The Mechanics of

Tractor - Implement Performance

Theory and Worked Examples

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CHAPTER 5

TRACTOR PERFORMANCE ON SOFT SOIL - EMPIRICAL

CONTENTS

Note: The Title Page, Preface, Table of Contents, Index, Appendices and details of the Farmland tractor can be found with Chapter 1.

CHAPTER 5

TRACTOR PERFORMANCE ON SOFT SURFACE - EMPIRICAL

5.1 INTRODUCTION

5.1.1 General

In Chapter 3 we considered the experimental evaluation of the 'ideal' performance of the tractor in terms of the engine and the tractor operating in various gears on a firm surface. While this shows the influence of those elements and is valuable for comparative purposes, it is of limited use in showing the performance on soft surfaces or for predictive purposes.

In Chapter 4 we considered the theoretical analysis which is conceptually correct in the way that it calculates the performance of the tractor as determined by the capacity of the surface to generate a reaction. However this approach has two difficulties associated with the measurement of the surface properties.

Firstly, it requires the measurement of six properties of the soil; three (cohesion, angle of internal friction and the deformation modulus) for the prediction of the tractive force and a further three (two sinkage moduli and an exponent) for the prediction of the rolling resistance. These require complex facilities and are likely to be time consuming if representative samples of the properties over an area are to be obtained.

Secondly, in general, agricultural soils are in a structured state in which the bonds between the soil aggregates are intact. Prediction of tractor performance in the field, based on the above properties, requires that the latter be measured with the soil in this undisturbed state. If the soil is disturbed during the sampling process for laboratory determination of the properties (as it is likely to be) the measured values of both cohesion and deformation modulus will be affected.

It is not possible to recreate undisturbed conditions in the laboratory after a soil has been disturbed and hence in-situ methods of measuring undisturbed soil properties have been developed (Baladi, 1987).

5.1.2 Empirical method

The alternative to experimental measurement or to a theoretical analysis that is adopted in many engineering fields is the so-called 'empirical' approach. This is based on a series of experiments that includes the major variables or groups of variables. From these a set of predictive equations is developed, often using techniques of dimensional analysis (Langhaar, 1978).

These equations can replace much experimental work, allow designs to be tried 'on the drawing board' and answer 'what if . . . .? ' questions. The designs and the answers are of course only as good as the choice of variables, the experimental data and the fit of the equations that are based on them.

The empirical approach (now frequently termed (computer) modelling) has proved to be useful in many complex engineering problems. It provides a ready and useful means of performance prediction for the tractor but it is not suitable as a basis for understanding the fundamentals of the processes involved. It has mainly been applied to the tractive processes but it may also include the engine and so provide a basis for predicting the performance for the tractor as a whole.

5.2 ENGINE PERFORMANCE MODELLING

Persson (1969) developed an equation for modelling engine performance based on power, speed, swept volume and heat value of the fuel, together with two constants estimated from the test data. However for an engine of given type and swept volume his equation can be reduced to the form given by Huynh and Brown (1981).

$$FC = A\,Q + B\,N^2 \qquad (5.1)$$

A and B are constants which can be determined if the fuel consumption, engine speed and power are known for two points on the performance characteristic for the engine.
With reference to the performance of the Farmland tractor as shown in Figures 3.2 and 3.3, consider two points on the performance characteristic at maximum governor setting as follows.

		Point 1	Point 2
Engine speed, N, rpm	=	2390	2250
Engine power, Q, kW	=	0	33.5
Fuel Consumption, FC, kg/hr	=	2.8	9.0

Substituting values for point 1 in Equation 5.1, gives

$$B = \frac{FC}{N^2} = \frac{2.8}{2390^2} = 4.9 \times 10^{-7}$$

Substituting values for point 2 in Equation 5.1, gives

$$A = \frac{FC - B\,N^2}{Q} = \frac{9.0 - 4.9 \times 10^{-7}\,(2250)^2}{33.5} = 0.19$$

Thus fuel consumption, $FC = 0.19\,Q + 4.9 \times 10^{-7}\,N^2$ (5.2)

Problem 5.1

Using Equation 5.2, estimate the fuel consumption for the Farmland tractor for engine power, Q = 15 kW and engine speed, N = 1600 rpm. Compare the answer with the measured value as shown in Figure 3.4.

For Q = 15 kW and N = 1600 rpm, from Equation 5.2,

$$FC = 0.19 \times 15 + 4.9 \times 10^{-7} \times 1600^2 = 2.85 + 1.25 = 4.1 \text{ kg/hr}$$

From the specific fuel consumption lines on Figure 3.4 for Q = 15 kW and N = 1600, SFC = 250 g/kWhr.

Measured FC = 250 x 15 = 3.8 kg/hr

The predicted value is within 8% of the measured value which is about the accuracy that can be expected with the empirical approach.

5.3 TRACTIVE PERFORMANCE MODELLING

5.3.1 Parameters

In the empirical prediction of tractive performance, only one soil parameter is measured for the prediction of both tractive force and rolling resistance. This parameter, known as the 'cone index', is not dependent on the measurement of deformation or sinkage as is required in the determination of the respective moduli in the theoretical approach.

Its measurement, being so simple, allows a rapid survey of the area of interest and incidentally reveals the great variability that frequently exists in both time and place, particularly due to the variation in soil texture and the effect of moisture content.

The development of the algorithms that constitute the tractive model requires an extensive series of measurements of cone index and corresponding tractor performance as reported by Frietag (1965), Wismer and Luth (1974), Gee-Clough et al (1978) and Parkhill (1986).

