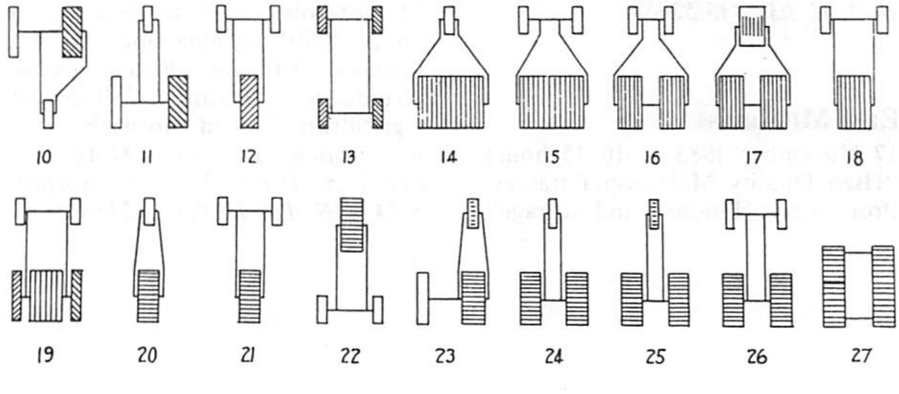
Early tractor development followed a similar pattern to that of the steam engine: first, the stationary engine was mounted on skids or wheels to make it portable and, later, a drive was provided to make it self-propelled. Over many years, automotive features were adopted and means for applying power, such as the belt-pulley, drawbar, pto and hydraulic controls became the accepted standard.

The agricultural tractor industry began in the USA at the end of the 19th century, it remained mainly American until the Second World War, after which substantial production began in Western Europe, mainly through USA multinationals. In Britain at the turn of the century, tractive power on the land was provided almost exclusively by draught animals for which there were adequate ploughs, harrows and other tillage equipment. Most of the ploughing was done by horses, a team of two ploughing about a half hectare per day.

Early petrol tractors usually had a large single-cylinder engine mounted on a heavy frame and placed on four wheels. Many of these early tractors suffered the same drawbacks as the steam tractors, being very heavy and cumbersome. About 1910, attention was turned to 'lightweight' tractors and, in 1913, a number of machines appeared which were relatively light in weight and in most cases had two or four-cylinder engines. About this time many ideas were tried out, some front driven, some rear driven (fig 1), some with ploughs under the frame and others pulling ploughs. These early tractors used a wide variety of transmission layouts (fig 2).

In Britain and the US, shortage of labour and high prices during the First

Fig 1 Wheel and track arrangements (Gray 1975)



John Withers was formerly Director of Engineering at David Brown Tractors Ltd and has recently accepted a new appointment as Director of Special Projects with GKN Sankey, Telford.

World War created demand for tractors and, by this time, in North America there were between 200 and 300 different manufacturers. The average and most popular sizes were 7½–10 drawbar kilowatts, 15–20 belt kilowatts. The design trend was towards four wheel, rear wheel drive with four-cylinder engines. The first practicable pto was introduced by International Harvester, as optional equipment, in 1918.

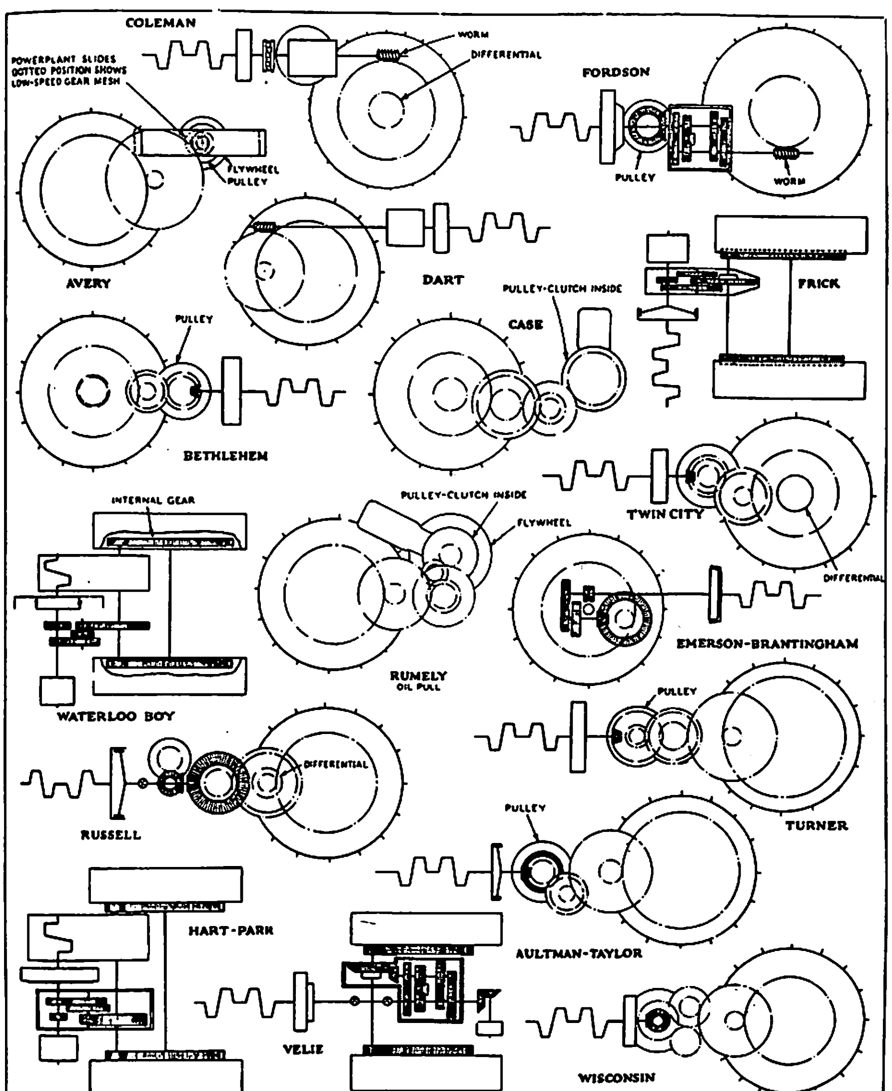
Few American tractors were imported into Britain in the years leading up to the First World War. But in April 1917, the British Board of Agriculture asked the Royal Agricultural Society of England to conduct tests with two Fordsons imported from Detroit. The tests showed the Fordson to be reasonably suitable for British farms and Lloyd George wanted it produced in Britain immediately. Henry Ford generously made a gift to the British nation of the patent rights of the tractor and agreed to establish a manufacturing plant in Cork, Ireland. The North American agricultural depression of 1920 put many tractor manufacturers out of business and, in 1928, economic problems in North America caused Henry Ford to abandon production of the Fordson there. Machines sold during the 1920–26 period were adapted to do everything about the farm; they were not all-purpose machines. Most were two to three plough tractors.

The next logical step was the lightweight, low price, all-purpose tractor for any kind of field work or stationary work — ploughing, harrowing, planting, cultivating, harvesting, threshing, etc. To construct a tractor rugged enough to plough and harrow the heaviest soils and yet still be practical in the lighter jobs proved a difficult problem.

Tractors with diesel engines were introduced in 1931, early engines were heavy-duty type, confined to tracklayers for earth moving and construction operations. In the USA which was behind Europe in this respect, smaller diesel engines were introduced about 1950 and, by 1960, were replacing petrol engines. Low pressure pneumatic tyres first appeared about 1932 but, by 1940, demand was almost 100%.

No account of tractor development, however brief, should fail to mention the vast contributions of Harry Ferguson. The mounted implement, 3-point linkage and hydraulic draught control, pioneered by Ferguson, became fundamental to most of the world's tractors.

Fig 2 Diagrams of power transmission mechanisms in different makes of farm tractors (Gray 1975)



Specific developments — 1950 to present

1951
Before the 1950s, little attention was paid to operator comfort. Around this time came the introduction of improved seats in place of the pressed steel, pan seats previously in general use. Disc brakes were introduced.

1952
Demand for greater power was increasing. Power steering was being introduced.

1953
Suppliers were providing accessories, such as turbochargers, to increase power. These unofficial modifications caused the tractor manufacturers problems, over-taxing engines and transmissions.

1958
Diesel tractor engines, overwhelmingly adopted in European markets, were becoming much more popular in the US. Transmission refinements such as Massey Ferguson's multi-power transmission were introduced.

1959
Three-point hitches were standardised.

The Ferguson three point hitch (BSS Category I), about which there had been much scepticism since its early beginnings, was adopted by the American Society of Agricultural Engineers and the Society of Automotive Engineers. The BSS Category II three point hitch, as used on the Fordson Major, was adopted by the American Society of Agricultural Engineers and the Society of Automotive Engineers.

An interesting development was the fuel cell tractor produced by Allis-Chalmers. The electricity driving the tractor came from 1008 individual fuel cells. A mixture of gases, mostly propane, fuelled the individual cells. The chemical reaction within the cells created a direct current flow which was used to operate the tractor which developed about 15 kilowatts. It was claimed that this power unit offered twice the efficiency of other engines of the period, had no moving parts, no exhaust or odorous fumes and ran extremely quietly.

Fuel cell dimensions	6 mm thick × 300 mm square
Fuel cell voltage	about 1 volt, open circuit

Total electrical output	15 kW
Fuel gas used	a mixture, largely propane
Type of motor	standard Allis-Chalmers 15 kW DC
Drawbar pull	13 kN
Tractor weight	2350kg

The tractor was never marketed.

1960
Tandem hitch
To obtain more drawbar power, tandem hitching in a variety of combinations was tried. The tandem hitch involved removing the front wheels of both tractors and hitching them together with a vertical hinge. One of the best examples was the Doe Triple-D which first appeared in 1957. In the US, the semi-tandem hitch was probably more common, involving removal of the front wheels of the rear tractor only. In each case, control of both tractors was from the rear vehicle. Many problems experienced with matching engine speed and gear changing would be eased with today's technology.

1961
By the 1960s, exhaust driven turbochargers, compressing incoming air into the combustion chambers at boost pressures of between 0.7 and 1.4 bar, were introduced. About this time, tractors with dry-type air cleaners began to gain acceptance.

International Harvester produced the experimental HT 340 where they paired a gas turbine with a hydrostatic transmission. The turbine was similar to the turbo-prop engine used in some light aircraft but much smaller, weighing only 27kg. Running at 57,000 rev/min, it required considerable reduction gearing to drive the hydraulic pump which, in turn, drove the hydraulic motor which propelled the tractor.

1963
Tractor power increased as, each year, manufacturers introduced new models; this encouraged the adoption of front wheel assist tractors and the true four wheel drive tractor gained a market share.

About this time, Roosa pioneered the rotary-type fuel injection pump which today, because of its simplicity and lower cost, has superseded the in-line fuel injection pump on most diesel tractors.

1965
By the mid-1960s, nearly all the major tractor manufacturers had or were making refinements to their hitches. Massey-Ferguson introduced the pressure control hitch, providing controlled hydraulic weight transfer for pulled-type implements. The first Japanese-built agricultural tractors appeared on the world scene.

1967
International Harvester had installed a hydrostatic transmission into their experimental HT340 turbine tractor and, in 1967, announced their IH 656 hydrostatic tractor. This utilised a

Table 1 Four wheel drive trends in Western Europe

Tractor power, hp (kW)	*4WD Tractors in each power group, %*				
	1978	*1979*	*1980*	*1981*	*1982*
0–39(0–29)	15.7	17.2	28.9	30.7	31.8
40–49(30–36)	12.6	14.3	18.4	23.2	26.4
50–59(37–44)	23.2	26.4	33.9	34.8	38.0
60–69(45–51)	23.3	24.6	35.7	43.5	47.4
70–79(52–59)	23.8	28.1	40.3	48.1	54.2
80–99(60–74)	48.6	51.1	59.6	61.9	64.9
100+ (75+)	75.5	72.4	82.2	87.8	89.1

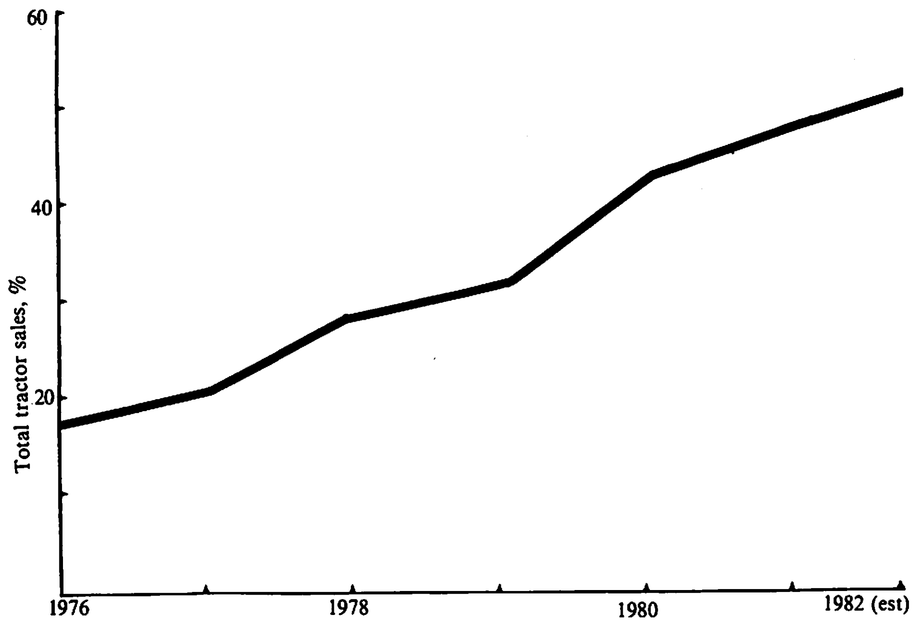


Fig 3 Europe – four wheel drive trends (1976–1982)

piston-type hydraulic pump and a piston-type hydraulic mower. The motor connected to the input shaft of a high-low transmission. The hydraulic pump fastened directly to ywheel and eliminated the engin h. A pedal enabled the operator to stop the tractor by releasing the oil pressure. The final drive components — differential, bull gears and rear axle — were those used on the conventional drive model.

1968
Tractor safety began commanding considerable attention in many countries in Europe and the USA. The Swedish test institute did much pioneering work on tractor safety cabs and developed the pendulum impact test in use today.

