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<p>OPTIMIZING THE TRACTIVE PERFORMANCE OF 4WD TRACTORS OPERATING ON A FRICTIONAL SOIL</p>
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BY

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Optimizing the tractive performance of 4WD tractors operating on a frictional soil

ABSTRACT

The present investigation aimed to develop a simple method of predicting the optimum performance of a medium size 4WD tractor performing a draught operation on a frictional soil in particular. The data obtained could provide an appropriate ballasting recommendation for the optimum combination of tractor power, weight and working speed on such soils taking account of minimizing the undesirable effect of soil compaction.

A wheel torque/weight transducer system was developed to measure the forces applied on the tractor wheels. One side of a MF 3065 tractor was equipped and instrumented. The system fitted to each wheel consists of three link transducers, two modified wheel discs, wheel angular position measuring device and fifth wheel device together with a Datalogger and a portable computer. All transducers output were linear with a coefficient of determination, $R^2 > 0.9994$ and were repeatable.

Field experiments were conducted on sandy loam soil condition to determine the peak tractive efficiency of the tractor in work. Three operating variables at three levels were considered including tractor ballast weight, working speed and implement pull setting. Soil compaction effect for a particular traction situation was assessed by three field measurement methods of soil dry density, penetration resistance and water infiltration rate.

Five relationships of predicting tractor ballast recommendation proposed by Reece (1968), Brixius and Zoz (1976), Dwyer (1978), Gee-Clough et al. (1982) and Bloom et al. (1983) were chosen to present the existing ballast method. These relationships were modified to be at similar conditions of wheel slip, coefficient of traction and tractor power to describe the ballast recommendation as a non-dimensional number R_n and takes the form of :

$$\frac{W}{P^*} = \frac{R_n}{V}$$

where W is the dynamic tractor weight, P^* is the tractor axle power and V is the actual forward speed.

The results of the study were compared with two concepts of existing work. Firstly, with the average ballast recommendation value used for all types of soil. The comparison showed that the ballast recommendation in terms of weight-power ratio is expected to be approximately 70 % of the amount of ballast recommended by the existing work for frictional-cohesive soil at a given speed operating at similar conditions of wheel slip and coefficient of traction. This means for the same pull at a particular power less weight is required because the soil under consideration has high angle of internal shearing resistance, ϕ than the average soil type.

The ballast recommendation for a medium size 4WD tractor operating on a frictional soil (sandy loam) with optimum slip value of 10 % is determined as :

$$\frac{W}{P^*} = \frac{1.3}{V}$$

compared with the value suggested by the theory for all soil types which is generally accepted as :

$$\frac{W}{P^*} = \frac{1.9}{V}$$

when operating under similar conditions of 10 % wheel slip and 0.4 coefficient of traction.

Secondly, the results were compared with an empirical approach of Dwyer et al. (1974), Gee-Clough et al. (1978) with the aim to extract the most related data to the tyre tractive performance operating on a sandy loam soil from all other types of soil. There was found to be a reasonable agreement between the two data sets which gave confidence to the accuracy of the modified equation to predict the ballast required when operating at maximum tractor efficiency. The recommended equation for relating maximum coefficient of traction $(Ct)_{max}$ and mobility number M for the frictional soil (sandy loam) becomes :

$$(Ct)_{max} = 0.62 - 0.82 / M \quad \text{for rear wheel}$$

$$(Ct)_{max} = 0.42 - 0.52 / M \quad \text{for front wheel}$$

The measured tractor thrust force was also compared with the calculated using the classical theory of traction mechanics (Janosi and Hanamoto, 1961 and Reece, 1967) and the results showed no significant difference between the measured and calculated thrust values at 95% confidence level.

The three methods of soil compaction measurement showed that there is a direct relationship between the tractor weight and /or wheel slip, and soil compaction effect. However, infiltration rate method seems to be the most sensitive one to demonstrate the compaction damage to the soil. The results obtained from this measurement indicated that under the optimum power conditions the tractor caused an acceptable level of soil compaction compared to the most serious effect that can occur. The optimum conditions in this soil type involved operating at 10 % wheel slip with mobility number of 6.5.

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List of Notations

ϕ :	angle of soil shearing resistance ($^{\circ}$)
σ :	normal stress (kN/m^2)
γ :	soil bulk density (kN/m^3)
ε :	transmission efficiency (%)
δ :	tyre deflection under load (m)
or $\cot$:	coefficient of traction (—)
or s :	shearing stress in the soil (kN/m^2)
F_H :	summation of horizontal forces applied on a driven wheel (kN)
F_V :	summation of vertical forces applied on a driven wheel (kN)
$\max$:	maximum shearing stress (kN/m^2)
θ :	angular position between wheel force transducers (rad)
λ :	ratio of thrust values at point 1 to point 2 on thrust-slip curve (—)
ρ :	ground pressure (kN/m^2)
$(C_t)_{\max}$:	maximum coefficient of traction (—)
A :	contact area (m^2)
AreaC.I. :	area under the curve of the cone index-depth relationship (bar.m)
b :	plate or tyre or track width (m)
B_n :	mobility number, $[Cbd/W] [(1+5) \delta/h / ((1+3) b/d)]$ (dimensionless)
$c\alpha$:	soil-interface adhesion (kN/m^2)
c :	apparent soil cohesion (kN/m^2)
C :	cone index (bar or $10^2 \cdot \text{kPa}$)
C_n :	wheel numeric, equal to Cbd/W (dimensionless)
C_{rr} :	coefficient of rolling resistance (—)
C_t :	coefficient of traction (—)
d :	wheel or tyre diameter; or depth of work (m)
$D_{st-tine}$:	Standard-tine draught (kN)
D_{tool} :	tool draught (kN)
E :	engine power (kW)
F_1, F_2, F_3 :	forces along the three transducer links of a wheel (kN)
F_{mult} :	multiplying factor to AreaC.I. to estimate S.S.F. ($10^2 \cdot$)
F_X :	tractor drawbar pull (kN)
G :	gradient of cone index (kN/m^3)
$G.F._{tool}$:	Geometric Factor of a tool (m)
H :	tractive thrust (kN)
h, h' :	tyre section and grouser height, respectively (m)
H_{base} :	tractive thrust due to track base (kN)
H_{cal} :	tractive thrust calculated (kN)
H_{max} :	ideal maximum thrust (kN)

H_{mr} :	tractive thrust measured (kN)
H_{side} :	tractive thrust due to track side (kN)
i :	slip (%)
I :	tool-index (—)
J :	deformation ratio ($J = i \ell / K$) (—)
j or d' :	soil deformation (m)
k_{ϕ} :	modulus of deformation due to friction ($N/m^{(2-n)}$)
K :	modulus of soil deformation of a soil shear strain curve (m)
k :	modulus of soil deformation (m) ; or rate of constant (—)
K' :	weight utilisation factor (dimensionless)
k'_c, k'_ϕ :	dimensionless moduli of soil sinkage (—)
k_c :	modulus of deformation due to cohesion ($N/m^{(1-n)}$)
L or ℓ :	length of contact patch (m)
m :	ratio of the area of the grouser tips to the total contact area (—)
M :	mobility number (dimensionless)
M_R :	motion resistance (kN)
n :	an exponent of deformation; or number of single tillage tools (—)
N_c, N_{α}, N_q :	dimensionless earth pressure factors (—)
p :	pressure on the plate (kN/m^2)
P :	wheel pull (parallel to soil surface); or tractor engine power (kN)
P^* :	total axle power (kW)
P_d :	tractor drawbar power (kW)
q :	surcharge pressure (kN/m^2)
Q :	wheel torque ($kN.m$)
r :	rolling radius of wheel (m)
R :	rolling resistance (kN)
$S.S.F.$:	Soil Strength Factor (kN/m)
S_n :	number of samples have been read during measured distance TD_f (—)
T :	travel time (sec)
$T.G.F.$:	Tine Geometric Factor (m)
TD_f :	travel measured distance of a fifth wheel (m)
TD_t :	travel measured distance of a tractor wheel (m)
TE or η :	tractive efficiency (%)
TF :	towed force on wheel (kN)
T_i :	time interval in the datalogger program instruction (sample/sec)
V or V_a or v :	actual forward speed (m/s)
V_0 :	no-load forward speed (m/s)
W :	vertical (dynamic) load on drive wheels; or total tractor weight (kN)
W' :	dynamic mass on the driving wheels/PTO power (kg/kN)
x :	distance from front end of the soil-vehicle interface (m)
X :	slip function (—)
z :	plate sinkage (m)
z_m :	mean sinkage to the centre of the grousers (m)