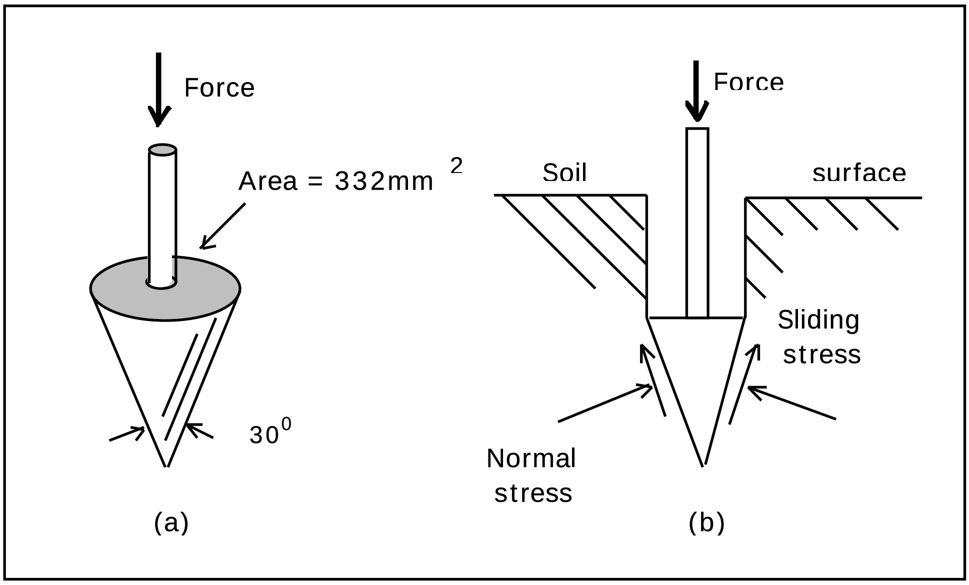


Figure 5.1: Cone penetrometer for measurement of soil parameter

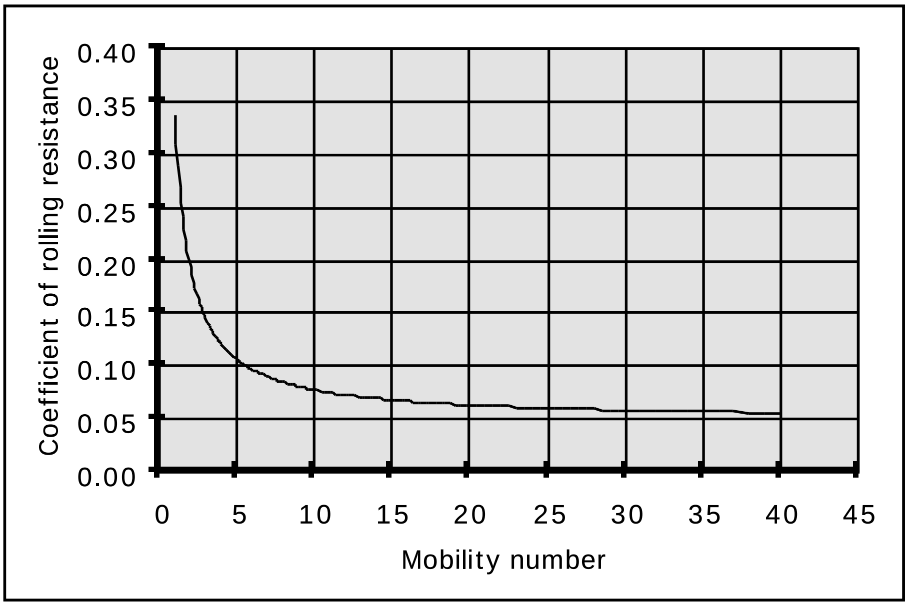


Figure 5.2: Variation of coefficient of rolling resistance with mobility number.

(a) Cone index

The soil parameter for empirical prediction of tractive performance is based on the force (kN) to push a circular cone (base area = 0.5 in^2; 322 mm^2) shown in Figure 5.1(a) into the soil at a constant speed of 72 in/min (30 mm/sec) (ASAE, 1998).

The parameter, termed the cone index is given by,

$$CI = \frac{\text{Force on cone}}{\text{Base area of the cone}} \quad \text{kPa} \tag{5.3}$$

The passage of the cone into the soil is resisted by the normal and soil - metal resistance forces as suggested in Figure 5.1(b). These in turn will depend on the strength and compressibility of the soil and soil / metal sliding characteristics of the cone surface all of which will depend on the soil texture, moisture content, etc.

The cone index does not therefore represent a soil 'property' as such but a complex and ill defined parameter or measure of soil 'strength' and deformability; it is assumed to be a correlate for tractive force and rolling resistance.

Typical values of cone index are given by Dwyer (1976) as shown in Table 5.1.

Surface Condition	**Cone Index, kPa**
Dry grassland	1500
Dry stubble	1000
Wet stubble	500
Dry loose soil	400
Wet loose soil	200

Table 5.1: Soil cone index for various surface conditions. Reproduced from Dwyer et al (1976) , with permission of Silsoe Research Institute.

The interesting aspect of this table is that it is based on:
(i) soil 'condition' as represented by the terms loose, stubble (implying moderately firm) and grassland (implying firm)
(ii) moisture condition as implied by the terms dry and wet

Soil texture is not specified because the above variables are seen to have the most significant effect on cone index.

(b) Mobility number

The early work on the empirical prediction of the performance of wheels on soft surfaces was carried out by Frietag (1965) in a military context. In this approach, dimensional analysis was used to effectively reduce the number of variables and so simplify the prediction equations.

This was applied to wheels on agricultural soils as reported by Wismer and Luth (1974) also Dwyer et al (1976). The latter authors used the cone index to calculate a dimensionless, tyre mobility number:

$$M = \frac{CI.b.d}{W}\sqrt{\frac{\delta}{h}}\,\frac{d}{d+0.5b} \tag{5.4}$$

where
M = mobility number
CI = cone index, kPa
W = weight on tyre, kN
b, d, h = tyre width, tyre diameter, tyre section height, m
δ = tyre deflection under weight W, m

They also established the empirical relationships (for soft surface conditions) between tyre mobility number and the performance parameters discussed in the following sections.