1970
Manufacturers faced problems of deafness suffered by tractor operators due to excessive noise exposure. Many attempts were made to reduce tractor noise to an acceptable level by improving transmission gears but the problem also involved noise from hydraulic pumps, engine, fan, induction, exhaust, etc and the greatest noise reduction potential lay within the cab design. It should be noted that many of the early safety cabs increased rather than reduced noise levels at the operator position.

1971
In compressing intake-air, the turbo-charger also increases air temperature considerably. Such preheating reduces the engine power. 'Intercoolers' were introduced, therefore, to cool the charge air and so enable efficient burning of more fuel to further increase power.

1974
In North America, there was a flow of large four wheel drive models. Deere introduced the 8430 and 8630: Steiger, its series 11 tractors; White — previously Oliver — their 112kW model; J I Case introduced their 2670 diesel — 165kW at 2200 rev/min (first Case tractor with intercooler).

Looking back — 1950 to present

This period brought significant changes to the industry. Fuels changed, economy records were set, petrol engines declined in usage and diesel became the overwhelmingly predominant fuel.

Farmers, seeking more power for larger areas and more competitive agricultural conditions, caused tractor manufacturers to increase engine displacement, use higher engine speeds, install turbochargers and other systems to dramatically increase power. Four wheel drive tractors were revived and have gained popularity (fig 3 and table 1). New types of transmissions, cabs, safety features, noise reduction, power steering, better instrumentation, improved operator comfort and convenience all came during this period.

Factors affecting the future

Over the last 25–50 years the drawbar orientated farm tractor, ranging in size and weight from the small horticultural style of tractor to 375kW 25–30 tonne monsters, has emerged as the most important machine in cropping.

The limit of power over the last decade was effectively 150kW for two-wheel-drive machines, the limit being the transmission of power to the ground. Recent evolution of the four wheel drive, articulated tractors and rapid farming concepts have improved power effectiveness by a factor approaching 3 but weight limitations are again reaching the limit, in terms of compaction and power loss.

Early tractors — which replaced the horse — operated at the same working speed of 3–4 km/h. This changed little until the mid-30s when pneumatic tyres were introduced. Since then, working speeds have more than doubled for many operations; while transport speeds have increased to around 29–32 km/h, probably the upper limit without axle springing and braking improvements (fig 4).

Fuel efficiency is becoming an increasingly important factor in farm economics. Fossil fuels will start to run out and become more expensive as they do so: this situation will accelerate the demand for alternative fuel sources and would have very significant effects on future tractor design.

Prof R L Bell's paper "Research and development for the next century", presented to the Institution in 1980, pointed out that, in the sequence of arable farming operations, there is considerable scope for improvements. Cultivations, where 25% of the fuel used in agriculture is consumed, can be minimised under certain soil conditions or made more efficient by applying the work through the implement rather than in a straight draught mode via the tractor wheels.

The implements and the work requirement dictate tractor design. Therefore, methods by which farming operation improvements are obtained will have very significant effects on tractor evolution.

The introduction of air-seeders, the increasing importance of fertiliser applications and chemical control make it increasingly likely that a multi-purpose tractor similar to the MB Trac/Deutz Intrac will gain popularity.

Many arable farming operations are limited by the shaking to which operators and machines are subjected when travelling at speed over uneven ground. The operator becomes fatigued; seed, fertiliser and spray distribution become imprecise. All wheel suspension will be introduced to overcome these difficulties.

Another factor which can considerably influence future tractor design will be the effects of legislation: witness the dramatic change in the European tractor configuration arising from legislation introducing, first the safety cab to give roll-over protection, and later the 'quiet' cab to meet noise regulations.

The future — 1985 to 2010

Some engineers and agriculturalists envisage crop production utilising wide span gantries to replace the present design of tractor. The gantry, it is suggested, should be the medium

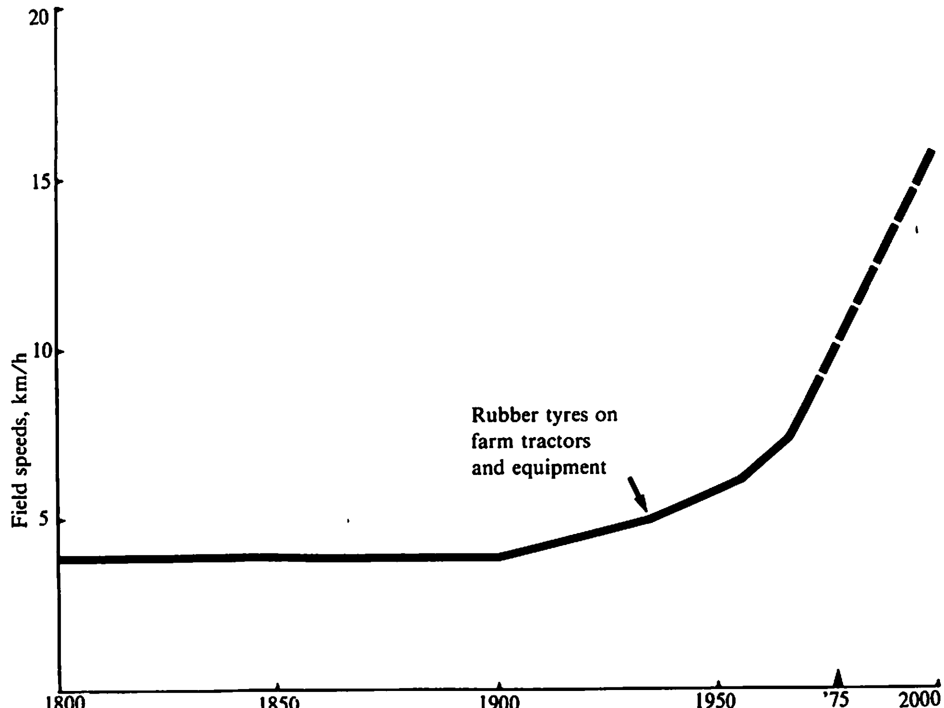


Fig 4 Trend in field speeds showing dramatic increase after tractors where equipped with rubber tyres

Courtesy: W J Promersberger (Larsen 1981)

through which many future electronic and computer-aided controls reach the field. As a system for carrying out a programme of field operations, it has great potential but limited to intensive farming operations where land suitability and conditions encourage its use. For the vast majority of farming operations throughout the world, a fully mobile, go-anywhere tractor will remain the means for conducting most farming operations.

The agricultural tractor is only one half of a machine combination and cannot start to serve its purpose until the other half — the implement — is added. As stated earlier, changes in methods of cultivation are likely to give rise to new implement development, which, in turn, will impact on tractor design. In the near future, I envisage major improvements in the following areas:

1 reduced maintenance;
2 increased driver comfort and convenience, application of power systems to drastically reduce control efforts, specifically for clutch and brake actuation;
3 simplification of controls;
4 improved implement hitching; introduction of "claw hitch" quick coupler, use of automatic coupling systems between tractors and implements to provide easy one-man coupling from the driver's seat will result in time saving and improved safety;
5 introduction of electronic draught and position control;
6 greater carrying space and passenger room;
7 introduction of air-conditioning;
8 cab tilt facility for ease of maintenance;
9 overall improvements with engines, transmissions, hydraulics, etc greatly accelerated by the recent pace of development in electronics and the application of micro-processors;
10 use of alternative materials;
11 greater overall operating efficiency;
12 greater safety.

Looking further ahead:

13 higher transport speeds;
14 front pto and hydraulic lift options;
15 automatic tyre inflation pressure adjustment to optimise draught/slip/drawbar power relationship;
16 wider application of electro-hydraulic control systems and the development of electronic management devices;
17 exploitation of engine/transmission control interaction using speed/load-sensing/wheel slippage inputs, controllable to achieve maximum fuel economy and/or maximum work rates;
18 vehicle suspension systems with means of automatic interaction between implement and tractor to achieve higher working speeds with optimum implement control under the full range of tractor and implement combinations.

Very much later:

19 remote control tractors, programmable or as slaves to master driver operated tractor;
20 one really universal tractor oil.

New form of tractor design

Frame

Present European tractor design generally makes use of the cast iron unit frame construction, dating back to the 1917 Ford. Because of the increasing percentage of cab tractors and the needs for improved comfort and higher operating speeds, the present form of construction may eventually give way to a frame type construction. The frame will combine both the chassis and the cab structure onto which the engine will be resiliently mounted with sprung axles front and rear: four-wheel drive, or front wheel assist, will probably be standard.

Engines

As yet, there appears no alternative to the piston engine and the diesel will continue as the main source of power. The "state-of-the-art" diesel engine is more fuel efficient, quieter, lower in vibration levels, produces more power per litre, lasts longer and needs less repair than its predecessors. Recent improvements in turbocharging, fuel injection, ignition enhancement, cooling and power transmission have made the diesel even more attractive. With these improvements comes added complexity and the correct maintenance of engines increases the need for simple but sophisticated engine protection systems, incorporating diagnostics. Air, fuel, and oil filters; engine and transmission oil; injectors, and injection timing and other operating parameters will be monitored.

Further improvements will be introduced to increase overall efficiency and further reduce noise levels and emissions, together with greater durability. Diesel engine developments using ceramics for the cylinder head and in the piston crown will be taken up by the tractor industry and will lead to further efficiency improvements and the eventual elimination of the present liquid cooling system and its associated penalties.

Much has been done on alternative engine forms and should it prove commercially possible to build a new geometric form of engine, with reduced rotary and reciprocating masses, it would probably have a good future, but this seems still a long way off. Alternatively, a breakthrough with the gas-turbine cannot be dismissed, although this form of power unit would introduce many problems with power transmission.

Transmissions

Short term there will be wider use of synchromesh gearboxes with helical gears. There will be a continued move towards more transmission speeds with power shift. Shifting will be accomplished by hydraulically actuated multi-plate clutches, operated automatically in response to load demands or by manual override.

Hydrostatic transmissions which have been receiving the attention of the industry off and on over the past thirty years are not likely to become widely adopted. Other forms of continuously variable transmissions may be developed, depending on their success or otherwise in automotive applications. One possible contender is the Van Doorne transmission.

There will be widespread adoption of hydraulically actuated multi-plate clutches for pto actuation, with components much in common with the transmission power-shift clutches.

Electronics

We can anticipate:

1 a driver total information system with dashboard displays presenting different types of information on demand, including the tractor diagnostics;
2 electronics to provide engine and drivetrain management to give precise control of power, transmission shifting, wheel slip monitoring, etc;
3 on-line computers to provide a degree of automatic control and/or data recording to achieve better management of each operation;
4 closed-circuit television to keep the operator informed on what is going on around him.

Hydraulics

The introduction of electronic/hydraulic implement hitch control systems will provide good ground following and less depth variation, whilst also maintaining more constant weight transference to allow forward travel speeds up to around 14 km/h, against the present limit of around 8 km/h. This will require hydraulic system response times considerably faster than those obtained with most current systems. In particular, the hydraulic power source and control means will have to provide the precise flow and pressure required at all times, both during on-load (draught and/or position control) and off-load (implement in transport position) conditions. Existing devices are expensive and have low contaminant tolerance levels, hence, scope exists for the hydraulic equipment industry to develop suitable components to meet cost and life criteria to make this type of control system generally acceptable.

Any hydraulic system is prone to malfunction due to the presence of contaminant; however good the capabilities of a filtration system, they will be largely lost if the filter elements are not changed or the strainers cleansed at suitable intervals. Hydraulic systems will provide easy access to critical components for cleaning or replacement as indicated by the tractor diagnostic display.

Conclusions

In the tractor industry, as a general rule, periodic design changes are made to the product to achieve a specific feature or performance. Usually, desired results are obtained without altering the entire vehicle. In practice, every effort is made to minimise changes and still achieve the objectives. There are few revolutionary developments but the conventional is only so because it is the product of a series of evolutionary development during which many alternatives have been tried and rejected. This situation will prevail until there are major changes in technology or operating circumstances.

We can be certain that social and political factors which, in turn, influence commercial and legislational considerations will be a major influence in future tractor development and will decide even the countries where the industries reside.

Table 2 shows Western European tractor sales and production volumes in 1963; contrast these figures with those shown alongside for today (1982 UK tractor registrations 26,118: source Agric Engrs Assoc report). I see the world trend towards higher power, more complex tractors, ending in a division in tractor design forming two distinct product lines:

for the developed countries — a sophisticated, complex, cab machine, incorporating the latest in technology;

for the developing countries — a basic, non-cab machine to satisfy a labour intensive marketplace and help overcome the disgrace of millions of people starving (every day there are another 100,000 or more mouths to feed).

There are no signs of hydrogen fuelled, turbine powered, hydraulically driven, screw-propelled, remote-controlled tractors yet and to those expecting to see revolutionary tractor configurations, I'm sorry to disappoint you! I re-emphasize that tractor configuration is dictated by the implements employed: without revolutionary changes in implements and methods of crop production, the basic layout is unlikely to change.

World economic factors and changes in mechanised farming are causing a contraction in volumes of tractors built in the UK (table 2). The total market

Table 2 Farm tractor sales of West European countries

	Number of tractors sold (wheel tractors only)					
	Domestic		*Export*		*Total*	
Country Produced	*1963*	*1982*	*1963*	*1982*	*1963*	*1982*
Great Britain	42,304	15,300	187,593	79,500	229,897	94,800
West Germany	65,671	30,500	30,059	42,500	95,730	73,000
France	47,885	21,700	17,713	16,900	65,598	38,600
Italy	35,145	26,000	16,855	75,200	52,000	101,200
Sweden	4,940	16,000	10,700	1,400	15,640	3,000
Austria	10,547	3,600	1,220	7,800	11,767	11,400
Others*	12,020	13,500	349	10,800	12,369	24,300
Total	219,512	112,200	264,489	234,100	484,001	346,300

During the year 1963, approx 186,000 tractors were sold in the USA.
During the year 1982 sales of tractors in North America were 120,000.
Above figures for 1982 are based on estimated shipments by major manufacturers.
Smaller manufacturers (predominantly supplying domestic market) would add 1100 to total.
* *Includes Finland, Spain, Switzerland and Belgium.*

which we serve is taking a reducing number of tractors, although the average power is increasing by approximately 1½% per annum.