1. INTRODUCTION

A major task facing modern farmers is to match power units to the size and type of machines so all field operations can be carried out on time with a minimum of cost under a certain operation condition. If the tractor is oversized for implements, the cost will be excessive for the work done. Also if the implements selected are too large for the tractor the quality and quantity of the work may be lessened or the tractor will be overloaded usually causing expensive breakdowns.

It is essential to understand the combination of the tractor and implement to achieve an optimum output of a wheel tractor performing a certain draught operation on a particular soil type and condition. To get an optimum performance of the tractor there has to be a proper matching of tractor power, weight, forward speed and implement draught. These factors have to be manipulated until the optimum operating condition is obtained.

Different methods of predicting tractor performance based on various criteria have been done. Originally, the semi-empirical approach for predicting wheel forces was based the pressure/sinkage characteristics of a rectangular plate (Bernstein, 1913; and Bekker, 1960). Based on this work, various tractive force prediction methods have been developed using soil mechanics theories (Janosi and Hanamoto, 1961; Reece, 1964 and Reece 1965).

The second approach developed is the empirical approach to evaluate the tyre performance of the agricultural vehicles (Freitag 1965; Turnage 1972; Wismer and Luth, 1973; Dwyer et al., 1974; Gee Clough et al., 1978; Brixius, 1987). This method uses dimensionless mobility numbers which involves Cone Penetration Resistance data obtained from the field. It allows simple prediction equations to be used by both the vehicle designers and users.

In addition, several mathematical models for calculating implement forces based on soil mechanics theories of Terzaghi (1962) have been developed to describe the soil tillage-tine relationship (Payne, 1956; Osman, 1964; Hettiaratchi et al., 1966; Hettiaratchi and Reece, 1967; Hettiaratchi and Reece, 1974; Godwin and Spoor, 1977).

Moreover, several prediction techniques of tractor ballasting recommendation were produced to provide the optimum combinations of tractor power, weight and speed to optimize the output of the agricultural tractor performing a draught operation (Reece, 1968; Brixius and Zoz, 1976; Dwyer, 1978; Gee Clough et al., 1982).

Most of the existing approaches of predicting tyre performance and implement draught requirements are:

- either highly theoretical and too complex to be understood by the ordinary farmer requiring an agricultural advisor to translate the complex relationship between the

soil and tool into a straightforward and reliable prediction method particularly when working in the field situations.

- or not practical due to the difficulty of measuring the fundamental soil properties (ie. the soil cohesion c , the angle of soil shearing resistance ϕ and modulus of soil deformation K) under field conditions particularly in remote regions.

However, some approaches such as the approach of Dwyer et al. (1974) and Gee-Clough et al. (1978) can provide a simple and straightforward method more suitable for the non technical farmers and other users. The approach of these two workers were based on data collected from many different soil types and conditions over a number of years. However, their results apply to frictional-cohesive soils only and should not be extrapolated to purely frictional or purely cohesive soils (Gee-Clough et al., 1982).

The present investigation seeks to develop a prediction methodology concerning the tractive performance on frictional loose soils in particular as found in Saudi Arabia, the place of interest, to produce some practical guidelines in this context taking account of any required modification to the theory which would provide a better prediction for this soil type.

1.1 Background to Saudi Arabia Condition

1.1.1 The country

The Kingdom of Saudi Arabia covers about four-fifths of the Arabia Peninsula with the Red Sea bordering its western and Arabia Gulf of the east. The population of the country about 16.5 million including non-Saudi residents according to the last statistics in 1992. The Kingdom can be divided into various main zones and characterized by a variety of geographical portions including vast deserts, high mountain chains, fertile plains and deep valleys. The country is characterized with high temperatures, in summer it reaches 50°C , humidity is low but it reaches 95% on the coastal areas. The average annual rainfall changes from region to region but it does not exceed 100 mm (Sial 1985).

Agriculture depends mainly on springs and ground water for irrigation. Only in the dissected high lands in the south of the country is rain fed agriculture practised but even there cultivation normally requires supplementary irrigation.

The total area of the country is about 220 million hectare and represents 5% of the arid zone of the world. It mainly consists of saline and alkaline desert soils. Because of the arid climate challenging obstacles to agricultural development, the majority of soils of the country are not cultivated.

1.1.2 Soils

Various researches have been done on the Saudi Arabia soils to provide a general framework for understanding the soils and their potentialities. These included morphological, physical and chemical properties of the soil in particular those under agricultural cultivation.

Bashour et al. (1983) examined soils in five major agricultural regions with highest potentials for development (Al-Kharj, Gassim, Hofuf, Taif and Wadi Dawasir). Their study showed that the textures of soils are mostly sand, loamy sand, and sandy loam. For the group of soils as a whole, however, sandiness is a distinctive characteristic.

Different soil studies have been done on AL-Hasa Oasis which is one of the most important zones in the Kingdom and the largest agricultural area in the eastern province of the country. Soil mechanical analysis by the Hofuf Agricultural Research Centre pointed out that the average soil texture of the Oasis consists of 75% sand, 12% silt and 10% clay classifying the soil as a sandy loam (Al-Tayeb 1983).

1.1.3 Agricultural system and types of farm size

The primary production sectors in Saudi Arabia are petroleum, agriculture and minerals. Oil revenues contribute the majority of the government gross national income. But these oil wells are not expected to last long. Therefore, the kingdom is trying to diversify the source of the national economy and reduce dependence on oil for national prosperity and government revenues by using the available resources to obtain specific goals based on the established priorities. Therefore, special emphasis is placed upon agriculture with the objective of minimizing the prevailing expenditure being spent on food imports. But the eventual success of agriculture would appear to be substantially limited by some challenging problems of which the most important are limited water shortage, poor soils, harsh climatic conditions, lack of manpower and lack of farmer training and research.

Traditionally agriculture has been centred around areas and valleys scattered throughout the country where artesian springs and shallow groundwater are available, or where rainfall alone is sufficient for the cultivation of the crops. At present, there are two kinds of agricultural farming systems based on the farm size and the technology level used in the farm :

i. Traditional Agriculture

Farms are small with total area between 0.5 to 10 ha but the majority are less than 2 ha. The smallholders use tradition and primarily non commercial farming activity. Human labour is the main source of power usually family individuals and foreign labours using simple hand tools such as hand hoes, sickles, spades and shovels. Animal

draught can be seen in some village farms in the south of country. They use surface irrigation methods mainly the flooding way to irrigate their crops. Most of these farms are old and were established many years ago and still practice traditional farming. In general, the farms are of the types of :

- either a land with old palm trees and inter-between fruit crops with small areas left open for vegetables.
- or an open area for some cereal crops and vegetables.