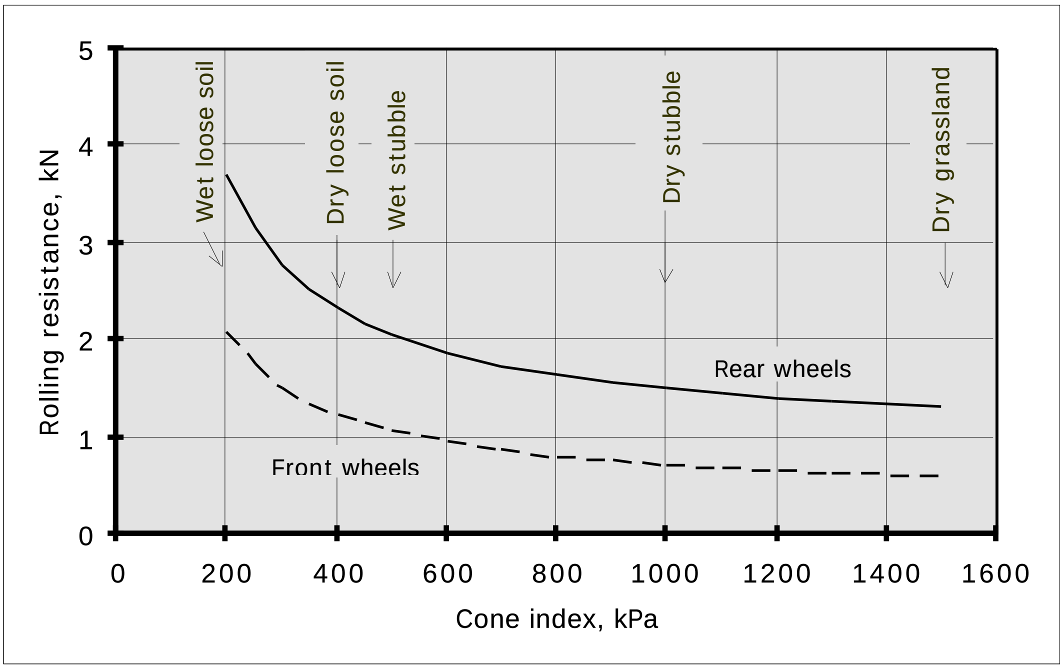


Figure 5.3: Effect of surface / soil condition on rolling resistance of wheels of the Farmland tractor.

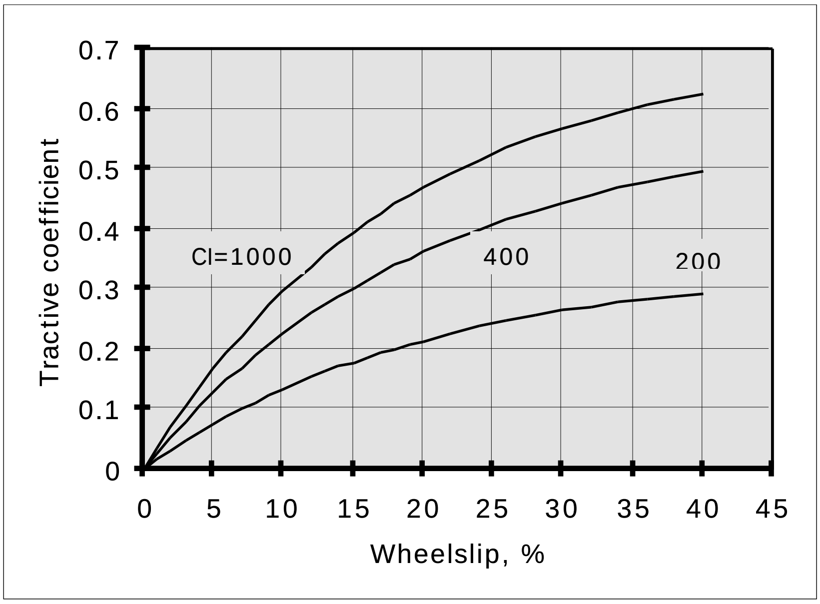


Figure 5.4: Variation of tractive coefficient with wheelslip for three surface conditions for the drive wheels of the Farmland tractor.

5.3.2 Prediction of performance measures

In the following sections the various measures of performance have been plotted for the range of cone index values over which the predictive equations apply. These range from 200 for loose wet soil to 1500 for dry firm grassland (Table 5.1). They are based on the mobility number using the static weights on the wheels in Equation 5.4; a second iteration based on the dynamic weight gave no significant difference in the results.

(a) Rolling resistance

The following equation was fitted to the rolling resistance data by Gee-Clough et al (1978).

$$\rho = 0.049 + \frac{0.287}{M} \qquad (5.5)$$

This is shown plotted in Figure 5.2 and shows how the coefficient increases significantly for small values of M (Equation 5.4) and hence for:

(i)	small values of CI	- soft surface
(ii)	small values of d	- small diameter tyre
(iii)	small values of b	- narrow tyre
(iv)	small values of δ/h	- stiff tyre
(v)	large values of W	- large weight

It also shows how the rolling resistance coefficient approaches a value of about 0.05 for firm surfaces (large values of M and hence of CI, d and b etc).

The rolling resistance is then calculated as the product of this coefficient and the dynamic weight on the tyre as discussed in Section 4.3.3

$$R = V\rho \qquad (5.6)$$

Figure 5.3 shows by way of example the rolling resistance for the two rear and two front wheels of the Farmland tractor when operating without drawbar pull on surfaces with a range of cone index values. The values of rolling resistance also represent the power loss in kW for each metre / second of travel speed.

Empirical data for rolling resistance of various tyres carrying various weights are given in Dwyer et al (1976).

It is interesting to note that here, as in Chapter 4, no account is taken of the effect of wheelslip on rolling resistance.

(b) Tractive coefficient[1]

The following equations, which were fitted to the traction data by Gee-Clough et al (1978) are equivalent to Equation 4.21.

$$\psi = \psi_{max}\,(1-e^{-ki}) \qquad (5.7)$$

where

$$\psi_{max} = 0.796 - \frac{0.92}{M} \qquad (5.8)$$

$$k\,\psi_{max} = 4.838 + 0.061\,M \qquad (5.9)$$

Figure 5.4 shows the variation in this tractive coefficient with wheelslip calculated for the Farmland tractor from Equations 5.7 to 5.9.