The principal UK manufacturers are subsidiaries of North American multinationals from whence policy is dictated: generally, this will mean that North America will continue to build the higher powered machines which form the basis of their domestic market for draught tractors and Europe, including the UK, will supply the declining market volume below 75 kilowatts. With this background situation, it is unlikely that we shall ever return to the heady days of the 1960s when Britain was the Western world's number one tractor producer. Tractor companies will aim to become viable production units with volumes little above the present depressed levels: not the ideal situation for individual manufacturers to tool-up and produce their own highly automated products! Tractor builders will probably be forced to look outside to specialised equipment suppliers — which will favour the frame concept.

Figure 5 shows the power trends in the European tractor market. In numbers, this power group is likely to dominate the world market, with the 75kW plus section taking an increasing share. There will be a slow-down in the power increase in the very biggest machines produced in much lower volumes.

A growing market for front lift and front power take off will influence future tractor design. With improved implement coupling and with implement visibility provided by optical means displayed forward of the driver using a "controllable eye" to provide all-round visibility about the tractor, implement and general working area, I visualise a forward mounted operator position with the power unit, transmission and hydraulics packaged below and rearwards of the cab. The platform area behind the cab would be usable for load carrying and might incorporate a hydraulically actuated structure for raising and lowering a carrier in similar fashion to the Dump-skip truck. The lift structure could be adapted to serve as a loader or crane.

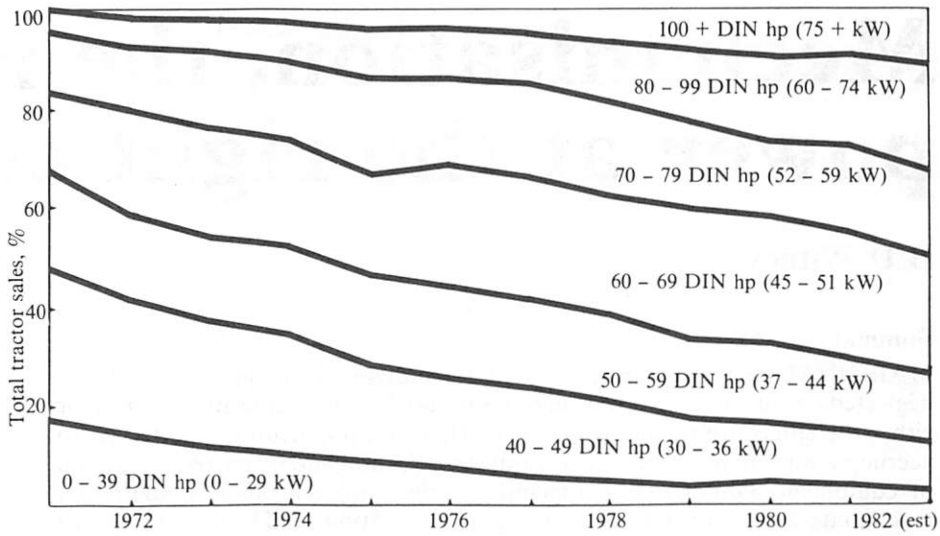


Fig 5 Europe – tractor power trends (1971 – 1982)

References

Fraser C (1972). *Harry Ferguson – Inventor & Pioneer.* John Murray, London.

Gray R B (1975). *The Agricultural Tractor 1855*–1950. Am Soc agric Engrs.

Larsen L (1981). *Farm Tractors 1950*–1975. Am Soc agric Engrs.

Bell R L (1980). Research and development for the next century. *Agric Engr,* 35, 60–62.

Mechanisation, the right power at the right cost

B D Witney

Summary

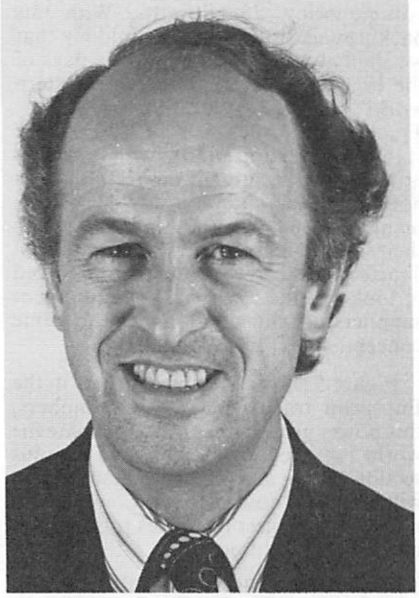
MARGINAL reductions in fixed costs for individual operations tend to be neglected because of constraints in other parts of the mechanisation system for either the enterprise or the whole farm. There are opportunities, however, to accrue savings in investment by careful size selection and by correct operation of equipment. Objectivity in machinery selection decisions is hindered by inadequate data on the cost of delaying field operations and by the difficulty of placing a monetary value on convenience.

A simulation model for estimating tractor power demand is used to outline the way in which a comprehensive machinery selection procedure can be developed and, in parallel with the long term project, the way in which such investigations can generate immediately applicable, practical solutions for individual aspects such as ploughing performance.

As implements increase in size and complexity, a reappraisal of the financial implications is often neglected in the face of popular appeal and convenience, one such example being a comparison between ploughing with larger mounted reversible and conventional equipment.

The cost effectiveness of a multi-purpose machine for destoning/planting/harvesting for the potato crop is demonstrated but self propelled harvesting is not economically justified.

Combine harvesting, on the other hand, is almost completely dependent on self-propelled units but there is still scope for saving investment. For small scale operation, economy options of using second hand self propelled machines, contracting or operating a new trailed machine are also compared.



1 Introduction

Oversize tractors and surplus power may well be a relic of the extravagant 70s but spare machine capacity continues to dominate Mechanisation Strategy like a monument to the changeable British climate. The uncertainty factor in farming is the catalyst for expansionist machinery replacement policies, despite the harsh economic reality of escalating overdrafts. It is always easier to err on the safe side and go for tackle of the next size in the output stakes. This induces the peace of mind designed to surmount a repetition of any recent problem — be it machine failure or poor weather so vividly recalled, or bad organisation so quickly forgotten.

'Buying bigger' also serves to emphasise two unique aspects of farming:

* the high personal commitment of management in the completion of day to day farm operations;
* the problems of risk assessment in machinery choice.

It is much harder to have an objective view of the effect of a combine harvester breakdown on the 10 year average of the enterprise gross margins when you have been up all night repairing the machine and the weather is about to break! In this respect, Machinery Management is very much like an insurance policy and raises two questions. What is the extra annual premium for peace of mind? And, more importantly, have you noted the *absence* of the fine print about the machine performance specification? The potato harvester with a 30% spare capacity in normal conditions may clog solid in a wet season. The machine becomes a costly failure whilst the crop is lifted by a squad — if you can find one.

'Mechanisation, the right power at the right cost' is not just about *machines* and *money*, it also includes *men* and *management*. The piecemeal approach to machinery replacement has been able to survive because the emphasis has been placed on substituting more complex equipment for a decreasing labour force and on reducing drudgery. If that was not enough, inflation quickly masked any mistakes. Now, however, power and machinery jointly represent the largest single item of expenditure subject to management control on an arable farm. With the rapid increase in these machinery costs relative to crop prices and with the general trend of rising energy values in real terms, the key to improving farm profitability rests in containing fixed costs.

The purpose of this paper is: firstly, to introduce a new approach which is being developed for tractor power and machinery selection as a computer simulation model; secondly, to mention some recent studies which provide practical guidance on individual facets of machinery choice, including those in which a capacity increase also introduces a transition from trailed to self propelled.

2 Total tractor power and fleet size

The total tractor power on a mixed arable farm is largely determined by the draught demand for primary tillage. Tractor fleet size, on the other hand is governed by need for simultaneous operations with individual machines, for example during crop establishment, and by the transport requirements during the Spring and Autumn peaks. These two components of tractor selection are, however, seldom scrutinised with equal attention to detail. Power always predominates and a common solution is approached by an iterative — or intuitive — process of replacing separate bits of hardware whenever a bottle-neck turns into a problem. The farmer applies his skill to match the work output of the equipment to the time available at an acceptable level of cost. He balances the extra cost of spare machine capacity against crop losses from delayed work; however, the time available is not fixed. Managers vary the acceptable level of operating conditions to suit the advanced or belated state of progress of work. This is a moving target which has to be replaced by a more objective selection procedure. Taking ploughing as an example, one such selection procedure is shown in figure 1 in the form of a flow chart (Witney 1982). The soil moisture content

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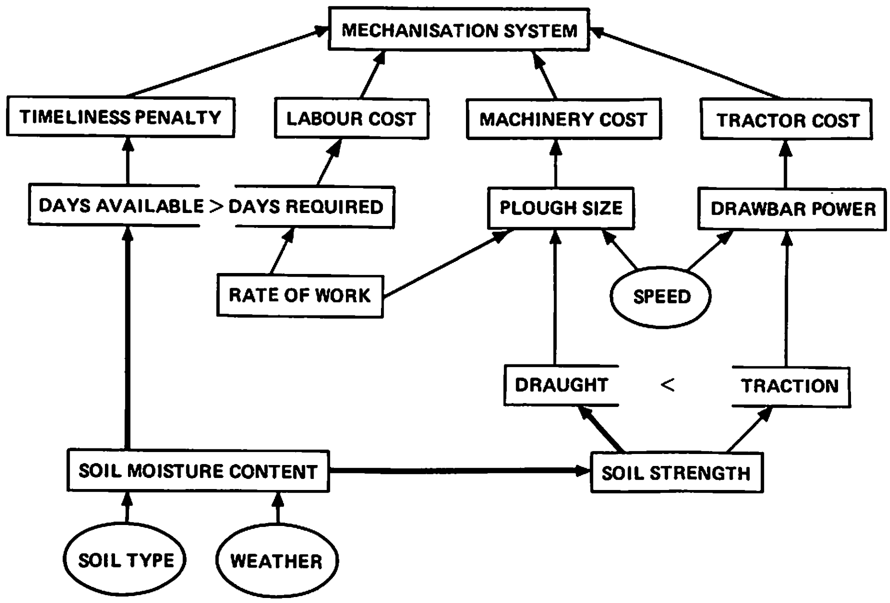


Fig 1 A systematic procedure to evaluate the implications of alternative mechanisation strategies relating to tractor power selection for primary tillage

Fig 2 The effect of soil moisture content on factors influencing tractor/plough size selection

SOIL CONDITION	VERY WET	AVERAGE	VERY DRY
No OF WORKDAYS	MANY	*Increasing Timeliness Penalties* →	FEW
TRACTION	POOR	← *Increasing Tractor Costs*	GOOD
DRAUGHT	LOW	*Increasing Plough Costs* →	HIGH

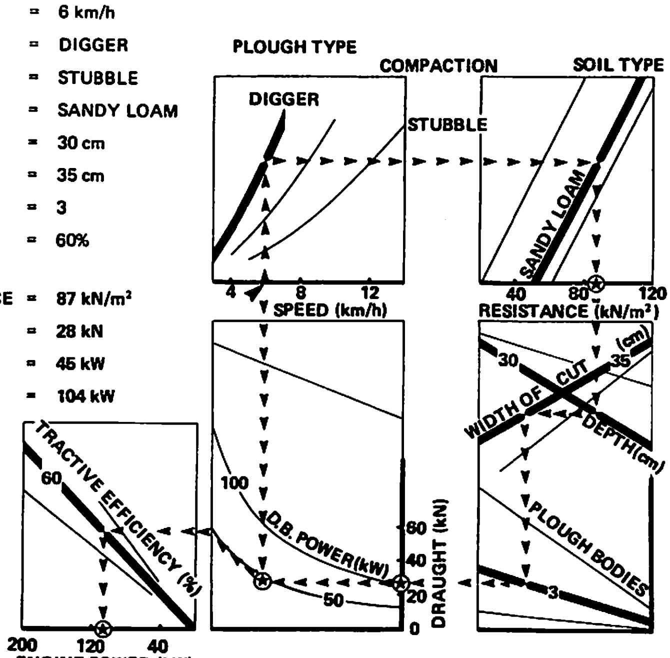
affects not only the plough draught and traction through the soil strength but also soil work days available. Thus, the cost elements for timeliness penalties, labour demand and for machinery and tractor usage can be assessed for the complete system.

In practical terms, the wettest conditions for soil working are limited by high tractor wheel slip and low tractive efficiency (fig 2). These incur high operating costs for reduced rates of work. Progressing to the dry end of the soil moisture scale, plough draught becomes excessive and the chance of working small. High power costs and excessive timeliness penalties are again generated. In between these two extremes, we find the economic optimum.

Fig 3 A simplified example of the Ploughing Performance Predictor nomograph for planning rates of work and size of tackle

SPEED = 6 km/h
PLOUGH TYPE = DIGGER
COMPACTION LEVEL = STUBBLE
SOIL TYPE = SANDY LOAM
DEPTH OF CUT = 30 cm
WIDTH OF CUT = 35 cm
NO OF PLOUGH BODIES = 3
TRACTIVE EFFICIENCY = 60%

PLOUGHING RESISTANCE = 87 kN/m²
TOTAL DRAUGHT = 28 kN
DRAWBAR POWER = 45 kW
ENGINE POWER = 104 kW



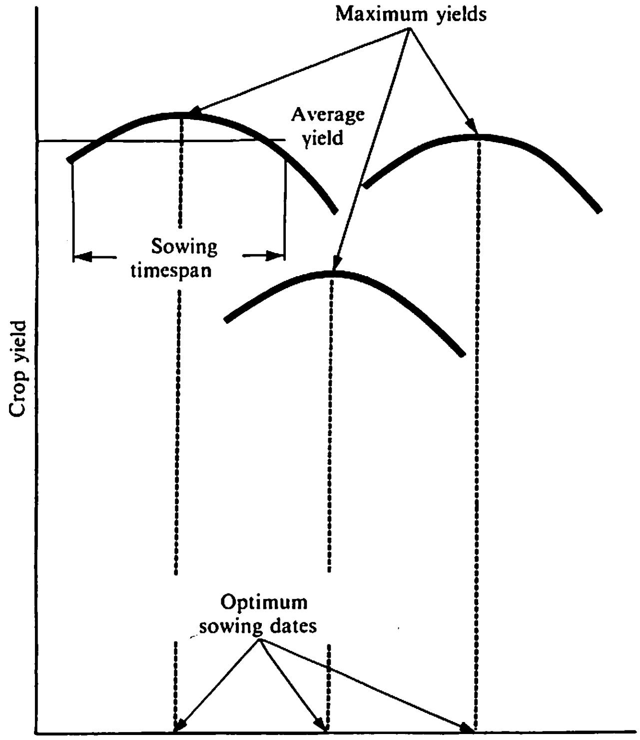
2.1 Ploughing performance

As the walking stick is the most widely accepted form of 'soil tester' in common use, the penetration resistance of the soil is acknowledged as the only functional indication of soil strength. Cone index is used to link plough draught with soil moisture content which itself was predicted from simple soil and weather variables (Eradat Oskoui and Witney 1982, Witney *et al* 1982). Using these equations, it is possible to condense plough performance data into the form of a nomograph (fig 3). The Ploughing Performance Predictor takes the hard work out of the calculation by portraying the relative significance of the various factors affecting plough draught in a series of linked graphs (Terratec 1982). A wide range of soil moisture values can be distilled to provide the lower plastic limits of light, medium and heavy soils; soil specific weights can be equated to the degree of compaction associated with well-trafficked headlands, stubble ground and loose soil after harvesting roots, whilst mouldboard shapes are loosely identified as digger, semi-digger and shallow plough bodies. Ploughing speed combines with width of furrow, number of plough bodies and field efficiency to give work rates. In addition, speed not only influences the total plough draught but also combines with draught to yield the drawbar power requirement and, with a knowledge of the tractive and transmission efficiencies of the tractor, the engine power rating of the tractor can be established.