Those who have enough open areas have started to use small size tractors and small tillage implements and other smallholders use single axle tractor as hand rotary cultivator because it is suitable for small area and easy to move between trees. Although, farmers have the tendency of introducing modern technology and mechanizing some field operations but they are facing problems such as limited area, access to the farm and cropping patterns, service and repair facilities, trained operators and finance.

ii. Modern Agriculture

Agriculture today is the product of evolving and varied responses of a flood of oil wealth as well as the high oil revenues. Recently the situation has changed. During the 1970s public land grants and associated financial incentives and technical assistance led to introducing huge amount of lands to agriculture and various investments in agricultural and animal production have been started. In addition, during the late 1970s and 1980s the attractiveness of the financial incentives available became obvious to many entrepreneurs and investments in large-scale specialised commercial enterprises increased tremendously. The result has been the creation of very large production units owned by private holdings and joint stock agricultural companies growing main crops like wheat, barley, maize as well as different varieties of vegetables. Other larger holdings have also appeared involving animal and poultry production. They mostly use mechanization applications and modern agricultural technology in their farm activities and different field operations and almost universally employing expatriate labour.

Modern private farms are usually large having area more than 50 Ha, however, agricultural companies have huge area of agricultural lands upto thousands of hectares such as Hail Agricultural Development Company (HDCO), National Agricultural Development Company (NADC) and Tabuk Agricultural Development Company (TADCO). Most of these large scale farms usually use a centre pivot irrigation system where crop is grown in circles.

This achievement has partly occurred as a result of the introduction of agricultural mechanization and modern technology.

1.1.4 Government policy and finance

The government has recognized that the agricultural sector is one of the most important sectors which are vital to the socio-economic development of the country and to alter the economy base the emphasis should be on this important sector. A major task for government backing of agricultural growth has been a desire to reduce the level of food imports and to minimize the prevailing cash flow being spent on importing agricultural commodities..

Therefore, the government has followed the strategy of providing agricultural and rural subsidies as well as constructing the basic projects and essential elements which serve agriculture. Development plans regarding government policy toward agriculture have been made through progressive five year plans. To achieve this, many projects such as land reclamation, building irrigation and drainage canals and constructing dams have been done. Huge sums of interest-free loans and grant liberal subsidies to farmers are provided.

1.1.5 Agricultural production

In the late 1970s the country was producing less than half the food it consumed. Less than one-half of the consumption of wheat flour, meat, milk and eggs were produced domestically and the Kingdom was lagging behind in agricultural trade balance.

However, the situation has changed since mid 1980s due to the massive development in utilization of oil wealth. Saudi agricultural performance has reached to a high level of development. Over US\$ 37 Billion is being spent on Saudi Arabia's prevailing five year plan (1990-1995) on further agricultural development, the upgrading and expansion of existing infrastructure and new projects investment. In just ten years, the Kingdom has substantially reduced its food import bill and started to export major crops such as wheat, fruits and vegetables.

To list the achievements in agriculture, the useful land for agriculture has increased about four times during the period 1980 to 1991 produced 3.88 million tons of wheat and 2.54 million tons of vegetables. The Kingdom has made a sizeable surplus in wheat and vegetables for export and has attained self-sufficiency and agricultural security in many food grains. The production of dated amounted to 520,000 tons while production of various fruits reached about a million tons. In the poultry sector, the annual production of eggs reached 2.5 billion while those of broiler chickens stood at 205 million. The annual production of milk reached 265,000 tons, while production of red meat amounted to 175, 000 tons. The country has almost achieved self-sufficiency in the production of fish.

1.1.6 Agricultural machinery

The agricultural sector in the Kingdom has developed fast in the last ten years and the products increased considerably meeting the country needs of the main agricultural products, particularly wheat. Farm power has been recognized to be one of the main driving forces behind this expansion which was made possible through encouraging rapid introduction of the farm mechanization and modern agricultural technology by the government. A program of subsidization was given through SAAB (Saudi Arabian Agricultural Bank) and huge amounts of subsidies have been paid to the farmers. Subsidizing farm machinery by about 45-50 % of the purchase price has encouraged farmers to buy different field machines of several sizes. This subsidy through agricultural banks covers machinery equipment related to cultivation, irrigation, drainage, plant protection, animal and poultry production and fishery industry. Consequently, Tractors and farm machines were introduced to the country on a large scale in a very short period of time.

As a result, modern private farms and agricultural companies apply almost full mechanization in their field operations and farm activities. The agricultural tractor has become the most important source of power unit in the farm. Various kinds and models of tractor of different types of category has been imported to the country. Models such as John Deere, Massey Ferguson, Case, International and Case have become well known. In general, tractor power size and driving system varies with the farm scale of production and activities involved in the farm. Conventional 2WD tractors with 30 to 70 kW could be found in the medium size farms. While the farms of agricultural companies with huge areas reach up to thousands of hectares usually have a wide range of tractor sizes both 2WD and 4WD tractors. There are many 4WD tractors in 60 to 80 kW power range.

Equally, there are many types and sizes of farm implements in Saudi farms which have been introduced for the task of farm mechanization and utilisation of mechanical power technology including :

- Primary and secondary tillage implements
- Planting, fertilizer and chemical application equipment
- Crop harvesting and handling machine
- Irrigation systems
- Poultry and animal production equipment

1.2 Difficulties of farm machinery utilization in Saudi farms

The introduction of farm machinery has played a big role in modern agriculture. Tractors and field equipment were imported on large scale and at a high rate. Consequently, some difficulties and problems have occurred due to improper selection, limited experience of the local farmers and the shortage of research programs. The excessive breakdown incidents and inability of using machinery at its full working capacity are the major problems facing the private farms.

Babeir (1989) developed a microcomputer model to help decision making in tractor and implement selection. The model determines, for a given farm size, the minimum tractor power requirement along with the minimum implement sizes. His model examined the existing machinery systems in some wheat and barley farms in Saudi Arabia. He showed that all the machinery systems reported in the survey were oversized for the farm area being worked. He believed that agricultural subsidies have encouraged farmers to own different machinery with different sizes. In addition, the absence of knowledge of selecting proper farm machinery has caused farmers to own unneeded machinery, to oversize them and to perform unnecessary field operations. This reflects the fact that farmers bought their machinery without any concern for real needs because of the government subsidies.

Al-Suhaibani (1990) investigated the mechanization provisions and the mechanization distribution among the modern farms in the mid-region of Saudi Arabia. He studied 56 modern farms on the basis of tractor power and implement size distribution per unit area and compared the results the finding of other studies. He concluded that mechanization provision in Saudi farms much higher as compared to that in Indiana or Nebraska (U.S.A.) where the acquisition per unit area is double or more which considered as highly overpowered. Also, he concluded that the lack of farming experience, shortage of technical data and research were the main reasons of improper selection of farm equipment.

Al-Suhaibani (1992) conducted preliminary study to evaluate the performance of farm machinery used for different operations in growing wheat farm, from 37 different farms with areas ranged from 13 ha to 492 ha in the middle region of Saudi Arabia. He listed the following conclusions:

1. The field efficiency was very low in comparison to internationally recommended standards.
2. The variations of the field efficiency among farms or within the farms for different operations were great, and followed no specific pattern as a function of farm size.
3. The study showed that the farms were over mechanized in many cases by more than 100%, especially by combines or grain drills which added extra unnecessary costs.

He referred these problems mainly due to the same reasons mentioned in the last reference.

Such an approach is required to help farmers how to match power unit to the type and size of farm implements and to utilize and maintain them to achieve a proper machinery system for different farm enterprises. New farmers and agri-bussinessmen can also obtain advantages from this target.

1.3 Hypothesis and aims

1. An appropriate method can be developed and used as a guideline to optimize tractor field performance on a frictional soil based on the existing theory with minor modifications.
2. Farmers and other advisory workers can optimize tractor power and weight in relation to the implement combination selected on this soil type for medium size 4WD tractors.