[1] In the literature this tractive coefficient (represented here as ψ) is based on the 'net tractive effort' or the pull generated by the driving wheels, ie, the tractive force less the rolling resistance of those wheels as defined in Equation 4.5. The drawbar pull for the tractor requires the subtraction of the rolling resistance of the front wheels as in Equation 5.10

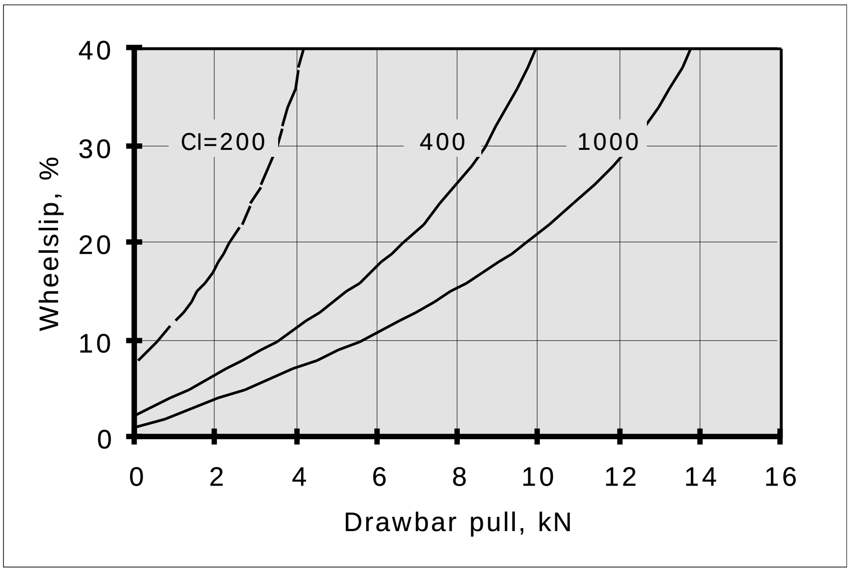


Figure 5.5: Variation in wheelslip with drawbar pull for the Farmland tractor on three surface conditions

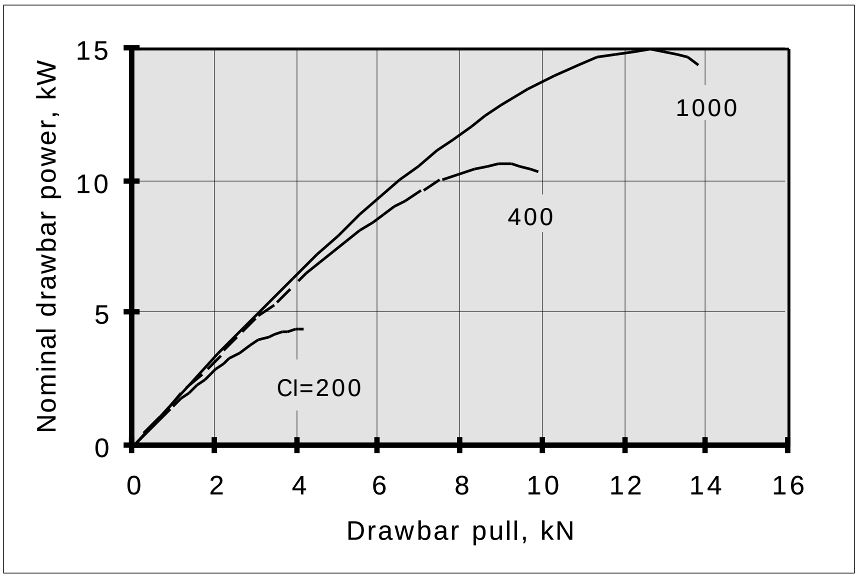


Figure 5.6: Variation in draught power with drawbar pull for the Farmland tractor operating on three surface conditions

(c) Drawbar pull

The drawbar pull for the tractor is then calculated from the tractive coefficient for various wheelslips less the rolling resistance of the front wheels.

$$P = V_r\,\psi - V_f\,\rho_f \qquad (5.10)$$

It is shown in Chapter 6 that the dynamic weight on the front wheels (V_f) and rear wheels, (V_r) are a function of P, the corresponding static weights W_f, W_r and the dimensions of the tractor. Thus

$$V_r = W_r + P\,\frac{y'}{x}$$

$$V_f = W_f - P\,\frac{y'}{x}$$

Substituting in Equation 5.10 gives

$$P = \frac{\psi W_r - \rho_f W_f}{1 - \frac{y'}{x}(\psi + \rho_f)} \qquad (5.11)$$

Figure 5.5 shows the variation in drawbar pull with wheelslip for the Farmland tractor for three surface conditions.

(d) Drawbar power

The drawbar power is then calculated from the drawbar pull and the travel speed as in Equation 2.6.

$$\begin{aligned} \text{DB power} &= P\,V \\ &= P\,Vo\,(1-i) \\ &= P\,\frac{\pi D\,N_e}{q}\,(1-i) \qquad (5.12) \end{aligned}$$

Figures 5.6 and 5.7 show the variation in nominal drawbar power with drawbar pull and wheelslip for the Farmland tractor in 5th gear and an assumed constant engine speed of 2250 rpm. Again the performance is shown for three surface conditions.

It will be noticed that the maximum drawbar power and the wheelslip at which it occurs are both dependent significantly on the surface condition.