The Ploughing Performance Predictor includes all the plough performance variables which influence the tractor drawbar power required: only the ranges of the parameters are restricted. It is, however, a practical approach which provides a solution to only part of the machinery selection puzzle. It answers the question: what power level of tractor is required for a particular plough and field condition? Further data are required on tractive performance and on the working time available before suitable tractor plough combinations can be identified for given soil and weather conditions.

2.2 Matching tractor plough and time available

Traction, as well as draught, is related to cone index (Dwyer *et al* 1974, Gee-Clough 1980). Tractor performance can be determined for different tyre loadings and soil moisture contents. Matching feasible combinations of drawbar pulls, travel speeds and plough draught produces relatively few realistic alternatives. The overall rate of work gives the time required for each option. This time can be compared with the available work days when the soil workability is within acceptable moisture limits. If the available work days are insufficient for the task in hand, then for winter cereals at least, sowing is delayed and the crop yield reduced.



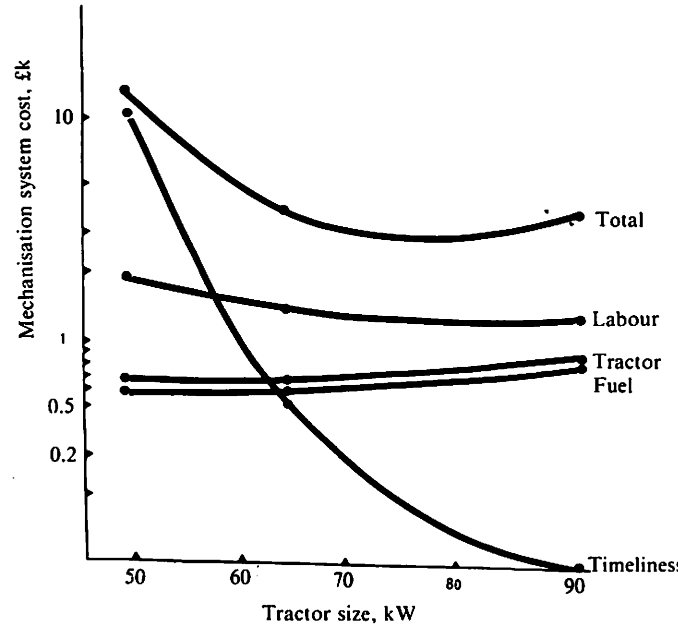


Fig 5 The effect of tractor power level on the total cost of ploughing 400 ha for Winter wheat

Fig 4 (left) Three similar crop yield functions showing different maximum yields, optimum sowing dates and an average yield for a time span when sowing is in progress

Timeliness penalties are evaluated from a crop yield function, once this has been established from experimental data. The graph of yield against time of sowing gives the maximum yield and the average yield for a time span when sowing is in progress (fig 4). Using a general form of the yield function, experimental data determines the shape of the yield curve but specific values for the maximum yield and for the optimum date of sowing can be introduced to give a more accurate local estimate of the crop losses on individual farms in areas remote from th e experimental site (Eradat Oskoui 1982).

At the completion of this exercise, machinery costs are analysed to give the present annual values from the actual cash flow (Audsley and Wheeler 1978) and the various cost components combined to produce the total mechanisation cost. In the example of the logarithmic value of costs against tractor power level, the timeliness penalty decreases to zero as the tractor power level increases (fig 5). Labour costs also decline but fuel and machinery costs rise to provide a total cost curve with a minimum value. This analysis demonstrates the viability of the approach but the acceptability of the minimum value is obviously influenced by other mechanisation aspects of the farm business which have not been incorporated and even by other aspects of ploughing.

2.3 Ploughing system and implement hitching

The foregoing example evaluates the performance of two wheel drive tractors with conventional ploughs. Now, however, the market is dominated by the reversible plough. Their main advantage lies in their ability to produce a level field surface by shifting all the soil in one direction. There is also the saving in field setting out time. The extra weight of the second set of bodies enabled a medium sized tractor to utilise a high drawbar power at maximum efficiency, especially on heavy soil (Dwyer 1974). On light soil, however, the extra weight of a mounted reversible plough is of no advantage because drawbar power is restricted by the steering stability of the tractor. A mounted conventional plough can efficiently utilise 25% more power than a mounted reversible plough. This represents the difference between a 5 furrow conventional and a 4 furrow reversible plough. In addition, two-wheel drive tractors developing a drawbar power of more than 40–50 kW must work at speeds in excess of 7 km/h or they will sacrifice either steering stability or tractive efficiency.

In conventional ploughing, the optimum land width is a balance between the time wasted in excessive headland travel if the lands are too wide and the extra effort involved in more ridges and finishes with narrow lands. An early study by Hunt (1973) overestimates the ideal number of ridges by a factor of two because insufficient time elements were attributed to setting up and finishing the lands. Due allowance for the extra time involved reduces the sensitivity of land width to plough size but retains the influence of field size on the number of ridges. Table 1 shows the field efficiencies obtained for different sizes of ploughs operating at 6.5 km/h in a 12 ha field and in a 24 ha field. A peculiarity of the field efficiency concept is that the values fall with larger equipment because the time in work becomes a smaller proportion of the total operating plus idle time. The reversible plough, with its constant turning time per pass, has an almost constant field efficiency for any particular field shape, whereas the field efficiency for conventional ploughing falls more quickly as plough size increases. Translating this concept into a more practical measure of total time to complete the field, it is interesting to note that changing to a reversible plough of the *same* size as the conventional has only a marginal effect on the time involved.

With fully mounted equipment on a two wheel drive tractor, the ability to pull an extra furrow by opting to stay with conventional ploughing yields a small but positive advantage in work rate. The time

Table 1 Overall rates of work for different ploughs operating at 6.5 km/h in two field sizes

No. of furrows	*Plough width, m*	*Field efficiency, %*		*Overall rates of work, ha/h*		*Total time to complete field, h*		*Time saved by Conv + 1 extra furrow, h*
		Rev	*Conv*	*Rev*	*Conv*	*Rev*	*Conv*	
Field size of 12 ha								
3	0.9	94.4	—	0.55	—	22	—	
4	1.2	93.9	87.7	0.73	0.66	16	18	4
5	1.5	93.3	82.5	0.91	0.80	13	15	1
6	1.8	—	80.5	—	0.94	—	13	0
Field size of 24 ha								
3	0.9	97.1	—	0.57	—	42	—	
4	1.2	96.8	89.7	0.76	0.70	32	34	8
5	1.5	96.6	88.2	0.94	0.86	26	28	4
6	1.8	—	87.4	—	1.02	—	24	2

in hand adequately compensates for the extra cultivation to level out the ridges and finishes. Furrow matching is often better with conventional ploughs, especially on side slopes and two tractors can operate in one field without interference. Thus the higher capital cost of reversible ploughs is hard to justify except in terms of convenience, less skill for ploughing and reduced danger to the combine harvester table at harvest (table 2).

As tractor size forges ahead, the weight transfer aspect declines in importance because semi-mounted or trailed equipment is necessary to maintain tractor stability or uniformity of depth. Even here, the popular appeal of the reversible is too strong to be swayed by cost savings. Indeed, hanging hardware on the front is having a surprising impact on the market. The downward thrust of a front mounted plough enhances the weight on driven front wheels of a four wheel drive tractor (fig 6). Ploughing performance is improved by increasing the number of bodies through better traction (Traulsen 1982). Individual front and rear ploughs are shorter and give better depth control on undulating ground compared with a single long unit. However, the horizontal thrust from the front plough is considerably offset from the tractor centre line and produces a large steering force which must be counteracted by adjusting the hitch for the rear mounted plough to compensate. This dictates the use of a larger plough of at least 4 bodies on the rear in conjunction with a 2 body or, at most, a 3 body plough on the front. With the steering factor and the high cost of the hydraulics for indexing and slewing the front unit as well as lifting, it is surprising to find the market potential so buoyant except where a step price increase of changing to a semi-mounted configuration from the largest conventional plough is involved. The extra cost of the reversible becomes more significant as the popularity of auto reset bodies increases and represents a surcharge of 30% or more.

Even so, the effect of plough choice on the overall level of fixed costs is very small in comparison with the high capital cost of specialist crop production equipment which is used for a relatively short period each year.

There has been a trend towards combining cultivation operations by the use of tillage trains to reduce operating costs but relatively few attempts at designing a multi-purpose machine to decrease investment charges.

3 Economics of combined and multiple operations

One of the most recent examples of combined and multiple operations is associated with stone windrowing which has now become an accepted part of seed potato production in Scotland. In the space of 6 years, equipment design has evolved rapidly from its simple beginnings as a single row machine almost identical with a potato elevator digger. Two row trailed machines are

Table 2 Investment comparison for different types and sizes of ploughs

	Investment comparison for ploughs, £						
	No of furrows						
	3	4	5	2+3	6	3+4	8
Reversible, mounted	2500	3000	4200		—	—	—
Reversible, front + rear mounted	—	—	—	3300+2500	—	3700+3000	—
Conventional, mounted	1700	2200	2700		3500	—	—
Conventional, semi-mounted							6600
EXTRA COST OF 1 FURROW *SMALLER* REVERSIBLE		300	300		700 or 2300		100
EXTRA COST OF 1 FURROW *SMALLER* REVERSIBLE WITH AUTO RESET		1100	1200		2200 or 3300		1600

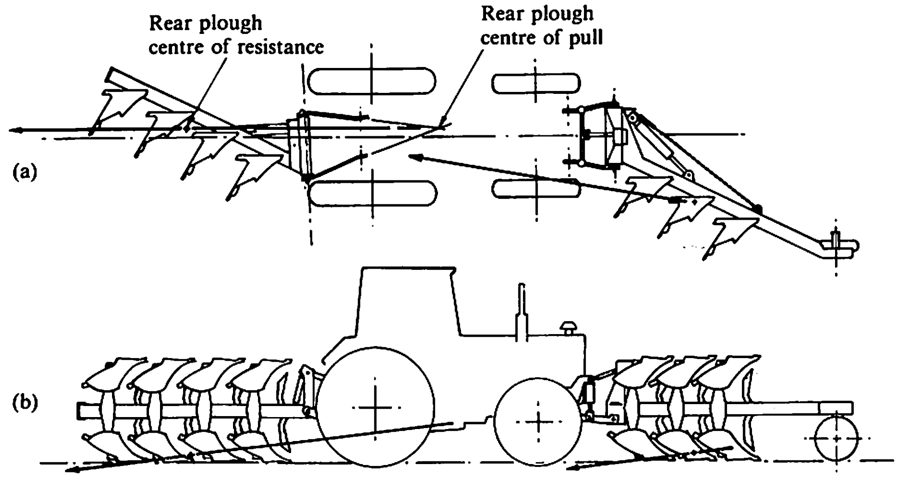


Fig 6 The effect of line of pull with front and rear mounted ploughs on (a) steering and (b) weight transfer

Table 3 Operational requirements with different mechanisation systems and team sizes for potato crop establishment and harvesting

	Team size for various mechanisation systems, no. of men			
	Traditional trailed planter and harvester	*Individually trailed destoner, planter and harvester*	*Multi-purpose trailed destoner/ planter/ harvester*	*Multi-purpose, self-propelled destoner/ planter/ harvester*
Ploughing	1	1	1	1
Cultivating/disc	1	1	1	1
Broadcasting ½ fert Transporting	{2}	{2}	{2}	{2}
Forming beds	—	1	{1}	1
Placing ½ fert	—	—		—
Transporting	—	—	½	—
Rotary cult Ridging	{2}	— —	— —	— —
Destoning	—	1	{1}	
Planting Placing ½ fert	{1}	{1}	 —	{1}
Transporting	1	1	1	1
TEAM SIZE, SPRING	4	3	2	2
Harvesting	1	1	1	1
Pickers in field	4	2	2	—
Transporting	2	2	2	2
Pickers in store	—	—	—	2
Stacking	1	1	1	1
TEAM SIZE, AUTUMN (Full time + casuals)	4 + 4	4 + 2	4 + 2	4 + 2

{ } *indicates a combined operation*

now available with the facility for not only destoning the land but also for potato planting in a combined operation (Witney, 1980). One new machine is designed in modular form to facilitate multiple use as a destoner/planter and as a potato harvester. This concept was also tried in reverse a few years ago by offering a destoner/planter conversion for a self propelled potato harvester (Witney, 1976). The selection of these options involve more than just a simple investment appraisal because organisational aspects of the whole farm become involved.

The individual operations for establishing the potato crop are first to open up the field in preparation for destoning and to broadcast half the fertiliser (table 3). When soil conditions are right, one man and a medium power tractor are required to operate the destoner at an overall rate of work of about 0.5 ha/h over an extended working day. Two men and two additional medium power tractors are required for the planter with an overall rate of work of about 0.6 ha/h and for ferrying seed and the fertiliser for placement with the seed. Manual filling of the planter is commonplace.