1.4 Objectives

The aim of the study is to provide farmers and advisory workers with a methodology which can be used to obtain the maximum output from the agricultural tractors working in arid frictional soils. The objectives of the project are :

1. to develop a technique for measuring the forces applied on the tractor driving wheels i.e. the vertical force and horizontal thrust.
2. to predict the relationship between the tractor power, weight and forward speed for the tractor working in a frictional soil and to compare these results with an existing theory so an appropriate field operating condition and ballasting recommendation could be provided for such soil.
3. to calculate the actual draught implement size based on previous work (Desbiolles 1994) altogether with the results of the optimum tractor performance obtained from the present investigation.
4. to provide guidelines for farm machinery utilization and management for arid frictional soils in ways which minimise the undesirable effect of soil compaction.

2. LITERATURE REVIEW

2.1 Introduction

This chapter aims to review the literature related to the aims and concept intended in the present project. The previous work presented includes the traction theories, implement force prediction and tractor ballast recommendation methods. It includes also the instrumentation systems used to evaluate the forces between the tractor and implement. In addition, soil compaction background is given. The emphasis was made on the principle of the previous work studies and the development achieved in the recent years.

2.2 Traction theory

Traction is the force derived from the interaction between a device and the floatation medium. The device is usually a wheel, track, propeller, etc. and the floatation medium is the concrete, soil, ice, etc. The wheel is required to produce at its contact with the ground, forces to provide thrust. The thrust should be large enough to provide traction, overcome the rolling resistance and to overcome the uphill component of the system when moving on sloping surfaces.

However, limiting thrust conditions occur when one of the following situations occurs:

- torque to the driving device is at maximum
- slip due to limiting grip at the interface
- strength failure of the floatation medium

The maximum thrust which a wheel or track can produce will depend on the maximum shearing stress which the soil can provide and the area over which this stress is generated. The maximum shearing stress $\tau_{\max}$ is given by Coulomb's equation :

$$\tau_{\max} = c + \sigma \tan \phi \quad (2.1)$$

where c is the soil cohesion, σ is the normal stress and ϕ is the angle of soil shearing resistance.

Micklethwaite (1944) assumed that multiplying Coulomb's equation by the contact area or area in shear A gave the ideal maximum thrust $H_{\max}$. His equation can be stated as :

$$H_{\max} = Ac + W \tan \phi \quad (2.2)$$

where W , the load on wheel or track. This equation implies complete soil failure which would mean 100% slip for a wheel. In practice a tractor will work at a considerably low slip in order to be capable of useful work so it is unable to use all the potential shear strength of the soil.

To obtain the optimum performance from an off-road vehicle, it is necessary to understand the interaction between the wheel and the medium on which it operates. The presented section aims to review the main approaches of force prediction for off-road wheels.

2.2.1 Semi-empirical approach

This approach depends upon soil mechanics theory involving the measurement of the fundamental soil properties (c , ϕ , K) in the shearing and sinkage modes.

A semi-empirical approach to predict forces acting on wheels operating in soil was first initiated by Bernstein (1913). He proposed a theory based upon the pressure/sinkage characteristics of a rectangular plate. He stated that :

$$p = k z^n \quad (2.3)$$

where :

- p = pressure on the plate
- k = modulus of soil deformation
- z = plate sinkage
- n = an exponent of deformation

Experiments carried by Bernstein led him to propose the value of n was 0.5 for agricultural soils. His work has proved to be the basis of extensive theories of rolling resistance and soil deformation under ground drive systems.

Bernstein's work has been further developed by Bekker (1960). Bekker proposed, however, that the modulus of soil deformation was made up of two components, one due to the cohesive property of the soil and one due to the frictional property. The Bekker pressure-sinkage equation is :

$$p = (k_c/b + k_\phi) z^n \quad (2.4)$$

where :

- k_c = modulus of deformation due to cohesion
- k_ϕ = modulus of deformation due to friction
- b = plate width

Reece (1965) investigated the validity of the Bekker pressure-sinkage equation and found it to be unsatisfactory. He stated some reasons such as it does not fit experimental results at all well, it conflicts with bearing capacity theory and the values of k_c and k_ϕ have variable dimensions depending on n . Reece used classical soil mechanics to examine soil failure beneath a strip footing with respect to pressure sinkage relationship. He therefore proposed the following equation :

$$p = c k'_c (z/b)^n + b \gamma k'_\phi (z/b)^n \quad (2.5)$$

where k'_c and k'_ϕ are dimensionless moduli of sinkage. This relationship was shown to correlate well with practical results obtained by plate sinkage tests in sand and clay soils. It also, has the advantage of having an agreement with Terzaghi relationships for strip footing.

Bekker (1960) also proposed a general formula to define the horizontal shearing strength of the ground (psi) for the track laying vehicle as :

$$s = (c + \rho \tan \phi) / \gamma_{\max} [\exp (-K_2 + \sqrt{(K_2^2 - 1)} K_1 d') - \exp (-K_2 - \sqrt{(K_2^2 - 1)} K_1 d')] \quad (2.6)$$

where ρ is ground pressure (psi), K_1 and K_2 are slip parameters, $\gamma_{\max}$ is the maximum value of the expression in brackets [] and d' is soil deformation (in).

Based on Bekker work, Janosi and Hanamoto (1961) suggested a simpler equation for describing soil shear strain curves which has the form of :

$$s = (c + \sigma \tan \phi) (1 - e^{-j/K}) \quad (2.7)$$

where :

j = Soil deformation in horizontal direction

K = Deformation of modulus of a soil shear strain curve

Further, they obtained the gross thrust exhibited by a track by integrating Eq. (2.7) along the ground contact area. The normal pressure distribution was assumed to be uniform and the soil deformation under a track is proportional to the distance of soil particle from the front end of the soil-vehicle interface, x using the slip, i as a factor of proportionality. Thus :

$$j = i x$$

Hence, they proposed the following equation for the gross thrust H as :

$$H = (Ac + W \tan \phi) [1 - 1/J (1 - e^{-J})] \quad (2.8)$$

where $J = i \ell / K$ and ℓ is the length of contact.

Reece (1967) used Eq. (2.8) for wheel tractors and gave the gross thrust equation in the form of :

$$H = (b \ell c + W \tan(\phi)) \cdot [1 + (K/i \ell) e^{-i \ell / K} - K/i \ell] \quad (2.9)$$

He adapted the above equation in evaluating and assessing the performance of both 2WD and 4WD tractors under various conditions of ballast, load transfer and gradient. He stated that it was shown to describe adequately the slip-pull performance of wheeled and tracked agricultural tractors working on farm soils.

Reece (1965) used soil mechanics to predict the performance of tracklayer vehicles. He used an analysis based upon the general soil mechanics equation for soil cutting blades to predict the tractive force beneath the track base H_{base} . He also added the possible traction from the side of a track H_{side} which was obtained by consideration of static equilibrium. However, he overcame the problem of exclusion of slip due to the static equilibrium method by multiplying his developed expression by the second term of Eq. (2.9). Reece therefore proposed the following equations:

$$H_{side} = b^2 c N_c + b^2 c_\alpha N_\alpha + b^2 q N_q \quad (2.10)$$

$$H_{side} = 4ch' \ell \sin^2 (45 + \phi/2) + [2\gamma h' \ell z_m (45 + \phi/2)] \cos (90 - \phi) \quad (2.11)$$

$$H = (H_{base} + H_{side}) \cdot [1 + (K/i \ell) e^{-i \ell/K} - K/i \ell] \quad (2.12)$$

where :

$N_c = (1-m)\ell/b$ (dimensionless)

$N_\alpha = m\ell/b$ (dimensionless)

$N_q = (\ell/b) \tan \phi$ (dimensionless)

$c_\alpha =$ soil-interface adhesion (Ib/in^2)

$q =$ surcharge pressure (Ib/in^2)

$h' =$ track grouser height (in)

$\ell =$ track length (in)

$\gamma =$ soil bulk density (Ib/in^3)

$b =$ track width (in)

$c =$ soil cohesion (Ib/in^2)

$\phi =$ angle of shearing resistance (degrees)

$z_m =$ mean sinkage to the centre of the grousers (in)

$m =$ ratio of the area of the grouser tips to the total contact area

Komandi (1968) studied the relationship between the soil's shear diagram and the thrust-travel reduction curve of the vehicle. He used the work of Bekker (1960) and Janosi and Hanamoto (1961) to establish a method of evaluating the physical characteristics of the soil and the shear diagram if the thrust-travel reduction curve (TTRC) is known.