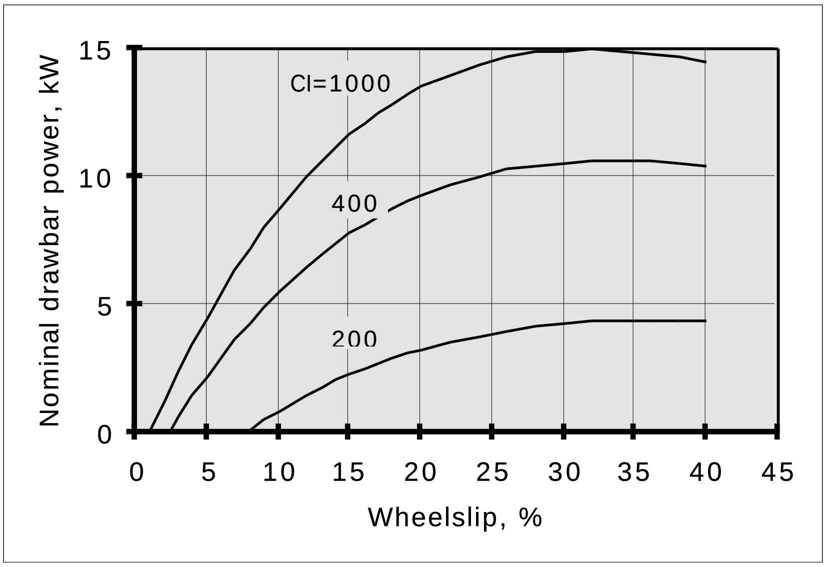


Figure 5.7: Varation of drawbar power with wheelslip for the Farmland tractor operating on three surface conditions

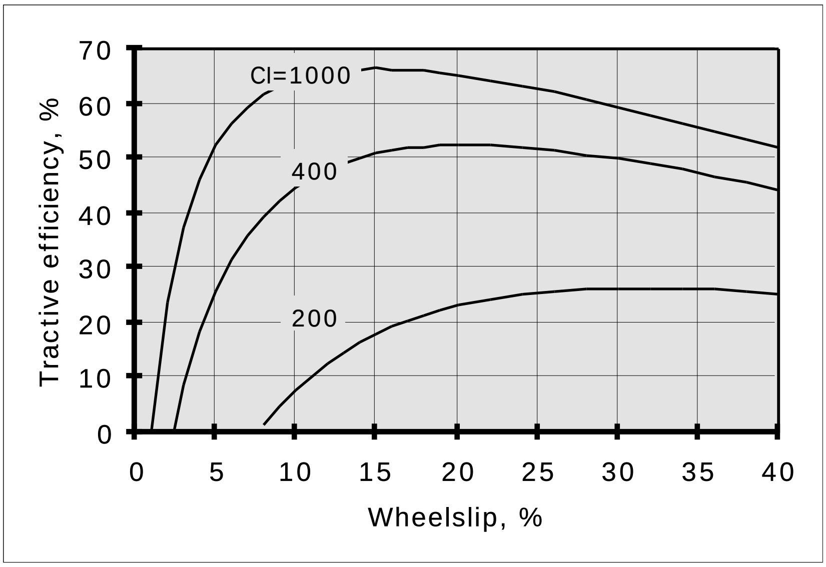


Figure 5.8: Variation of tractive efficiency with wheelslip for the Farmland tractor operataing on three surface conditions.

(e) Tractive efficiency

The tractive efficiency is based on an equation of the form given in Equation 2.10.

$$\eta_t = \frac{P}{P + R}\ (1\text{-}i)$$

For the tractor as a whole this includes the rolling resistance of the front wheels. Substituting for P and R from Equations 5.6 and 5.10, respectively gives:

$$\eta_t = \frac{V_r\,\psi - V_f\,\rho_f}{(V_r\,\psi - V_f\,\rho_f) + V_f\,\rho_f + V_r\,\rho_r}\ (1-i)$$

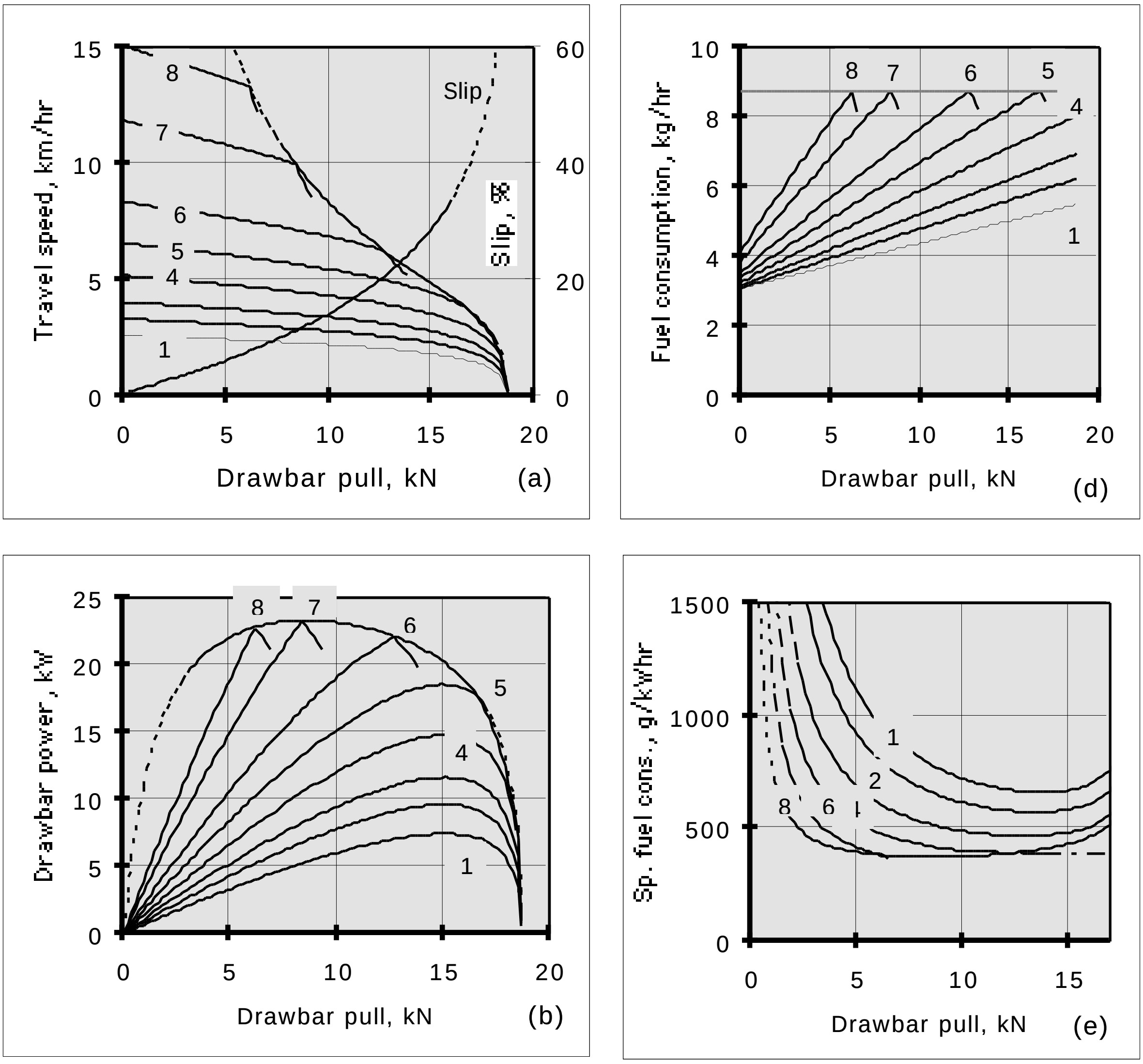
$$= \frac{P}{V_r\,(\psi + \rho_r)}\ (1-i) \qquad (5.13)$$