When destoning and planting are combined, fertiliser placement is not feasible as part of the planting operation, instead, deep placement of the fertiliser is combined with the earlier task of opening up the field so that only 1 man and 1 tractor are required, although a second tractor may be left with the trailer on the headland. The existing two row planter can be attached to the combined machine. Two men and two tractors are involved for the destoning/planting operation but a more powerful four-wheel drive tractor is desirable to haul the heavier machine and the transport tractor must be equipped with a fork lift to load the hopper of the planter. A large capacity hopper and mechanised handling minimise the turn round delays on the headland but, inevitably, the overall rate of work, of say 0.4 ha/h, for the combined machine must be less than the rate for destoning alone. On the plus side, the availability of 3 or 4 men, full time, makes it possible to operate a split shift system to maximise the area covered in favourable soil and weather conditions.

Table 4 Investment comparison and rates of work of potato crop mechanisation systems

	Investment and performance comparison of various mechanisation systems			
Equipment/operation	*Traditional trailed planter and harvester*	*Individually trailed destoner planter and harvester*	*Multi-purpose trailed destoner/ planter/ harvester*	*Multi-purpose self-propelled destoner/ planter/ harvester*
Furrow opener	std	std	std	std
Destoner, 2 row	—	£12,000	£16,500	+£3,000
Tractors	std	std	+£2,500	std
Planter, 2 row	std	std	std	std
Trailers	std	std	std	+£2,000
Harvesters:				
1 row complex	£14,000	—	—	—
2 row straight through	—	£20,000	+£9,000	£52,000
In-store trash separation	—	—	—	+£2,000
TOTAL	£14,000	£32,000	£28,000	£59,000
Planting overall rate of work	0.5 ha/h	0.5 ha/h	0.4 ha/h	0.4 ha/h
Harvesting seasonal rate of work	0.9 ha/day	1.5 ha/day	1.5 ha/day	1.8 ha/day

Conversion of the destoner/planter to the harvester mode is accommodated during a slack period and, with a larger tractor available, the seasonal rate of work is marginally advantageous over the same size of harvester pulled by a less powerful two-wheel drive tractor. The extra cost of the large tractor is not wholly allocated to the investment comparison for the potato enterprise but only the additional cost over the size of tractor which the farmer would most likely have as standard.

A self-propelled destoner/planter/harvester saves the use of one tractor during the spring work but the unit is unlikely to replace the tractor. It is perhaps reasonable, however, to discount any higher operating costs against savings from leaving the tractor in the shed. Just as there is an extra cost for converting the trailed destoner/planter to a harvester, so conversely there is a charge for converting the self-propelled harvester to a destoner/planter.

The investment comparison for each potato mechanisation system is summarised in table 4. Firstly, the table emphasises the dis-economies of scale or the non-linear price/performance ratios (Elrick 1978). Changing from the traditional system with a single row manned harvester, through a system of individual destoning, planting and harvesting equipment to a system with a self-propelled multi-purpose machine in each case approximately doubles the level of investment but improves the seasonal rate of work by only 50% or less.

Secondly, table 4 demonstrates the cost-effectiveness of a trailed multi-purpose machine, such as the Elbar destoner/planter/harvester, (fig 7) despite the inclusion of an investment premium for a larger tractor which is arguably not essential or already available. The level of investment is less than for a system of individual machines with comparable design features and no more expensive than alternative systems of individual machines which include any trailed, 2 row, straight through harvester of more basic design but equipped with a limited picker facility. The machinery selection decision, however, must also take account of the advantage of a smaller team size in Spring against a lower planting performance and possible timeliness penalties for larger cropping areas.

Fig 7 The Elbar multi-purpose machine equipped for (left) destoning and planting and (right) harvesting

4 Self-Propelled

Whilst trailed harvesting equipment is firmly entrenched for potatoes, the market for combine harvesters is predominantly for self-propelled units which represent the largest machinery purchase on the farm. Careful choice of specification and operating policies can give a substantial saving in both capital and operating costs. Elrick (1982) considered the selection of three different sizes of conventional combines related to their drum widths (table 5). The potential rates of work increased in the same ratio, 4:5:6, which is not a wide performance range compared with other types of farm machinery.

Although a larger size of machine covers the ground faster, the financial benefits of size are less clear cut because, within reason, harvesting delay losses and machine costs cancel each other out (table 6). For the comparison, it was assumed that the machines are operated for 4 hours/day and traded in at 800 h — reached sooner by the smaller machine — at 6, 7 and 8 years, respectively. The crop yield is valued at £500/ha with an exponential loss trend of 5% within 18 days and 15% within 36 days.

The least cost size is within a few hundred pounds of the second choice and, in most cases, the final selection is influenced by the peripheral benefits such as releasing capital for other purposes or saving time for other jobs. The two harvest areas serve to illustrate the upper limit for the small combine is being reached at 120 ha and that the largest combine required more than 150 ha for least cost operation. A good spread of ripening with winter cereals is of greater financial benefit than a size change (eg size 2, 22 day versus 8 day spread saves £3,400/annum whereas size 2 versus size 3 saves nothing on 150 ha crop area). Equally, the same output from a smaller combine saves £1,000–1,500 per annum on the machine and gives the same results as far as delay losses and duration of harvest are concerned. This is not unreasonable on many farms by a speed increase of 10% and by combining for ½ hour longer each day.

5 Economy options

Finally, one of the repercussions of trend towards larger more expensive self-propelled tackle, be it combines or tractors, is that new machines are hard to justify below a certain scale of operation. The economy options are contract, second hand and trailed and these alternatives are examined for combines in table 7 (Elrick 1982).

New machines can compete with contract down to about 80 ha with a size 1, high specification machine or to about 50 ha with a machine of lower specification. Good second hand machines (half price at 3 years old) are cheaper than contract down to 30 ha but below that crop area, the machines must be progressively older and kept longer with a greater risk of breakdowns.

Contracting is very competitive, especially where the available team is small and there is no one spare to drive an owned combine.

Table 5 Combine harvester size and performance

Combine size category	Drum width, m	Overall rate of work, ha/h	Combine price, £
1	1.05	1.04	29,000
2	1.30	1.29	37,000
3	1.55	1.54	50,000

Table 6 Total harvesting costs (machine plus losses) for different crop areas and combine sizes (Elrick 1982)

Combine size	Harvest duration, day	Machine cost, £/annum	Delay cost, £/annum Spread of ripening 8 day	15 day	22 day	Total harvest cost, £/annum Spread of ripening 8 day	15 day	22 day
Harvest area 120 ha								
1	29	4,670	4,800	3,240	2,100	9,500	7,900	6,800
2	23	5,590	3,480	2,280	1,470	9,100	7,800	7,100
3	20	7,030	3,060	1,860	1,380	10,100	8,900	8,400
Harvest area 150 ha								
1	36	4,670	8,100	5,625	3,900	12,800	10,300	8,600
2	29	5,590	6,000	4,050	2,625	11,600	9,600	8,200
3	24	7,030	4,600	3,000	1,950	11,600	10,000	9,000

Table 7 Cost comparison for combine harvesters including self-propelled new and second hand, self-propelled on contract and trailed (Elrick 1982)

Area, ha	Machine costs (depn, int and repairs), £/annum: New size 1 £30,000	New size 1 £20,000	Contract (£45/ha)	Second-hand £10,000 3 yr old	Second-hand £5,000 6 yr old	Second-hand £2,500 9 yr old	Trailed £9,000
100	4,200(8)	2,800	4,500	—	—	—	—
80	3,900(9)	2,600	3,600	1,700(10)	—	—	—
60	3,600(10)	2,400	2,700	1,650(10)	1,300	—	—
40	3,500(10)	2,350	1,800	1,600(10)	1,250	—	1,650(6)
30	–(10)	2,300	1,350	1,450(12)	1,100(14)	750	1,550(7)
20	—	—	900	1,400(12)	1,050(14)	700	1,500(8)
10	—	—	450	1,350(12)	1,000(14)	700	1,400(8)

Age at disposal shown in brackets alongside the cost.

A new trailed combine gives the reliability of a new machine with the costs of a used self-propelled unit, provided a suitable tractor is available.

6 Conclusions

The continued use of oversize farm equipment emphasises the problems of assessing the risk element through delayed field work and the importance attributed to convenience because of the close involvement of management in day to day operations.

The tractor power demand for ploughing can be determined from soil and weather variables but further work is required to identify the tractor fleet size for arable farms.

The convenience of reversible ploughing incurs an investment surcharge over conventional ploughing at similar seasonal work rates. The extra cost becomes more significant with the inclusion of auto reset bodies (an optional extra gaining widespread popularity in stony land) and of front mounted ploughs (promoted with overzealous enthusiasm).

The use of a trailed multi-purpose machine for destoning/potato planting/harvesting is shown to be cost-effective but the reduced labour input for the Spring work is offset by a marginal reduction in work rate and the total area which can be handled by the multi-purpose machine compared with separate operations. There is no economic justification for changing from trailed to self-propelled potato harvesters in terms of work rate but the transition may be worthwhile where it results in a reduction of the tractor fleet.

In contrast, the combine harvester market is biased toward self-propelled. For larger cropping areas, it is possible to reduce the capital investment by careful attention to spread of crop ripening. Below a certain scale of operation, new machines cannot be justified. Good second hand machines are cheaper than contract down to 30 ha but the reliability of older owned machines becomes increasingly suspect. A new trailed combine traders convenience for the reliability of a new machine at the cost of a used self-propelled — provided a suitable tractor is available.

Inevitably, the purchase of an individual machine interacts with the rest of the machinery complement, with the cropping programme and with the convenience element. As farm machinery is changing to more of a replacement market, there is an opportunity to realise savings in fixed costs by optimising the complete mechanisation system and to abandon the piecemeal approach completely.

Acknowledgement

The assistance of J L Anderson, East of Scotland College of Agriculture is much appreciated in the development of table 3.

References

Audsley E, Wheeler S (1978). Actual cost of machinery calculated using actual cash flows. *J agric Engng Res*, 23, 189– 201.

Dwyer M J (1974). Implement coupling and control. *Agric Engr,* 29, 61–66.

Dwyer M J, Comely D R, Evernden D W (1974). The development of a handbook of agricultural tyre performance. Natn Inst agric Engng, Dept Note DN/T/517/1415.

Elrick J D (1978). Containing power and machinery costs. East Scot Coll Agric Conf Report: "Farming to beat inflation", 44–49.

Elrick J D (1982). How to choose and use combines. Scot Agric Coll Publ No. 88.

Eradat Oskoui K, Witney B D (1982). The determination of plough draught — part 1 prediction from soil and meteorological data with cone index as the soil strength parameter. *J Terramechanics* 19, 2, 97–106.

Eradat Oskoui K (1982). Personal communication.

Gee-Clough D (1980). Selection of tyre sizes for agricultural vehicles. *J agric Engng Res,* 25, 261–278.

Hunt D (1973). *Farm power and machinery management.* 6th ed. Iowa State Univ. Press.

Terratec (1982). Ploughing performance predictor. Terratec, S Barnton Ave, Edinburgh.

Traulsen H (1982). The role of the mouldboard plough? *Agric Engr,* 37, 12–14.

Witney B D, Wilson T S (1976). Benefits and opportunities with windrowing technique. *Arable Farming,* Potato Demonstration Supplement, Sept, pp5–9.

Witney B D (1980). Ways and means of stone windrowing. *Arable Farming,* Spring Potato '80 Supplement. March, pp 14–18.

Witney B D, Eradat Oskoui K, Speirs R B (1982). A simulation model for predicting soil moisture status. *Soil and Tillage Res,* 2, 67–80.

Witney B D (1982). The basis of tractor power selection for primary tillage. Proc 9th Conf, Int Soil Tillage Res Org, Osijek, Yugoslavia, 389–394.

Off-Highway/Self-Propelled Vehicle Conference

Edited Summary of the Discussion

Questions following Paper 1, (M J Dwyer — Soil dynamics and the problems of traction and compaction)

Mr J G Beck (Sigmund Pulsometer Projects Ltd)

Q Does the illustration, shown by Dr Dwyer of the comparative size of a rubber tyred wheel with a tracked vehicle, refer to a two or four wheel drive?

A *The comparison was between the same weight on a single track and on a single tyre.*

Mr T C D Manby (Silsoe Consultants)

Q Dr Dwyer has mentioned tyre carcass stiffness and I wonder if there is a future in the development of even greater carcass flexibility. Secondly, certain workers about 15 years ago did not make the assumption that an even pressure occurred all over the tyre footprint. Has Dr Dwyer discarded this work?

A *Carcass stiffness, as well as mean air pressure, were included in mean contact pressure at the footprint. Carcass stiffness obviously became a more important part of mean contact pressure as air pressure was reduced. It is agreed that variation in pressure within the contact area is important but has not yet been fully investigated and will be looked at in the future.*

Q Should we not be asking for even more flexible tyres than those already provided by radial tyres?

A *Yes, but a compromise has to be kept between flexibility and carcass strength.*

Mr S D Cartmel (Staffordshire College of Agriculture)

Q Is it feasible to estimate the level of ground pressure exerted under the rear sprocket of a track-lying tractor, when an implement is being lifted on its linkage?

A *The variation in pressure would depend partly on soil type and condition, but I guess that the high pressure points could well be double that of the mean, which was normally of the order of 0.35 bar.*

Mr H J Carnall (Carnall Associates)

Q Does Dr Dwyer know if figures are available for tyre carcass deflection pressures?

A *There is a certain amount of information available but it is not widely distributed. The National Institute of Agricultural Engineering and the Agricultural Engineers Association hope to correct this as the former are collating information on tyre carcass deflection pressures and will make this available.*

Questions following Paper 2, (D A Crolla — Suspension and steering design of off-highway vehicles)

Mr J A Munson (Ford Tractor Operations)

Q There is some concern that, with the introduction of a suspension system, the driver could become further divorced from feedback particularly on slopes and in relation to steering.

A *There are implications, but the safety aspect is likely to be associated with increased forward speeds rather than directly with the suspension system unless this did something unexpected. As with other vehicles, however, learning time was necessary.*

Questions following Paper 3, (J Withers — Past, present, future of the agricultural tractor)

Dr P A Cowell (National College of Agricultural Engineering)

Q Is there any possibility of the reduction of tractor noise at source to reduce environmental pollution rather than by just insulating the drivers cab?