Komandi suggested that the experimental thrust-slip curves obtained in the field may be used for a realistic determination of K value. He mentioned a simple way to evaluate the deformation modulus. Two points on the experimental thrust-slip curve to be chosen but not too close together. It is recommended that the points should be taken from around 10-15 % slip for tracked vehicles and 30-40 % for the wheeled

vehicles. Then, the values of the thrust and slip relevant for each point on the curve can be determined. Hence, K value (mm) can be calculated from the simplified equation developed by Komandi which takes the form of :

$$K = i_1 i_2 \ell (1 - \lambda) / [i_2 - (i_1 \lambda)] \quad (2.13)$$

where :

- i_1 = slip at point 1 on the thrust-slip curve
- i_2 = slip at point 2 on the thrust-slip curve
- ℓ = contact length
- λ = H_1/H_2
- H_1 = thrust at point 1 on the curve
- H_2 = thrust at point 2 on the curve

2.2.2 Empirical approach

This approach depends upon a parametric measurement using a standardized cone penetrometer followed by empirical correlation of wheel performance. The cone penetrometer was originally developed at the US Army Engineers Waterways Experiment Station, Vicksburg, Mississippi, as an instrument to assess trafficability of soil. Subsequently, its use has been extended and it has become a standardized equipment for characterizing soil in detailed vehicle mobility studies.

Freitag (1965) initiated a method based upon dimensional analysis to produce to non-dimensional numbers, one for sand and another for clay soils. His prediction technique based upon two non-dimensional mobility numbers was proposed thus:

$$\text{Clay mobility number} = C b d / W (\delta / h)^{1/2} \quad (2.14)$$

$$\text{Sand mobility number} = G (b d)^{3/2} (\delta / h) \quad (2.15)$$

where :

- C = cone index
- G = gradient of cone index
- d = tyre diameter
- h = tyre section height
- δ = tyre deflection under load

He therefore used the values of (C, G) to characterize the soil, and the parameters of (W, b, d, h, δ ,) to characterize the wheel.

Turnage (1972) did further work to the relationships proposed by Freitag and included an additional term to take the width/diameter ratio of the tyre into account. His modified version of the clay mobility number M was :

$$M = [C b d / W] (\delta / h)^{1/2} \cdot [1 / (1 + b / 2d)] \quad (2.16)$$

Wismer and Luth (1973) developed a series of empirical equations which could predict the field performance of wheel vehicle. He proposed the following expressions to define towed force, the net traction (pull) and the torque of a driving wheel respectively as :

$$TF/W = (1.2/C_n + 0.04) \quad (2.17)$$

$$P/W = 0.75 (1 - e^{-0.3 C_n i}) - (1.2/C_n + 0.04) \quad (2.18)$$

$$Q/rW = 0.75 (1 - e^{-0.3 C_n i}) \quad (2.19)$$

where :

- TF = towed force on wheel
- W = dynamic load on the wheel, normal to soil surface
- C_n = wheel numeric, equal to C_{bd}/W
- P = wheel pull, parallel to soil surface
- Q = wheel torque
- r = rolling radius of wheel

Dwyer et al. (1974) at S.R.I (N.I.A.E.) assessed five different tyre sizes at a wide range of inflation pressure and vertical loads by means of the single wheel tester in many field conditions following the method of Freitag (1965). Empirical relationships were found between tyre mobility numbers, derived from tyre dimensions and soil cone penetrometer, and the following tractive performance parameters: coefficient of traction at 20% slip, coefficient of rolling resistance, maximum tractive efficiency, coefficient of traction at maximum efficiency and slip of traction at maximum efficiency using the mobility number of Turnage. They established the following relationships :

$$\text{Coefficient of traction at 20 \% slip} = 0.56 - 0.47/M \pm 0.1 \quad (2.20)$$

$$\text{Coefficient of rolling resistance} = 0.07 + 0.2/M \pm 0.05 \quad (2.21)$$

$$\text{Coefficient of traction at maximum efficiency} = 0.41 - 0.21/M \pm 0.1 \quad (2.22)$$

$$\text{Maximum tractive efficiency} = 78 - 55/M \pm 0.1 \quad (2.23)$$

$$\text{Slip at maximum efficiency} = 9 + 19/M \pm 0.07 \quad (2.24)$$

They found that these empirical relationships were valid for stubble, ploughed and cultivated only, however, they were not applicable for field with slippery surfaces overlying firmer soils such wet grassland or on land after vegetable harvesting. They used their prediction data in compiling the Handbook of Agricultural tyre performance (Dwyer et al. 1976).

Gee Clough et al. (1978) re-analysed the experimental data of Dwyer et al. (1974) using empirical approach based on the mobility number term of Turnage. He proposed the following equations :

$$(C_t)_{\max} = 0.796 - 0.92/M \quad (2.25)$$

$$k(C_t)_{\max} = 4.838 + 0.061 M \quad (2.26)$$

$$C_{rr} = 0.049 + 0.287 / M \quad (2.27)$$

where :

$(C_t)_{\max}$ = maximum coefficient of traction

k = rate of constant

C_{rr} = coefficient of rolling resistance

He found that these empirical relationships are again valid for stubble, ploughed and cultivated only, however, dry grass fields and fields with a loose, wet surface cover gave results significantly different from all other fields. In addition, he found the coefficient of traction-slip data from the experiments always fitted well to the following relationship :

$$C_t = (C_t)_{\max} (1 - e^{-ki}) \quad (2.28)$$

where C_t is the coefficient of traction (pull developed by tyre /load on tyre) and i is the wheel slip.

Gee-Clough (1980) used his empirical equations, which stated above, to demonstrate the effect of varying tyre diameter and width on tyre tractive performance in different field conditions. He produced curves which give the axle load required per unit available axle power to enable operation at maximum efficiency to be achieved in any field condition. He checked the accuracy of his prediction in validation experiments and it has been found to be satisfactory.

Brixius (1987) presented a series of equations to predict the tractive performance of bias ply tyres operating in cohesive-frictional soils. These equations are modified version of those originally published by Wismer and Luth (1973). The equations can predict wheel torque, motion resistance, net pull and tractive efficiency as a function of soil strength, wheel load, tyre size, tyre deflection and for dual and single tyres. Brixius developed his traction equations based curve fitting procedures to analyse results from field data tests. These results were obtained in separate experiments conducted by Deer & company, USAE Waterways Experiment Station, the National Institute of Agricultural Engineering and the U.S. Army Tank Command. His modified equations are :

$$Q/rW = 0.88 (1 - e^{-0.1B_n}) (1 - e^{-7.5i}) + 0.04 \quad (2.29)$$

$$M_R/W = 1.0/B_n + 0.04 + (0.5 i)/\sqrt{B_n} \quad (2.30)$$

$$P/W = Q/rW - M_R/W \quad (2.31)$$

$$TE = (P/W) / (Q/rW) \cdot (1 - i) \quad (2.32)$$

where :

B_n = mobility number, equal to $[Cbd/W] [(1+5)\delta/h / (1+3) b/d]$

M_R = motion resistance

TE = tractive efficiency

Q, W, P, i and r as before.