Figure 5.8 shows the variation in tractive efficiency with wheelslip for the Farmland tractor for the three surface conditions. This will be the same for all gears (speeds) because Equation 2.10 is independent of speed.

Again it will be noticed that:

(i) the maximum tractive efficiency and the wheelslip at which it occurs both depend significantly on the surface condition.

(ii) the wheelslip at maximum tractive efficiency is much less than that at maximum drawbar power.



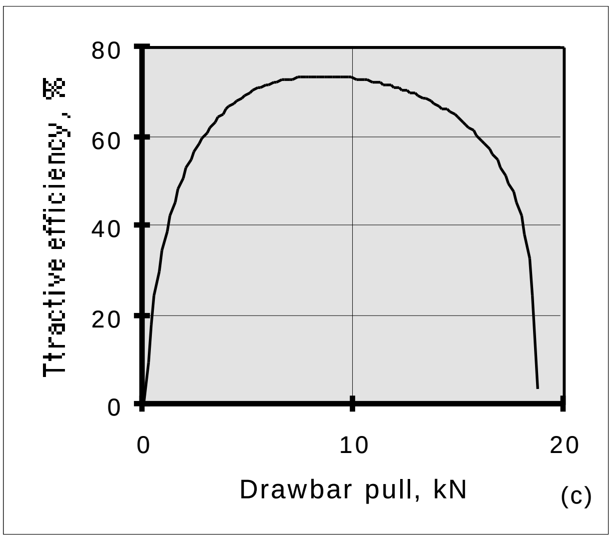


Figure 5.9: Performance of Farmland tractor in gears on soil; CI=1500 kPa, ballast = 6 kN. Graphs for some gears omitted for clarity.

5.4 TRACTOR DRAWBAR PERFORMANCE[2]

When the empirical models of the engine and the tractive process are combined we obtain a set of graphs representing the drawbar performance of the tractor as a whole. These may be plotted in various ways to illustrate aspects of the performance that are of interest; in the following, the various measures of performance are plotted against drawbar pull as the independent variable.

5.4.1 Performance in various gears

Figure 5.9 shows the results of an analysis of the performance of the Farmland tractor at maximum governor setting with maximum ballast (6kN) on firm grassland (CI = 1500 kPa) . Where applicable, the corresponding envelopes of performance, as discussed in Section 2.2.5, are also included. The graphs have been truncated in the full fuel range for clarity, For the cone index and weight values considered, three of the gears are limited by engine torque and five are limited by wheelslip.

Figures 5. 9 (a) - (c) show the graphs of travel speed, drawbar power and tractive efficiency versus drawbar pull. There is only a single graph for wheelslip and tractive efficiency because it is assumed that the travel speed and power losses due to wheelslip and rolling resistance are independent of speed and hence gear.

Figure 5.9 (d) and (e) shows the graphs of fuel consumption and specific fuel consumption versus drawbar pull.

The shape of these graphs is consistent with that which would be expected on the basis of the simple theoretical analysis (for torque limited gears) given in Chapter 2 and the experimental results given for all gears when the tractor is tested on a firm surface as given in Chapter 3.

[2] The assistance of Mr. G. Parkhill in providing the data and algorithims for this section is gratefully acknowledged.