A *Work, which offers promise for noise reduction, is being undertaken at Essex University. No development work has yet been undertaken with an agricultural tractor but commercial firms are keeping a close watch on developments in this area.*

Mr D Tapp (Freelance Engineer)

Q If comparatively high speed tractors are developed with suspension systems, does Dr Crolla consider that there will be a significant gyroscopic effect on the suspension and steering of such tractors?

A *The effect on the vehicle body would be potentially small but the effect on the suspended axle would result in severe problems of torque and inertia. With front wheel drives, additional steering problems would occur.*

Mr H J Carnall (Carnall Associates)

Q Do you consider that there is place in the future for lockable torque converter transmission?

A *It is unlikely that these will have great impact; rather one may see coupling of power units such as had been achieved in the past by Doe.*

Mr J B Holt (National Institute of Agricultural Engineering)

Q What would be the effect of legislation on the design of agricultural vehicles, particularly with respect to road speeds?

A *The greatest impact is likely to result from legislation of which we were as yet unaware, as had happened recently with noise. Undoubtedly, however, there would be further changes of effecting braking safety and noise.*

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The mechanisation muddle — which way forward?

D W Jewett

Summary

A PERSONAL view is given of some of the things which seem to be wrong with the available "Off Highway/Self Propelled Vehicle" choice; and what wrong choices are made among the available 'wrong' machines. Some suggestions are made on how this situation might be improved in the hope it will provide food for thought.

Choice of tractor

With few exceptions, farmers only have available to them tractors offered by the traditional tractor manufacturing industry which is an industry of large, mainly multi-national companies using mass production techniques to manufacture 'worldwide' rather than regionally orientated designs. In this environment, basic changes in design concept inevitably imply that enormous amounts of capital investment would be necessary for such large companies. Consequently, many seem to have concentrated 'new' product ranges on machines made by someone else, for instance the Japanese, and have put less effect into Design, Research and Development, employing 'Marketing Men' to push the newly and appropriately painted product at prices 'the market can stand'.

Can one think of an example either in or out of Agriculture where a power unit has been adapted and developed to such a highly complex state, enabling it to vary its form of power output, as we see in the mass produced agricultural tractor? Considering this machine was originally designed to replace the draught capability of the horse, it represents no mean achievement. Perhaps, however, there is a limit as to how far this development of a "maid of all work" should go, especially if it means the user has to purchase equipment he does not require when buying a standard tractor.

In addition, we might ask the question as to whether the replacement for the horse concept we have become accustomed to is the correct machine for present day farmers. Rather than develop an existing concept to its limit, should we not be looking more seriously at alternative concepts, that are more likely to suit current and future farming needs?

Many Agricultural Economists suggest that UK farmers have many more tractors than they require and some go so far as to suggest that if tax allowances were not so generous, this would not be the case. Should the taxpayer subsidise excess tractor capacity? It would appear that the problem of over-mechanisation may be solved by cutting tax allowances!

Interestingly, some 70% of Massey Ferguson tractors sold in the UK market in January 1983 were leased (Massey Ferguson 1983). This suggests farmers are not looking for 100% tax allowances to set against excessive profits, although there is evidence to suggest that this position is changing because of last year's profits. Nevertheless, the probability is that UK farmers are significantly "overtractored". Certainly, personal experience indicates that many farmers could manage with fewer tractors, especially if they were prepared to make more extensive use of contractors, share ownership, make small modifications to their farming system and use matched equipment for the tractors retained.

Equally, however, it can be argued that present designs of tractor do not allow farmers to maximise their use and, consequently, poor utilisation results. There is some good evidence to substantiate this fact in the 1969–70 Joint ADAS/NIAE Study of Utilisation, Performance and Tyre and Track Costs (ADAS 1972). More recent work also suggests this to be the case. Average utilisation seems to be of the order of 35% – 40% of maximum power and rarely exceeds a mean of 50% (Matthews 1983).

This raises the question: 'Can multiple operations be carried out with these tractors to make better use of the power available, so saving labour as well as improving capital utilisation?' Adaptions to existing tractor concepts to facilitate this are well known, for instance the Ferranti front linkages and bridge links for direct drills. A much more sensible approach however would seem to be the concept of a system tractor; the Deutz Intrac and the M B Trac are the most notable examples of this.

To maximise the use of this concept, a front linkage is needed together with a front pto with dual speeds, full power and total independence of the rear pto. If, in addition, a forward position for the operator is provided, improved control results and makes possible an extra load carrying capability over the rear wheels of the tractor which might include a 'fifth wheel' coupling. Four wheel drive and quick coupling arrangements for mounted implements are virtually essential to maximise the use of such a unit.

If sales are any indication, UK farmer interest in such a concept of tractor has been very limited. However, if sales of M B Tracs are examined, the German picture looks rather different. In 1981, 9900 units were produced of which 5320 were exported and, in 1982, 13,200 units of which 7555 were exported. Obviously, German farmers like this concept of tractor.

It would seem that the 'system tractor' has much to offer towards solving the utilisation problem but is unlikely to increase in popularity in the UK, unless a major manufacturer produces and markets this type of tractor in volume.

Another area where new product development seems necessary is farm transport. A significant number of tractors spend half their working lives on this job. They travel slowly and would be uncomfortable and illegal at 'normal' transport speeds. With heavy, unbraked trailers travelling downhill, many tractors are unstoppable. How long can farmers have special rules which can only be considered as unfair and anti-social to other road users? How long before a manufacturer rectifies these problems? The Trantor seems to be the only step in the right direction in the UK. In the USA and Canada, large numbers of 1–1½ tonne pick-up trucks, often with fifth wheel trailer capacity, are frequently used in the farm transport operation.

Choosing tractors

A wide variety of choice in traditional tractor models is available to the UK farmer, the majority being produced by the 'multi-nationals'. Most manufacturers offer a range of sizes, in two and four wheel drive, with variations available on a standard specification, for instance, live and independent pto, cross or radial ply tyres, pick-up hitches, spool valves, etc. Experience suggests that, by and large, these machines are well tried and tested products, with similar technical specifications and reliability. They should be, since development has taken place over a very long time and the

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Dave Jewett is Head of the Department of Engineering at Seale Hayne College

original Harry Ferguson patents have run out. A lot of user experience has been gained with disc brakes, independent pto, power steering, etc which has effected design modifications over a period of time.

How then does the farmer choose which to have, assuming he knows the power category he is looking for? Often he comes to the conclusion that annual costs will be similar between the available choices. The proximity of a dealer and the service for repairs and spares that he can offer must be important. The discount being given, trade-in allowance, availability of cheap finance and the matching to existing equipment are some of the factors which are likely to have a big influence on his final decision. The basic mistake which seems to be made most frequently is to assume that annual costs for a similar powered tractor will be similar, whether the machine is red, blue, white, green, brown or orange.

Traditional methods of costing tractors are the ones used by accountants, farm management advisers, *et al*, based on reasonable assumptions for depreciation over X years, plus repairs at Y% of original cost plus fuel at N p/litre and M litres/hour, etc. A more realistic approach, when trying to arrive at the correct decision of "which tractor?", is to look at actual or actual historic costs.

The major items of cost are depreciation, interest, fuel and replacement parts. Variations between makes of tractor in maintenance costs, ie tyres, batteries, filters, lubricating oil and the labour to do the jobs are likely to be very small, as is the case with tax and insurance charges. One can almost consider these latter items as a standard cost, independent of manufacturer. Assuming the amount of money spent on a tractor is similar, interest charges will also be similar. The cost items that are likely to be 'variable' are, therefore, depreciation, fuel costs and specialist replacement parts. These are considered below.

Depreciation

It is only possible to get an accurate measure of the real cost for depreciation by taking actual second hand values of tractors and it is only when tractors are some 4 or 5 years old that the information is sufficiently reliable to be a true measure. Table 1 shows that the percentage depreciation may not mean an excessively high annual depreciation charge if the tractor was very cheap in the first place, ie the Zetor compares well with the Massey Ferguson and Ford for annual depreciation charges. Obviously, if interest charges are taken into account at the original selling price, the Zetor figure looks good, even though it shows the highest percentage of depreciation.

It is important to note from table 1 that if you bought one of the tractors shown in the 30-39 kW range in 1976 and sold it in 1982, it might have cost as much as £3,980 in depreciation or as little as £1,955.

Fuel Consumption

Much has been made of low specific fuel consumption by some tractor salesmen in recent years, and rightly so! Bodies like the Royal Agricultural Society of England and the National Institute of Agricultural Engineering have been very good at compiling and distributing information from OECD test reports to inform farmers about tractor performance in this area (RASE 1982). However, the data disseminated is technical and not financial.

It is possible to convert with a reasonable degree of accuracy from one to the other, as long as it is appreciated that tractors only work on average at 35-40% of maximum power. As mentioned earlier, some work carried out (ADAS 1972) confirms that this occurs and calculations from records of total fuel used against total recorded proofmeter hours of tractors used on

Table 1 Rates of depreciation of tractors in the 30-39 kW range, as grouped by the Royal Agricultural Society of England Tractor Test Results, 1981

Make and model	*Year of manufacture*	*Original list price, £*	*1982 resale price*, £*	*Annual depreciation rate, £*	*Depreciation, %*
Ford 4600	1976	4,967	2,560	402	48.5
	1977	6,178	3,045	626	50.8
IH 534	1976	5,073	1,500	595	70.5
	1977	5,913	2,020	778	65.9
Leyland 262	1976	5,122	1,795	555	65
	1977	5,845	1,850	799	68.4
MF 565	1976	4,920	2,965	326	40
	1977	6,268	3,060	641	52
Zetor 6911/	1976	3,300	870	405	73.6
6718	1977	3,954	1,105	570	72
David Brown	1976	4,429	1,710	453	61.4
995	1977	5,625	2,315	662	58.8
John Deere	1976	6,180	2,200	663	64.4
2030	1977	7,130	3,100	806	56.5

**Source of resale prices: British Agricultural and Garden Machinery Association Market Guide to Used Farm Tractors and Machinery, November 1982 – previous adjusted averages (Tyndall 1983).*

Table 2 The costs of fuel of tractors worked for the equivalent of four hundred and six hundred hours per annum at max power at pto speed 540 rev/min.

		Annual use of 400h		*Annual use of 600h*	
Make and model	*Max power rating,* kW*	*Fuel cost per year, £*	*Fuel cost per year per kW of max power, £*	*Fuel cost per year, £*	*Fuel cost per year per kW of max power, £*
30-39 kW					
John Deere 1630	33.8	913.80	27.00	1370.70	40.50
Fiat 480	32.6	814.50	25.00	1221.75	37.50
Ford 4100	30.5	872.20	28.60	1308.30	42.90
IH 584	36.2	992.80	27.40	1489.20	41.10
Leyland 262	39.5	1125.70	28.50	1688.50	42.75
MF 265	42.2	988.50	23.40	1482.75	35.10
Same 60.2RM	39.1	984.60	25.20	1476.90	37.80
Zetor 6911	40.8	1071.20	26.25	1606.80	39.40
40-49 kW					
David Brown 1390	43.8	1145.70	26.20	1718.50	39.30
Fiat 780	47.7	1219.80	25.60	1829.70	38.40
Ford 6600	49.4	1311.40	26.50	1967.10	39.75
IH 784	45.6	1203.20	26.40	1804.80	39.60
Leyland 272	44	1327.00	30.20	1990.50	45.30
MF 590	48.1	1291.00	26.80	1936.50	40.20
Zetor 7011	41.5	1057.20	25.50	1585.80	38.25
Deutz D720S	46.9	1144.40	24.40	1716.50	36.60
50-69 kW					
Fiat 880	53.9	1325.70	24.60	1988.50	36.90
Ford 7600	60.8	1677.50	27.40	2501.20	41.10
John Deere 3140	67.3	1852.30	27.50	2778.50	41.25
IH 955	59.6	1512.40	25.40	2268.60	38.10
David Brown 1690	64.7	1739.10	26.80	2608.70	40.20
Zetor 8045	55.4	1524.80	27.50	2287.20	41.25
Same Panther	55.8	1546.70	27.70	2320.00	41.55

**Power range groupings as per Royal Agricultural Society of England Tractor Test Results, 1981 & 1982 (Tyndall 1983)*

Seale-Hayne College farm also act as confirmation.

Fuel costs in table 2 are calculated on the assumption of two levels of annual use, 1000 proofmeter hours and 1500 proofmeter hours. The annual use of 1000 hours is considered to be typical for fairly new tractors and 1500 might be true of some hard worked tractors on arable farms and certainly not uncommon for the tractors of an agricultural contractor. It is assumed these tractors work on average at 40% of maximum pto power at 540 rev/min or the equivalent of 400 and 600 hours, respectively at this level of power output, when calculating total fuel consumed in a year.

The specific volume of 35 sec Gas Oil is 1.22 litre/kg at 15°C. A price of 20 p/litre is assumed for this fuel in these calculations. Taking maximum pto power at 540 rev/min and multiplying by the appropriate number of hours, 400 or 600, gives the number of kW h per annum. By multiplying by specific fuel consumption, fuel usage in kg is predicted. Multiplying by 1.22 gives the volume in litres and, by price per litre, the total annual cost. The results of such calculations shown in table 2 indicate that, in the 30–39 kW category at the equivalent of 400 hours at maximum power, the best to worst is £814.50 to £1125.7 or a difference of £311 per annum.

This is not, however, a strictly fair comparison as the tractors concerned are of different power outputs. By dividing total fuel costs by maximum pto power at 540 rev/min or omitting this figure from the original calculation, you arrive at the cost of fuel per kW of power per annum for the equivalent of 400 or 600 hours as shown in the table. This figure is probably a more accurate guide from which to work.

If we assume an average tractor of 45 kW in the 40–49 kW range, best to worst is from £24.4/kW to £30.2/kW per year, a difference of £5.8/kW or £5.8 × 45 = £261 per annum at 1000 hours proofmeter reading, or 26p per proofmeter hour difference in fuel cost.

As can be seen from the tables, considerable differences exist between tractors and, equally, the more powerful the tractor and the more it is used, the more important this consideration becomes.