These equations are limited to Bias ply tyres, however, Brixius suggested appropriate adjustments in several of the equation constants to be done in order to be used in traction prediction of radial tyres.

2.2.3 Chart prediction method

Zoz (1972) produced a graphical model of predicting field performance for farm machinery selection decisions based upon average tyre performance on four soil surfaces. This approach predicts drawbar pull, drawbar power, travel speed and slip of the 2WD tractor in either firm, tilled or soft sandy soils and concrete. It takes the account of rolling resistance, ballast and type of implement hitch (weight transfer and weight addition) in predicting tractor performance under a particular field condition. However, this approach is limited to 2WD tractor.

Hunt (1983) presented a table for the draught, power, and energy requirements for many field machines. These values given were not descriptive for any individual operation ignoring soil characteristics and tine specifications. Moreover, the values had a wide range between the upper and lower limit for a particular single operation.

Zoz (1987) developed lotus templates to predict the performance and ballast requirements of both 2WD and 4WD tractors on soil and concrete including drawbar pull, travel speed, wheel slip and drawbar power. The templates have two calculation modes of "performance" and "weight". In performance mode, the static front and rear weights along with specified soil and tyre parameters are used for calculation of slip and drawbar pull values. In the weight mode, a given slip and specified percent of the dynamic weight remaining on the front axle are used to calculate the static front and rear weights and the drawbar performance values. The computer program of the templates is available in a diskette for the interested users.

Witney (1988) presented a graphical method, i.e. the ploughing performance predictor chart, to estimate the power requirement of the various characterises of a particular plough. This method can be also used to estimate tractor engine and drawbar power along with details of operating speed, plough type, number of plough bodies, working depth and width cut, tractive efficiency and soil condition. However, it is limited to the prediction of mould plough performance.

2.3 Implement force prediction

Soil dynamics has been known for many years. Numerous investigations have been conducted to predict soil cutting forces based on the determination of soil-tine interactions.

Several mathematical models for calculating implement forces based on soil mechanics theories of Terzaghi (1962) have been developed to describe the soil tillage-tine relationship. Some models were established to be applicable only for two-dimensional soil failure with wide tines (Osman, 1964; Siemens et al., 1965; Hettiaratchi et al, 1966; Hettiaratchi and Reece, 1974). There are also some models suitable for three-dimensional soil failure with narrow tines (Payne, 1956; Hettiaratchi and Reece, 1967; Godwin and Spoor, 1977; McKyes and Ali, 1977). With the development of rapid computing power, numerical methods have been also developed to solve soil cutting problems (Yong and Hanna, 1977 and Chi and Kushwaha, 1989).

Kirisci (1994) gave an extensive review of literature for most of the soil-tine interaction models which have been developed over the previous fifty years.

However, most recently a simple semi-empirical model for predicting the draught requirement of a wide range of primary tillage implements was developed by Desbiolles (1994). This approach was based on a concept proposed by Godwin and Spoor (1977) which is applied to a single 45 rake angle tine working in a reference soil condition. Such model describes the soil properties in terms of a Soil Strength Factor (S.S.F.) and specify the tine in terms of a Tine Geometric Factor (T.G.F.) theoretically determined, where the product of both factors at a certain depth, gives the standard-tine draught D as :

$$D_{st-tine} = S.S.F. \times T.G.F. \quad (2.33)$$

This concept was extended to any single tillage tool, such that their Geometric Factors could be empirically determined :

$$G.F._{tool} = D_{Tool} / S.S.F. \quad (2.34)$$

Consequently, a comparative draught-relationship (tool Index I) was established in laboratory soil conditions for each tillage tool as follows :

$$I = \text{Tool draught} / \text{Standard-tine draught} \quad (2.35)$$

This relationship then was validated in filed environment to form the basis a prediction model in the form of :

$$\text{Predicted tool draught} = I \times \text{Standard-tine draught} \quad (2.36)$$

His investigation demonstrated that such model can achieve a good performance in a wide range of soil conditions for both single tillage units and full implements within 20% prediction error on average.

The other part of Desbiolles study is that he correlated between the S.S.F. parameters and cone-index (C.I.) data (i.e. the area under the curve of the cone index-depth relationship AreaC.I.). He produced a new simple semi-empirical approach for predicting the tillage implements based on using cone-index data in the form of a multiplying factor as :

$$F_{\text{mult}} = \text{S.S.F.} / \text{AreaC.I.} \quad (2.37)$$

The prediction method was found satisfactory in sandy-loam soils (within 20% on average), but less reliable in clay soils (within 40% on average). This approach provides a quick and simple estimate of the expected draught requirement of tillage implements in a particular field condition.

Kirisci (1994) as a parallel research project to the above reference has developed a field method for predicting the draught force of tillage implement under different field soil conditions. It was based on the same concept of Godwin and Spoor (1977). His prediction method includes two stages. Firstly, measuring the draught force acting upon the standard. Secondly, determining the Soil Strength Factor for the field by using the measured tine draught and a geometrical factor from the work of Desbiolles (1994). Then the force requirements of the implements at operating depth were predicted using Eq. (2.34). The predicted values were compared with the measured draught of full tillage implements conducted in the field.

He found that the model was adequate for predicting the draught of tillage implements within a $\pm 20\%$ error if two extremes cases are ignored considering the variation in both geometrical and soil strength factors. This method has the advantage of that it does not require to measure soil strength properties and a simple standard tine can be used to predict the draught requirements for a particular field.

2.4 Methods of ballasting recommendations

Ballast recommendations for a farm tractor are usually referred to parameters that are known or easily determined such as tractor weight and PTO power. Ideally, these recommendations are based on the ratio of tractor weight to its available power. To obtain maximum power output for a wheeled tractor there has to be an appropriate matching between essential parameters such as tractor power, weight, actual speed and draught force.

The optimum combination between these factors aids the tyres to transmit the tractor torque to the ground in a form of useful power which enable a tractor to pull, efficiently, an implement in addition to moving its self. Several rules and methods have been offered in recent years to predict tractor field performance based on the amount of ballast added. Most of these methods try to provide certain recommendations of optimum weight/power ratios at different speeds for the tractor working in field conditions.

Charles (1967) attempted to provide guidelines for establishing the optimum tractor condition required for the Nebraska Tractor Standard Test so the tractor can perform to its optimum drawbar-horsepower capabilities, 2WD tractors in particular. He stated that there are many considerations should be investigated before determining the optimum quantity of ballast that must be added to obtain desired vehicle weight. These include the physical dimensions and characteristics of the basic tractor, the operating speed at which maximum drawbar horsepower is to be obtained and the type of ballast used to obtain the required axle weights. He suggested that the rear axle ballast should be added in the correct quantity to achieve a maximum horsepower at a slip rate of as near 5.7 % as possible and at some travel speed between 6.4 and 8.8 km/h.

Reece (1968) gave relationship between tractor power, weight and working speed of the form of :

$$\frac{W}{E} = \frac{\epsilon (1-i)550}{X \mu K' v 1.47} \quad (2.38)$$

where:

- W = total tractor weight (lb)
- E = engine power (hp)
- i = slip (%)
- ϵ = transmission efficiency (%)
- X = slip function
- K' = weight utilisation factor
- μ = coefficient of traction
- v = field speed (mph)

He proposed some appropriate values for each term in the equation when working with 4WD tractor. Thus, when these values used considering a slip value of 20% and coefficient of traction of 0.865 as he suggested, his ballast recommendation for 4WD tractor becomes as :

$$W/E = 318/v$$

which can be written in metric units as :

$$W/P = 0.85/V \quad (2.39)$$

where :

W = total tractor weight (kN)

P = engine power (kW)

V = forward speed (m/s)

Brixius and Zoz (1976) produced a ballasting recommendation for 4WD tractors which was of the form :

$$W/P^* = 1.48/V \quad (2.40)$$

They quoted a design value of 13% for slip and 0.5 for coefficient of traction.