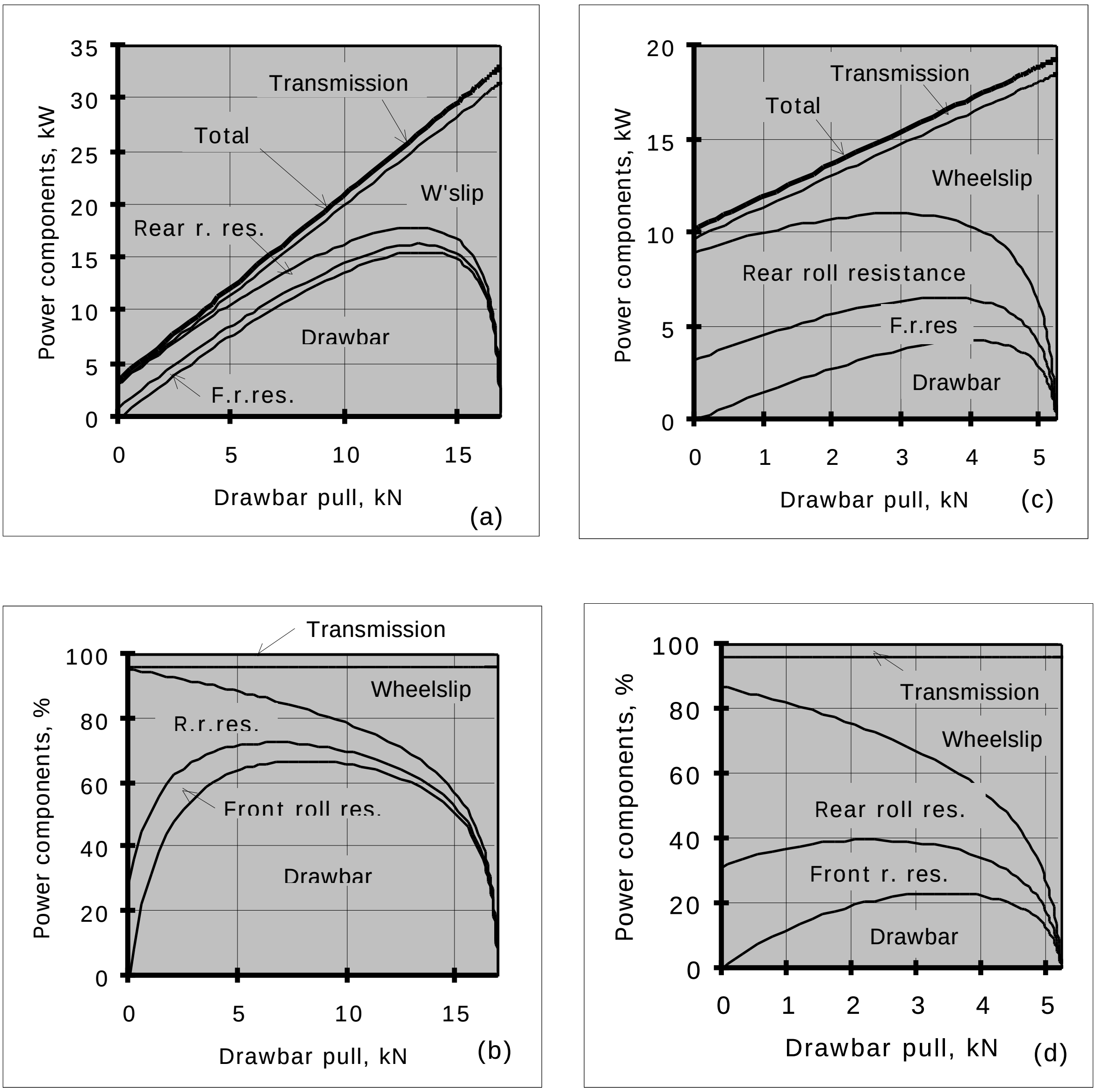


Figure 5.10: Power distribution to drawbar and losses for Farmalnd tractor in 5th gear with 6kN ballast; (a) and (b) for soil, CI = 1500 kPa; (c) and (d) for soil, CI=200 kPa

5.4.2 Distribution of power components

Another interesting way to illustrate the performance of the tractor is to calculate the distribution of the components of the total engine power and plot them in absolute and percentage terms. Figure 5.10 (a) and (b) shows this for the Farmland tractor at maximum governor setting with maximum ballast (6 kN) operating in 5th gear on a surface with CI = 1500 kPa (firm grassland). Power losses in the transmission were assumed to be 4% of the total power being transmitted.

Figure 5.10 (c) and (d) shows the distribution for the tractor in the same condition but with soft, wet surface for which CI = 200 kPa. For this gear on both surfaces, the tractor performance is limited by wheelslip.

(i) Power losses due to wheelslip, which arise from the relative motion of the wheel and ground surface, increase as the drawbar pull increases from the defined zero value at zero drawbar pull to 96% for the maximum sustained pull when the wheelslip is 100%.

(ii) In terms of the empirical model, the rolling resistance force for both front and rear wheels is assumed to be constant (neglecting the effect of weight transfer); no account is taken of the effect of wheel sinkage due to wheelslip on the rolling resistance of the rear wheels. These power losses therefore decrease as the travel speed decreases due to increased wheelslip. They are a large percentage of the total losses at small drawbar pulls particularly for soft surface.

(iii) After losses are considered, the remaining power appears at the drawbar. It reaches a maximum when the increase in drawbar power due to increased drawbar pull just balances the increase in power losses mainly due to the increase in wheelslip. The drawbar power, expressed as a % is, in effect, the tractive efficiency; this reaches a maximum at a lower drawbar pull and wheelslip than does the absolute value of drawbar power.

The greater drawbar pull, the smaller power losses and the increased drawbar power that the tractor develops on the firm surface (a) and (b), compared to that on the soft surface (c) and (d), can be seen.