Replacement parts

Replacement parts normally form a minor proportion of a tractor's total running costs compared to other items. To make comparisons of cost on an annual basis is difficult, since knowledge of how frequently radiators, wheel centres, silencers, etc need to be changed is limited. There are however significant variations in the prices of spare parts, tables 3 and 4. Obviously as tractors get older, more spare parts are likely to be required. It could be argued that depreciation is less important in a farm situation where tractors are run until they are scrapped. In those circumstances, the price of spares, however, must be rather more important.

It can be seen, when consideration is made of the 'variable' elements of depreciation, fuel cost and replacement parts, that significant differences in cost can arise when owning different coloured tractors of similar power and it is suggested that this should be given much more thought when farmers are making a decision to buy either a new or second hand tractor.

Choice of self propelled machines — particularly combines

An examination of this area of the Agricultural Engineering market place quickly shows that they are almost exclusively imported machines and probably some 30–40% of the total agricultural machinery imports to the UK (DOI 1978). This sector is dominated by the multi-nationals and two major European producers who manufacture outside the UK; these companies have extensive production facilities and more than adequate capacity and marketing resources which effectively discourage entrants. Again, as with tractors, this means it is likely to be very difficult to get major changes in design concept accepted.

Once again, Agricultural Economists will argue that farmers have too many of these machines already. Total combine numbers (HMSO 1982) for the UK are approximately 55,400 to harvest some 4,150,000 hectares or 75 hectares each. However, an examination of combines sold, during the last 10 years, and reasonable estimates of the amount of work we could expect them to do, indicate a total capacity of 4,156,785 hectares. In other words, the reserve capacity that is available for combining is in machines more than 10 years old, of which there would appear to be about 26,500, assuming no machines less than 10 years old have been scrapped.

The above calculation assumes that, on average over the country, there will only be some 150 hours of good combining weather per year whilst crops are ripe to be harvested, thus 10 year old combines will only have worked for some 1500 hours. This may well mean that the harvesting/processing part of the machine is significantly worn. However, what of the chassis, engine, transmission, cab, hydraulic components and controls which probably represent some two thirds of the capital cost of the machine? Most of the engines used are ones from which approximately 10,000 hours of life could be reasonably expected with correct care and maintenance.

An examination of major design parameters of other self propelled machines used in Agriculture for grass and root harvesting, such as engine size, wheel base, speed range, auxiliary power sources, cabs and hydraulic services, show great similarity with the combine. Can the specialist harvesting equipment for various operations not be fitted to a standard power unit? In addition, could this base power unit not be used for other agricultural operations, for instance spraying (with front mounted boom and large capacity tank carried in middle of the chassis) or with a cultivator at front and a drill behind?

Table 3 Abbreviated table showing spare part prices of the selected tractors (Hollinshead 1981)

Tractor make & model	*Power, kW*	*Radiator price, £*	*Fuel Pump price, £*	*Fan belt price, £*	*Total price, £*
Fiat 880	66	163.00	225.80	3.01	391.81
Leyland 802	61	104.75	243.00	5.23	352.98
Zetor 8011	63	104.40	298.25	1.50	404.15
David Brown 1490	62	204.74	330.27	1.65	536.66
MF 590	59	75.36	208.00	3.21	286.57
IH 884	61	165.21	592.92	3.40	761.53
Ford 6600	58	177.75	523.59	3.43	704.77

Table 4 Part prices of selected tractors, accurate as on December 6th, 1982

*Tractor make & model**	*Radiator price, £*	*Silencer price, £*	*Rear Wheel centre (12 × 36) price, £*	*Total price, £*
30–39 kW				
Ford 4600	186.64	25.50	111.31	323.55
Fiat 450	152.59	40.78	109.20	302.57
IH 584	256.77	39.78	83.73	380.28
MF 565	86.00	37.40	119.00	242.40
40–49 kW				
David Brown 1390	193.55	40.29	126.77	360.61
Fiat 780	203.67	55.66	159.35	418.68
Ford 6600	186.64	25.60	111.31	323.55
IH 784	256.77	39.78	155.75	452.30
MF 590	87.00	37.40	119.00	243.40
50–69 kW				
David Brown 1690	244.96	52.80	133.97	431.73
Fiat 880	203.67	72.25	143.92	419.84
Ford 7600	186.64	45.32	125.16	357.12
IH 955	418.17	72.91	211.06	702.14

**Tractors are grouped by power rating as per Royal Agricultural Society of England Tractor Test Results 1981 & 1982.*

Machines to suit these requirements have been successfully marketed and used in other parts of the world. Unfortunately, it seems we cannot easily obtain machines of this type in this country, designed to meet the needs of European environments and work loads, at a price the market can stand.

There has been interest in recent years in whole crop harvesting of cereals and work done in Sweden has been well publicised (Lucas 1983). It is of interest to note that the machine developed by Scandinavian Farming AB, the SF 80, is designed as a multi-purpose tool carrier, along the lines previously described. However, it is a large capacity machine expected to cost some £90,000 for the base unit using a 236 kW engine. Surely, there must be a place for something smaller which has a multi-purpose use.

One might ask the questions: "How long can the existing situation continue?" and "Is it really economic to buy a new combine every 5 years and what does it actually cost to do so?" The answer to the last is probably in excess of £40/hectare plus fuel and labour. Could this be afforded at current world prices for cereals? Certainly at present it does not look as though American and Canadian farmers can.

The conclusion on self propelled machines would seem to be that the major companies, selling in the UK but manufacturing outside it, are making available machines which are for specialist use only. Much more attractive concepts of machines seem possible but the UK farmer has no opportunity to buy. Consequently, the choice would seem to be wrong but no real alternative presents itself at the moment.

References

ADAS (1972). Wheeled and tracklaying tractors. A joint ADAS/NIAE study of utilisation, performance and tyre and track costs 1969–70. Farm Mechanisation Studies No 21 Min Agric Fish Food.

DOI (1978). The Agricultural Engineering Industry. A Department Industry Study, February.

HMSO (1982). Agricultural statistics, United Kingdom, 1980 & 1981.

Hollinshead P (1981). Tractor spares — value for money or rip-off *Livestock Farming*, April p 50–52.

Lucas N G (1983). Hydrostatic tool carrier is harvester base unit. *Power Farming*, Jan, pp 12–15.

Massey Ferguson (1983). Private communication.

Matthews J (1983). Private communication. Nat Inst agric Engng, Silsoe, Beds.

RASE (1981). Tractor test results 1981. A summary of OECD and Nebraska tractor test reports. Royal agric Soc Eng, Stoneleigh, Coventry.

RASE (1982). Tractor test results 1982. A summary of OECD and Nebraska tractor reports. Royal agric Soc Eng, Stoneleigh, Coventry.

Tyndall A W H (1983). A study of the economics of selecting tractors on their major costs. Higher Nat Diploma Special Study, Seale Hayne College, Newton Abbot.

Edited summary of discussion concluded

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Questions following Paper 6, (D W Jewett — The mechanisation muddle, which way forward?)

Mr D Tapp (Freelance Engineer)

Q Does Mr Jewett think that, by using specific fuel consumption figure derived from pto power tests, he made a really fair comparison? Why not also use drawbar test fuel consumption figures as some tractors give more economic fuel use from drawbar tests while others from pto tests?

A *Pto fuel consumption figures were more readily available than drawbar figures, as the former were quoted in the Royal Agricultural Society of England booklet. OECD test reports were required for both sets of figures and these were harder to obtain. Nevertheless, the relevance of the questioner's criticism is acknowledged.*

General discussion questions

Dr P A Cowell (National College of Agricultural Engineering)

Q At present, potential tractor work rate is being increased by developing larger powered tractors to pull wider implements. This results in a weight penalty with the ensuing deeper compaction levels in soils. Alternatively, increased work rate could be obtained by using higher forward speeds with tractors fitted with suspension systems. This method results in problems with implement depth control. Would each one of the speakers like to comment on the way he thinks that tractor development should proceed?

A *Mr Jewett stated that "we should still proceed, in the immediate future, with fixed axles. There is still a great deal of opportunity to improve tractor utilisation as the present average tractor utilisation figure is comparatively low."*

Dr Crolla argued that suspension would not necessarily create greater problems of implement control since the present day tractor was hardly a stable platform. However, his view was that there will be a move away from the type of tractor used as a "jack-of-all-trades" to vehicles of a more specialised nature.

Dr Witney replied that he was concerned at the increasing weight of tractors on 4 wheels giving more and deeper compaction. One answer was to fit the higher powered tractors (ie the heavier ones) with 3 axles and six wheels, perhaps all being driven.

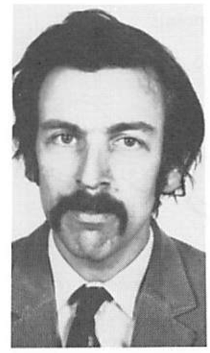
Dr Dwyer did not think things were quite as bad as Mr Cowell feared. At present we can transmit 60 kW per axle, and this can virtually be doubled by fitting dual wheels. Increasing speed around our present ranges was unlikely to cause excessive problems he felt. He also anticipated a move toward more specialist vehicles, particularly for transport, but with the continued support of the existing multipurpose tractor.

Mr Withers considered that the future market for UK manufacturers was for specialised tractors. It was apparent now that the conventional tractor can be made abroad (as in Eastern Europe) much cheaper than in the UK.

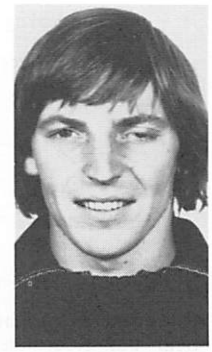
We had an industry with a high technical base and best use of this would be made with the production of more specialist vehicles. He did not think that the problem of implement depth control on a tractor with suspension would be solved in the immediate future but there was no doubt that a solution would be found in the longer term.

Whole crop harvesting of cereals in Scotland

JEL Boyd and A Longmuir



John Boyd



Sandy Longmuir

Summary

A DIRECT cut, precision chop, forage harvester was used to cut and thresh barley with grain moisture contents of up to 41.5%. The disc cutting mechanism caused some grain loss from the header. Serious leakage of grain from the harvester was cured by fitting additional steel plates under the feed and chopping mechanisms.

Density of the chopped whole crop material in trailers was 94–153 kg/m^3. Losses of light material occurred when the whole crop was blown into silage trailers in windy conditions.

Whole crop barley was separated into grain and material-other-than-grain in a horizontal wind tunnel, using air speeds of 8–11 m/s. Reduced air speeds and a secondary separate device would be needed to produce clean grain samples without excessive grain loss.

The labour requirement and the work output per season should be similar to those for a combine and baler system.

Introduction

This report describes the progress in an ongoing project at the North of Scotland College of Agriculture on whole crop harvesting of mature cereals as an alternative to combine harvesting. Methods and equipment for whole crop harvesting on an industrial scale have received considerable publicity (Lucas 1978, 1982, 1983). A farm-scale approach investigated at Nottingham University (Wilton *et al* 1980) showed that cereals could be cut and threshed with a modified forage harvester and separated before drying using a horizontal wind tunnel. By comparison with conventional methods, this system should:

- allow harvesting to start earlier in the year and continue in most weather conditions;
- reduce grain losses by harvesting before shedding becomes serious;
- be able to work efficiently on sloping ground;
- clear fields quickly in one operation;
- collect the light fraction of material-other-than-grain which the combine and baler cannot recover;
- use cheaper equipment;
- use equipment already employed for harvesting other crops.

The object of the project is to find out whether these apparent advantages are likely to be obtained in practice on a farm scale and to develop the equipment nearer to a stage suitable for commercial application.

Harvesting

The forage harvester being used by the North of Scotland College of Agriculture is a conventional trailed precision chop type with two pairs of feed rolls and a cut-and-throw cylinder. It was supplied with one of the standard header options, having a 2.4 metre wide, 6-disc, direct cutting mechanism. However, a special combine-type pick up reel was fitted in place of the standard 4-bat grass reel.

A tractor with a rated pto power output of 49 kW has been able to pull this harvester and an 8.5 m^3 trailer in level fields of barley at either 3.7 km/h or 4.9 km/h, depending on crop density. This equates to spot work rates of 0.9–1.2 ha/h.

There have been no blockages or mechanical problems with the disc cutting mechanism but there has been appreciable loss of single grains, especially with more mature crops. Probably, the cut stalks fall so that some of the heads contact the rear of the discs, where kernels are threshed out and spun off as from a fertilizer spreader. The tractor driver and bystanders have been hit by flying grains. Various simple modifications were tried out in order to reduce this grain loss, but with limited success. No doubt, the discs would be well suited for whole crop cereals harvested green for silage but, for mature crops, a reciprocating knife is probably required. This might be cheaper and use less power than the discs.

As supplied, the harvester's header was designed to 'float', with skids controlling the stubble length. The skids were satisfactory when moving across the rows of barley but, when the harvester travelled along the rows, the skids tended to 'bulldoze' and earth and stones entered the machine. Height control by skids was clearly unsatisfactory for cereals, so independent hydraulic control of the cutting height from the tractor seat was fitted.

This entry of stones into the machine showed up a limitation of the standard forage harvester for cutting cereals. With a self-propelled combine, the driver often sees a stone while it is still on the header; there is time to take action while it is travelling up the feed elevator and before it reaches the threshing cylinder; and there is usually a stone trap. None of these applies to a trailed forage harvester. There are various possible approaches to stone damage protection. A stone trap could perhaps be fitted. An instant feed roll stop would help if the driver saw a stone on the header, but the pillars of a tractor safety cab often block the view of the cutter bar. Possibly, stones among grain could be detected in the same way that stones in potatoes are detected by X-ray sensors. The acoustic stone and metal detection system under development at the National Institute of Agricultural Engineering (Klinner and Wood 1981) might be suitable. This aspect of whole crop harvesting needs further study.

As soon as harvesting began, it was obvious that large quantities of grain were falling to the ground along the line of the feed and chopping mechanism. Most fell through a large gap between the header auger and the front lower feed roll. Grass silage would still be long material at this point, but barley at 40% moisture content is partly threshed on the header and grains fell through the gap. A steel plate was made to fit over this gap. Another stream of grain fell through between the front and rear lower feed rolls. The front roll on this machine is fluted and acts like the metering mechanism of a grain drill, sending any threshed grains onto the ground. This second source of loss was cured by fitting a plate closely round the front lower feed roll so that grain falling through was carried round and returned to the header. The third source of leakage, a small gap below the chopping cylinder, was easily stopped by means of a steel plate (fig 1). Similar modifications would probably be needed for most of the forage harvesters on the market.