Domier and Willans (1977) examined various combinations of forward speed and ballast on different field surface conditions. He found the maximum tractive efficiency usually occurs at a gross traction ratio of 0.4 to 0.5. He came to the conclusion that weight to power ratio of 60 kg/kW for 2WD tractor was the best compromise value at field speeds above 8 km/h .

Dwyer (1978) used an average values from field tests on the tractive performance of tractor drive tyres in many different field conditions to produce the optimum weight on the drive wheels per unit of axle power to ensure operation at maximum efficiency. He observed that for a 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 and the highest tractive efficiency likely to be attained by a wheeled vehicle in most field conditions was about 70%. He gave the following equation to calculate optimum ratio for the power required at the driving wheels to the weight carried by them, related to the speed as :

$$W/P^* = 1.75 /V \quad (2.41)$$

where P* is the total axle power.

However, Gee Clough et al. (1982) cited a slightly different equation for Dwyer (1978) as :

$$W/P^* = 1.79/V \quad (2.42)$$

He suggested operating at a slip value of 10% and coefficient of traction of 0.4.

Gee-Clough et al. (1982) developed ballast recommendation based on traction prediction equation assuming that if slip is held at 20% then the minimum value of the ballast number to ensure the tires can deliver the available tractor power is 1.26. Thus :

$$W/P^* = 1.26/V \quad (2.43)$$

Brown (1982) discussed tractor ballast recommendations based data from Australia, USA and the UK. He developed an equation to predict operating weight for agricultural tractors in the form of :

$$W' = 282.1 / [V \times \eta/\mu] \quad (2.44)$$

where :

W' = dynamic mass needed on the driving wheels kg per kW of PTO power

V = actual speed in km/h

η = tractive efficiency

μ = coefficient of traction

Thus, for any given working speed the mass required per PTO kW to achieve maximum tractive efficiency depends on the value of η/μ at maximum tractive efficiency. He assumed that the value of η/μ at maximum tractive efficiency was found relatively constant over a wide range of tractive conditions and $\eta/\mu = .55$ was chosen as a basis for ballasting recommendations. He suggested that the ballast recommendations for 4WD and for 2WD tractors respectively as :

$$W' = 500/V$$

$$W' = 600/V$$

Bloome et al. (1983) suggested that when performance is traction limited, a minimum ballast is given by the following equation assuming a coefficient of traction of 0.5 at 20% wheel slip is reasonable :

$$\text{km/h} \times \text{kg} \times 1/\text{PTO power (kW)} = 540 \quad (2.45)$$

which can be written in the following form and in metric units as :

$$W/P^* = 1.4/V \quad (2.46)$$

Rutherford and McAllister (1983) from A.D.A.S. and N.I.A.E respectively have adapted the following formula to guide farmers for determining the optimum load on the driving wheels of the tractor as :

$$\text{Optimum load on driving wheels (kg)} = \frac{650 \times \text{PTO power (kW)}}{\text{speed (kmh)}} \quad (2.47)$$

The total weight on the driving wheels is considered to include the static weight on the axle plus the weight due to implement (both from manufacture data or Weigh Bridge figure) plus the amount of ballast required (cast iron weight or water).

They have produced a simple slide calculator which works out the above equation. It also gives guidance on the selection of suitable tyres.

Zang and Chancellor (1988) developed an automatic control system of ballasting position which used with a 67 kW, two wheel drive tractor and sensed the soil vertical reaction at the front axle. The control system moved 1000 kg (two 500 kg weights on each side of the tractor) in a fore and aft mode to maintain this reaction force at a predetermined, safe, but otherwise minimum level. They found that the system resulted in improvements in tractive performance and fuel efficiency of two wheel drive tractors during tillage of about 5% over the performance of such tractors when operated without variable proportioning systems.

2.5 Instrumentation systems

With the development of various types of agricultural tractors and implements for the manipulation of soil in the best way to meet crop requirements, the necessity of a thorough understanding of soil forces subjected by implements and tractors has become more important. The forces developed at the implement working in the soil are transferred to the tractor through the tractor/implement interface. Accurate measurement of these forces is in respect of estimating tractive ability of the tractor and implement draught requirement. The instrumentation and data logging systems are an essential tool in this context.

2.5.1 Three point linkage dynamometer

Implements are connected to the tractor in two ways, either by drawbar (trailed) or by three point linkage (mounted). In the case of trailed implements, measuring of forces can be simply be done by inserting a dynamometer between the tractor drawbar and the implement. However, it is rather difficult to measure forces when implements are attached to the tractor through three point linkage. Various force measuring systems and three point linkage dynamometers have been used since 1960s. All the recent designs have used electrical resistance strain gauges to measure the forces in a specially constructed load cells.

Most of the designs (Frame type) require special attachments to be fitted in between the tractor and the implement which necessitates moving the implement back from its original position and often creates difficulty in interchanging the implements. Some designs (Link type) have problems associated with calibration and cross sensitivity.

Kirisci (1994) reviewed a list of different designs for the three-point linkage dynamometers, discussed their uses and explained their advantages and disadvantages.

2.5.2 Tractor rear wheel torque meter

The torque applied to driven wheel of a tractor can be measured by using a torque meter system. This is useful in studies requiring a knowledge of the applied wheel torque such as weight transfer studies.

Anderson et al. (1974) designed a torque meter to measure the torque applied to the tractor rear wheel. The sensing elements of the transducer were manufactured from En 24 steel heat treated to give a minimum yield stress of 700 MN/m². He listed the requirements of a driven wheel torque transducer for use in agricultural studies as follows :

- installation with minimum disturbance to tractor construction,
- negligible vertical and side load interactions,
- ready interchangeability, and
- low hysteresis and good linearity.

This system was limited to measure only the applied torque and not to measure the vertical forces on the driven wheels.

2.5.3 Tractor rear wheel torque and weight meter

An alternative technique to determine the relationship between the tractor performance and the draught force requirement of the tillage implements is using the tractor wheel torque/weight dynamometer. This type of instrumentation has the advantage of :

- direct measurement of the forces applied on the tractor wheels,
- it can be used with any field implement regardless of the type of implement attachment,
- the direction of the forces between the tractor and implement does not need to be determined, and
- with universal modified wheel discs this system may be fitted to a wide range of tractors.

The measured forces on the tractor wheel can be resolved into two components. One is a vertical force representing the dynamic vertical load on wheel and the other is a horizontal force representing the thrust exerted by the wheel. Dynamic weight in this context means the average forces transferred from the working implement; it does not refer to the dynamic loads caused by the mass inertia effects due to high speed travel.

Watt (1991) and Al-Suhaibani et al. (1994) developed an instrumentation system to measure the tractor and implement performance in the field. As a part of the instrumentation a wheel torque/weight dynamometer was designed and mounted on an MF 3090 tractor.

The design replaces the standard wheel centre and connects the wheel hub to the wheel rim by two rings. The outer ring, which is connected to the wheel rim, is jointed to the inner ring, which is connected to the wheel hub, by three pairs of links. Each pair of links has a load sensing clevis bolt at one end and a plain clevis bolt at the other end. Each load sensing clevis bolt is orientated so as to measure the force being transmitted along each pair of the links. The pairs of links are equi-spaced on and tangential to a circle between the rim and the hub (Fig. 2.1).

The design includes a shaft encoder which is used to determine the angular position of the wheel at the rate of 100 pulses per revolution and hence the direction of measured forces. The shaft encoder also provides a signal marker pulse per revolution which is used to mark the start of the count for the wheel angular position pulses. These counts are used for the calculation of the component of the wheel forces. The shaft encoder is mounted on the mudguard above the wheel and the motion of the wheel is transmitted to it by a flexible drive. The signals from the load sensing clevis bolts move through amplifiers and then through the flexible drive to a slip ring unit which is mounted next to the shaft encoder. The signals from the three load sensing clevis bolts and from the shaft encoder are passed to an onboard data logger to be stored.