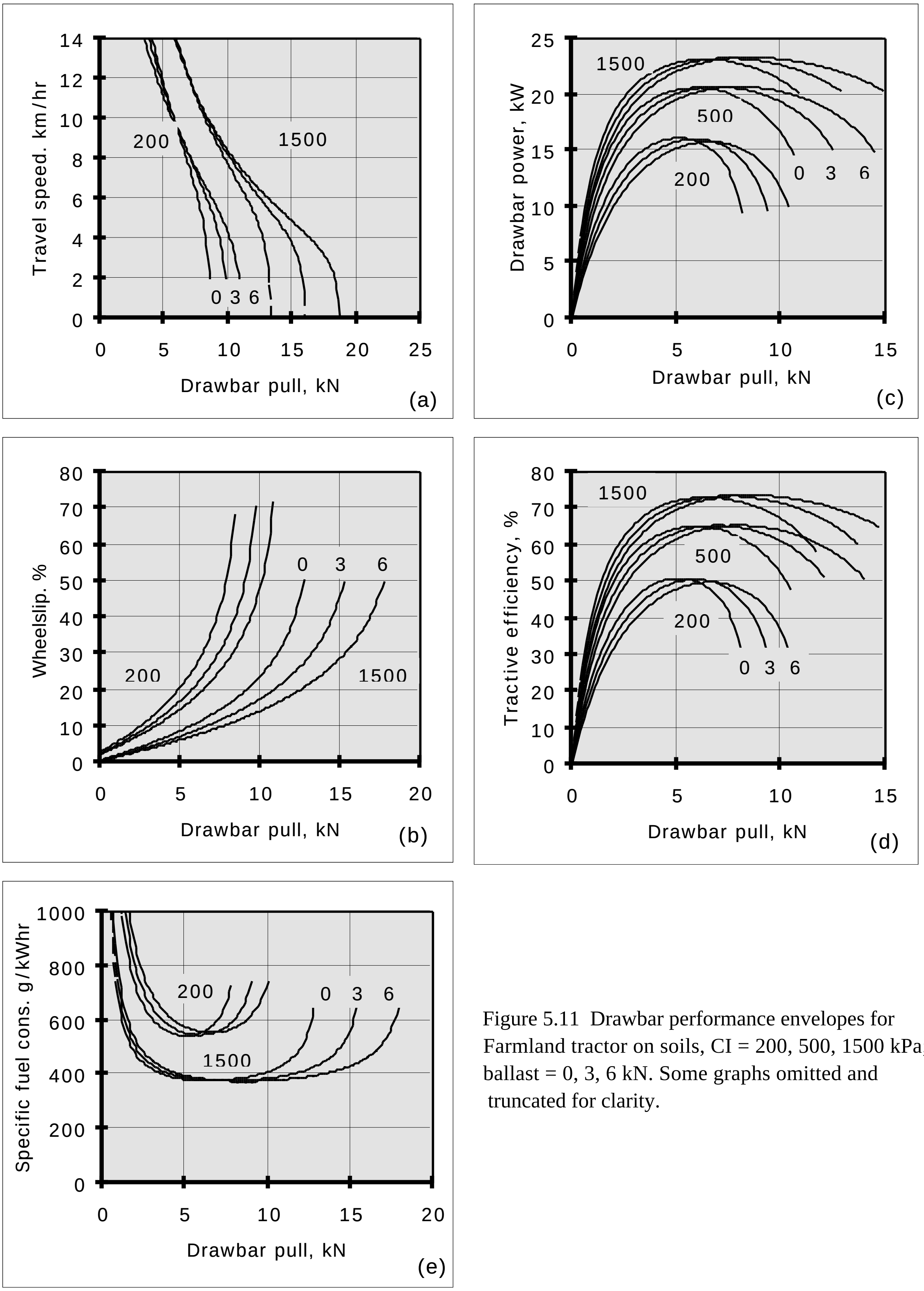


Figure 5.11 Drawbar performance envelopes for Farmland tractor on soils, CI = 200, 500, 1500 kPa; ballast = 0, 3, 6 kN. Some graphs omitted and truncated for clarity.

5.4.3 Effect of surface and weight

The graphs in Figure 5.9 show in detail the performance of the tractor in various gears and the envelopes within which the tractor works. The influence of weight and surface condition on performance can be adequately shown by omitting the detailed performance in the gears and considering only the performance envelopes.

Figure 5.11 shows the graphs of travel speed, wheelslip, drawbar power, tractive efficiency, drawbar specific fuel consumption versus drawbar pull. Three values of cone index (CI = 200, 500, 1500 kPa) and 3 levels of added weight (0, 3 and 6 kN). Some of the graphs have been truncated and others at 500 kPa have been omitted for clarity.

(a) <u>Drawbar pull</u>

(i) Surface condition and, to a lesser extent, weight have a significant effect on the maximum drawbar pull.

(b) <u>Travel speed and wheelslip</u>

(i) Surface condition has a significant effect on travel speed and wheelslip at all drawbar pulls.

(ii) Weight has a small effect on travel speed except at high drawbar pulls. Its effect on wheelslip is significant at all drawbar pulls.

(c) <u>Drawbar power and tractive efficiency</u>

(i) Surface condition has a significant effect on maximum power and maximum efficiency.

(ii) Weight has:
* a negative effect on maximum power and maximum efficiency for all surface conditions in the higher gears and lower wheelslips where rolling resistance losses predominate.
* a positive effect on maximum power and maximum efficiency for all surface conditions in the lower gears and higher wheeslips where these losses predominate.

These effects are illustrated by the fact that:
* for gears giving maximum power and efficiency at drawbar pulls less than about 7 kN, ie higher gears, adding weight <u>decreases</u> the maximum power and maximum efficiency.
* for gears giving maximum power and efficiency at drawbar pulls greater than about 7 kN, ie lower gears, adding weight <u>increases</u> the maximum power and maximum efficiency.

(iii) Surface condition and weight influence the drawbar pull at which maximum power and maximum efficiency occur.

(d) <u>Drawbar specific fuel consumption</u>

(i) Cone index has a significant positive effect (reducing SFC), particularly at high drawbar pulls.

(ii) Weight has a
* a negative effect (increasing SFC) for all surface conditions in the higher gears and lower drawbar pulls.
* a positive effect (decreasing SFC) for all surface conditions in the lower gears and higher drawbar pulls.

These effects are associated with the performance described in (c) (ii) above.

(iii) Surface condition and weight influence the drawbar pull at which minimum SFC occurs.

It will be seen from the above that surface condition has the major effect on tractor performance. Optimum performance will be achieved when the tractor is set up with tyres of a size and with a weight that minimizes the losses from both rolling resistance and wheelslip.

The other factor which is not shown by the above is the need to avoid excessive soil compaction. If additional weight is required for tractive purposes, fitting larger tyres, which allows a greater weight to be carried without excessive surface pressure, will usually be desirable.

5.5 CONCLUSION

As illustrated in the above examples, empirical modeling provides a powerful analytical tool to investigate the relationships between the tractor parameters and the performance variables. Further experimental work and development of the models will improve their capabilities and provide the user with further assistance in setting up the tractor. This requires consideration, not only by the appropriate tractor parameters but also the choice of implement size to give the appropriate drawbar pull. These matters are discussed in Chapter 7.

Performance models which use data in real time from an operating tractor and a local or global positioning system are now available (Yule, et al, 1999). These will allow the operator and / or the control system to 'learn' from its previous 'experience' and so develop strategies to achieve optimum performance under varying conditions in the field.

Problem 5.2

Determine the model parameters for a local tractor and plot its performance as described above.

Repeat the analysis for the tractor with:
(i) smaller tyres
(ii) larger tyres

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