This system of harvesting relies on the forage harvester to thresh the crop. With a nominal chop length of 19 mm, barley has always been completely threshed, the forage harvester being particularly effective at removing all awns. Increasing the nominal chop length to 38 mm produced a lot of unthreshed heads, even

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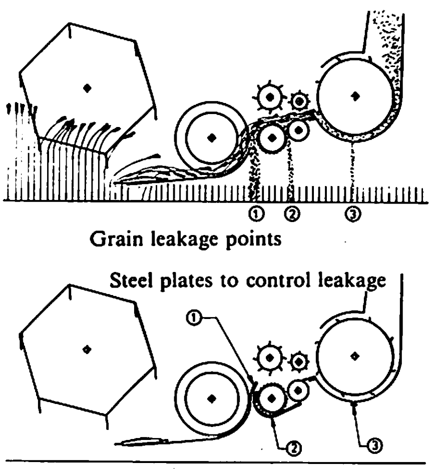


Fig 1 Grain leakage from forage harvester

with a dry crop. The cylinder speed and shear bar clearance have always been kept at the settings recommended by the manufacturer for silage. By varying these, it might be possible to improve the performance of the harvester in mature cereals.

Clearly the precision chop forage harvester is a suitable basis for a whole crop cereal harvesting system, but it seems that the available machines would need some modifications. However, most are minor changes, which could be easily incorporated during manufacture.

Transport

It has not proved easy to throw dry whole crop material into the available silage trailer, an 8.5 m^3 model with sheet steel sides and hessian-lined rear door. On windy days, a lot of light material was lost. To minimise these losses it was necessary to pull the trailer in line behind the harvester. Loads weighed from 800 kg to 1300 kg depending on moisture content, giving densities of 94–153 kg/m^3. An average load held the crop from 0.1 ha of barley.

To avoid losses and increase load sizes, the trailer would need a high mesh canopy. A typical farm trailer with a 3.5 x 2.0 m floor, but with a 2.2 m high canopy, should be able to hold the crop from 0.18 ha of barley. It is assumed that the travel speed of the trailer is 12 km/h, that the field changeover time is one minute and that it takes three minutes to discharge the load and turn round at the steading, then two such trailers should allow harvesting at over 0.75 ha/h in fields 1000 m from the steading.

A high mesh canopy and a grain-tight rear door should add only a little to the cost of an existing silage trailer.

By comparison with combine harvesting and burning the straw, whole crop harvesting will mean more wheel tracks over the field, perhaps in wetter soil conditions, but with lighter machines. However, if straw from the combine is baled and carted away, the tracking may be as great as with whole crop harvesting.

Separation

The whole crop separator developed by Nottingham University on the principle of a horizontal wind tunnel has been described in this Journal (Wilton *et al* 1980). The Nottingham equipment was acquired by the North of Scotland College of Agriculture in 1981 and reassembled in a modified form. It was fed from a silage dump box and a belt elevator and it was immediately apparent that the feed was too uneven. In the wind tunnel, any lumps of damp, chopped straw behaved like grains and fell down through the grain outlet. More uniform feed was obtained by increasing the speed of the belt elevator and fitting a rotating spreader above the wind tunnel, which resulted in improved separation.

Short pieces of straw among the grain were impossible to eliminate. An oscillating sieve cleaner under the grain outlet was tried, but the straws 'up-ended' and fell through the holes. However, a second pass through the wind tunnel was successful at removing many of the remaining straws. By the end of the 1981 season, with Golden Promise spring barley at around 18% grain moisture content, throughput of a 200 mm wide wind tunnel was about 1 t/h of grain.

The experience of the 1981 harvest showed that the unseparated whole crop material was very bulky and that if left overnight it heated and became lumpy, leading to poor separation. Clearly, a farm-scale separator would have to keep pace with the harvester. The wind tunnel itself performed well; the problems were in materials handling — how to get the whole crop into the wind tunnel and the separated fractions out. For simplicity, it was proposed in future to attempt only two-way separation into grain and material-other-than-grain (MOG) and not to collect the heavy and light straw fractions separately.

The approach for 1982 was to remove the cross belt conveyor from the dump box and let the crop, teased out by the beaters, fall directly into a wind tunnel of the same width as the dump box. Grain was removed from the bottom of the wind tunnel by an auger and elevator. A paddle blade fan was used to suck air through the wind tunnel. No attempt was made to remove the MOG from the air stream and then convey it mechanically — it passed through the fan and was blown directly to the store. This arrangement gave a wind tunnel about 10 times the width of the 1981 model, with much simplified materials handling (fig 2).

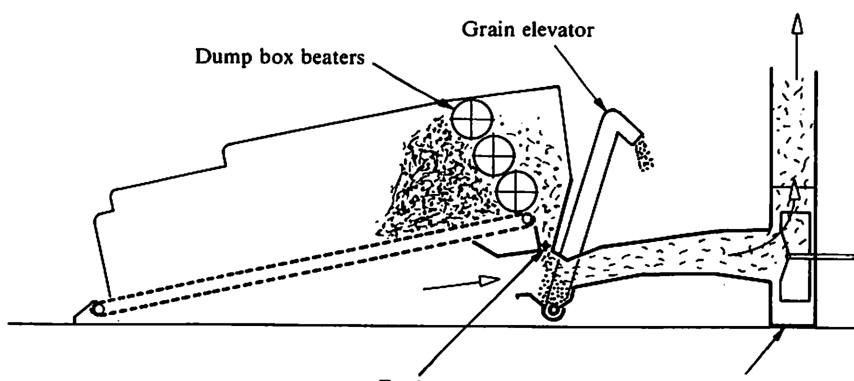
The Scottish Institute of Agricultural Engineering found that short straws could be removed from grain more easily if the crop was fed in through a pair of contra-rotating rollers, ensuring that all straws fell at right angles to the air stream (Hamilton and Butson 1978). For this reason, rubber-covered feed rolls were fitted to the North of Scotland College of Agriculture 1982 separator, though these had to be abandoned after a few trials owing to problems with the particular components used. Separation was poor after the rollers had been removed, some form of positive feed into the wind tunnel being necessary. No alternative contra-rotating rolls were available at the time, so a single feed roller with four rubber blades was fitted and used for the rest of the season.

Performance of the separator in this form was tested by varying the air speed and the throughput and by measuring the grain loss and the amount of MOG left in the grain. Air speed was controlled by adjusting the fan shaft speed. Throughput of crop was altered by changing the dump box bed speed. However, throughput was also dependent on the height of crop in the dump box and could not be replicated exactly. The duct carrying MOG into storage was modified so that its output could be caught in a large bag. The output from the grain spout was collected for corresponding periods. A small grain cleaner having two sieves and single aspiration was used to separate each sample completely into grain and MOG for analysis, this often requiring several passes through the cleaner.

As expected, high air speeds produced relatively clean samples of grain, but with unacceptably high losses. At low air speeds the losses were reduced, but the grain more contaminated. Results obtained with Triumph spring barley, harvested at 29.5% and 36.5% grain moisture content, are shown in fig 3. Three test runs were made with Golden Promise spring barley, which had a higher grain: straw ratio and was much drier (20.5% grain moisture content) than Triumph, though harvested only one day later. With Golden Promise, the grain losses were all under 4% and the MOG contamination in the grain was below 2%, while maximum grain throughput was 3.4 tonnes dry matter per hour.

Throughput had no clearly discernible effect on either the amount of grain lost among the MOG or on the amount of MOG left in the grain. This *may* indicate that the throughputs achieved were never high enough to affect the performance of the separator. Mechanical problems with the dump box and the grain conveying

Fig 2 Section through separator



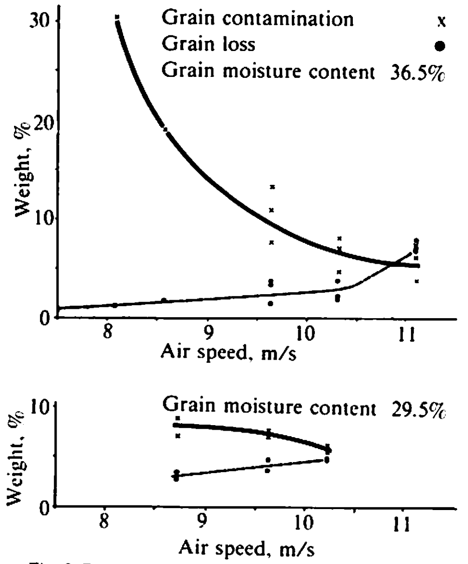


Fig 3 Separator performance for Triumph spring barley at two different grain moisture contents

equipment imposed the limitations on rate of throughput.

The levels of grain loss recorded in these tests would probably not be acceptable commercially and it is clear that lower air speeds would have to be used. To obtain reasonably clean grain samples with lower air speeds, some form of secondary separation would be needed. A modified separator is being constructed for the 1983 season and this would allow the effects of faster throughput, lower air speeds and secondary equipment to be tested.

Grain damage

Grain samples have been analysed to see how the whole crop harvesting system has affected damage levels. Golden Promise barley, harvested at under 20% grain moisture content and separated in two passes through the 1981 equipment, consisted of (Powell and Matthews 1981):

	% by weight
Whole seed — undamaged	32.3
" " — slightly damaged	53.0
" " — damaged	11.9
Half split seed	2.6
Inert material	0.2
Total	100.0

Triumph barley, harvested in 1982 at 22.8% to 41.5% grain moisture content, appeared to contain more broken grains. In one set of samples at 29.5% and 36.5% moisture content, 6% by weight of the grain output was broken grains, while 10% of the grain lost among the MOG was broken.

More detailed studies are being undertaken to assess damage levels, germination and seed vigour as affected by whole crop harvesting. Preliminary work indicates that the moisture content at harvest has little effect on the incidence and severity of visible damage to the grain, and that seeds at up to 30% harvest moisture content retain high germination and vigour.

Treatment of the separated fractions

With a whole crop harvesting system, grain can be cut at high moisture contents. This would not be well suited to in-bin or on-floor drying, but many continuous flow and batch driers can handle high moisture grain. Moreover, there is no compulsion to harvest at high moisture content, and nothing to stop the farmer cutting his crops at the same moisture content as with a combine. Work at Nottingham has shown how the MOG from whole crop harvesting can be used to dry the grain. Grain for stock feed can be preserved, without drying, in airtight storage or with chemical treatment (eg caustic soda or propionic acid).

Straw from crops harvested in dry conditions could be stored without treatment. The wetter straw might be ensiled, but chemical treatment would seem ideal for straw to be fed to ruminants. Caustic soda is well known for its ability to improve straw digestibility and has the added advantage of causing the bulky chopped straw to shrink rapidly. However, it is rather dangerous to handle. Ammonia and urea will also be considered for straw treatment in connection with whole crop harvesting at the North of Scotland College of Agriculture, as they appear to work well with damp straw.

System output

Experience has shown that whole crop harvesting is feasible at grain moisture contents up to 40% and in most weather conditions. There seems little doubt that harvesting could start on average two to three weeks before combining, giving an extended season with a predictable working week of 50 hours or more. If whole crop harvesting can indeed be carried out for 50 hours per week at 0.6 ha/h (that is an overall rate about half of the measured spot work rate) then the system output can be 30 ha/wk, which equals that of a small combine (SAC 1982). With a bigger tractor and skilled operators, the weekly output might be increased towards the 45 ha achieved by large combines. Using the extended season, the system capacity should certainly equal that of the combine.

Labour requirements

If the whole crop harvesting system operates at 0.6 ha/h with two drivers, then 3.33 man hours are needed to bring grain and MOG from 1 ha to the steading.

For a conventional system, taking the fastest output times for a large combine from the Scottish Agricultural Colleges' Farm Management Handbook, the work rate would be 1.55 ha/h, thus using 1.29 man hours per hectare for a combine driver and a trailer driver. Taking straw handling data from the same source, the method with the least labour input (making big round bales and carrying them, three at a time, on a trailer) adds another 2.06 man hours per hectare, if it is assumed that 3.5 t/ha of straw are handled. This gives a total of 3.35 man hours to bring grain and straw from 1 ha to the steading.

Thus, *on paper*, the labour requirements for whole crop harvesting appear to be the same as for a conventional system using a large combine and baler. The actual labour needed would depend also on whether the separator had to be supervised and, if so, whether this could be done by the grain drier operator.

Future work

To date, the whole crop system at the North of Scotland College of Agriculture has only been used to harvest a few hectares of barley. Future work is in progress to examine such practical questions as:

- can the harvesting rate be maintained in day-in, day-out operation;
- can a simple, reliable separator be made to perform adequately;
- how well can the system cope with other crops;
- will the grain damage levels impose more stringent storage conditions than usual;
- how can the material-other-than-grain best be handled, treated, stored and used?

References

Hamilton A J, Butson M J (1978). The pneumatic separation of grain from chaff and lights. Dep Note SIN/240, Scot Inst agric Engng, Penicuik (unpubl).

Klinner W E, Wood G M (1981). An experimental field rig for collecting forage crops and separating out stones and metal objects. Div Note DN 1054, Natn Inst agric Engng, Silsoe (unpubl).

Lucas N G (1978a). Whole crop harvesting — key to a whole new way of farming? *Power Farming*, 57, 8, 8–11.

Lucas N G (1978b). Whole crop harvesting/2. *Power Farming*, 57, 9, 8–11.

Lucas N G (1978c). Whole crop harvesting/3. *Power Farming*, 57, 10, 8–9.

Lucas N G (1982). Whole crop harvesting. 300 horsepower harvester ready to tackle cereal crops. *Power Farming*, 61, 12, 12–15.

Lucas N G (1983a). Whole crop harvesting. Hydrostatic tool-carrier is harvester base unit. *Power Farming*, 62, 1, 12–15.

Lucas N G (1983b). Whole crop harvesting. The next move. *Power Farming*, 62, 3, 26–29.

Powell A A, Matthew S (1981). Report on seed condition after whole crop harvesting of barley. Agricultural Botany Division, School of Agriculture, Aberdeen (unpubl).

SAC (1982). Farm Management Handbook 1982/83. The Scottish Agricultural Colleges.

Wilton B, Amini F, Randjbar I (1980). Whole crop cereals: a low-cost approach. *Agric Engr*, 35, 7–10.