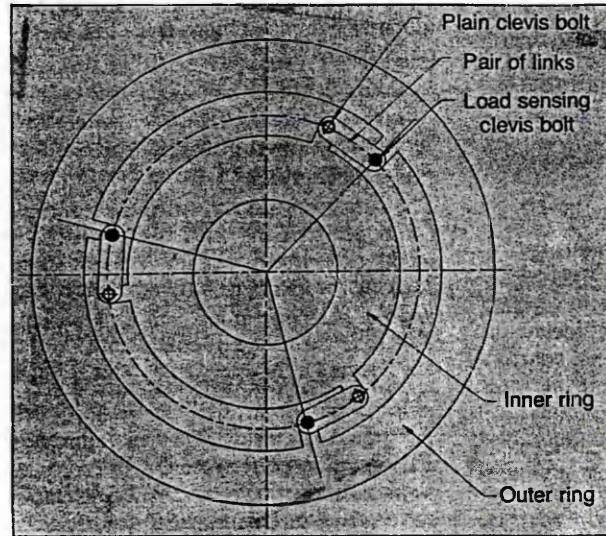


Fig. 2.1. A schematic layout for the wheel torque/weight meter system
(from Watt, 1991)

To calculate the forces acting between the rim and the hub, the forces F_1 , F_2 and F_3 along the line of the three links of a wheel are measured and their vertical and horizontal components are computed and summed (Fig. 2.2) according to the following equations:

$$\Sigma F_V = F_1 \cdot \sin \theta + F_2 \cdot \sin (\theta + 120^\circ) + F_3 \cdot \sin (\theta + 240^\circ) \quad (2.48)$$

$$\Sigma F_H = F_1 \cdot \cos \theta + F_2 \cdot \cos (\theta + 120^\circ) + F_3 \cdot \cos (\theta + 240^\circ) \quad (2.49)$$

where ΣF_V is the summation of vertical forces and ΣF_H the summation of horizontal forces. The transmitted torque can be computed by summing the forces in the three links and multiplying by the radius to the links.

This system provides a reliable method of measuring dynamic forces on driven tractor wheels facilitating the study of wheel tractive performance parameters.

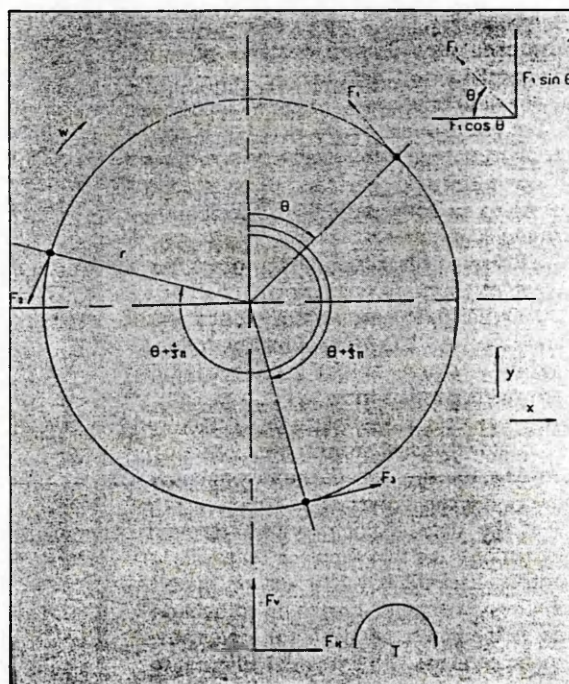


Fig. 2.2. Force diagram for the applied forces on tractor wheel
(from Watt, 1991)

2.5.4 Measurement of speed and slip

Wheel slip at a given operating load is an important parameter when optimizing the tractor performance performing a particular field operation. Since tyres and tracks operate at their maximum effectiveness within a certain range of slip, an operator can use slip as indicator if a tractor within an optimum band for a particular soil and load condition.

Slip is calculated from two other measurement values, usually speed or distance travelled where one being the measurement under load and the other being the measurement without load. The slip value is commonly expressed as a percentage in the form of the following formula (Turner 1993) as :

$$\% \text{ Slip} = \frac{\text{unloaded quantity} - \text{loaded quantity}}{\text{unloaded quantity}} \times 100 \quad (2.50)$$

When speeds are used, the loaded quantity is the actual vehicle forward speed and the unloaded quantity is the tyre or track surface speed. However, when distances are used, the loaded quantity is the distance measured after performing a certain load and the unloaded quantity is the true distance measured without load.

Turner (1993) reviewed a wide variety of methods and devices developed to obtain the two measurements for slip calculation. These methods fall into two groups, research project methods and on-farm methods :

(1) Research project methods

Those methods where an particular tractor is used with some modification made before the tests and where accurate measurements are important.

The research methods used for measuring vehicle forward speed include :

- Measurement of the rotation a non-powered vehicle wheel.
- Measurement of the wheel rotation of some form of additional or fifth wheel device.
- Measurement of vehicle speed directly with a doppler effect device (i.e. radar or ultrasonic unit).

Research methods to measure wheel surface speed include :

- Measurement of the driven axle rotational speed.
- Measurement of the speed of the engine or a drive train component.
- Measurement of the speed of the PTO shaft.
- Measurement of the surface speed of the tyre with a doppler effect device radar.

(2) On-farm methods

Those methods involved no modification to the tractor and less accuracy is obtained or required which can be grouped into :

- Performance monitor usage (typically a doppler radar unit supplied by the tractor manufacturer).
- Manual distance or wheel revolution counting.
- Visual inspection of the tyre rut in the soil.

2.6 Soil compaction

2.6.1 Introduction

The compaction of agricultural soil is a most complex and involved soil feature and has significant interrelationships with most of the identified physical, chemical, and biological properties of soils as well as with environmental factors such as weather, tillage and agronomic treatments, and crop use. In addition, the state of compaction of a soil largely determines the physical and related chemical soil conditions that control both the responses of crop plants required for effective farming and the conservation of soil and water needed for a permanent agriculture.

Soil compaction is now considered to be a multi-disciplinary problem in which machine-soil-crop-weather interactions play a great role and which may have dramatic economic and environmental consequences in world farming. Compaction problems are of world importance, particularly where advanced mechanization form a significant party of the agricultural production techniques. The development of modern agriculture has resulted in a trend towards an increase in the power of tractive devices. This in turn led to larger equipment which, besides having higher capacity, apply higher loads, higher pressures and greater soil-working forces to the soil with which they interact. However, wheel traffic and other associated soil-engaging tools are not the only cause of compaction, climatic and biological factors may also contribute to this effect.

Soil compaction can be defined as a process of densification in which porosity and permeability are reduced, strength is increased and many changes are induced in the soil fabric and in various behaviour characteristics (Soane and van Ouwerkerk 1994). Compaction results in changes in various soil properties which may impose a considerable effect at the end on plant growth and yield characteristics. The most obvious and direct effect of soil compaction is the decrease in volume and size of large pores resulting in an increase in soil density. The state of compactness affects many properties including the pore size distribution, the air-filled porosity, the water retention characteristics, the hydraulic conductivity, the various soil strength characteristics and other properties.

2.6.2 Effects of compaction on the soil properties

It is essential to consider the effects of compaction by vehicles on the soil properties to assess the incidence of plant crop responses to soil compaction. Effects of compaction on the most important soil properties are discussed briefly below :

(1) Soil microstructure

Microstructure encompasses all aspects of soil structure that are revealed when soil structure is examined at a magnification of x5 or greater. The microstructure plays a great part in determining the properties and behaviour of soils as it regulates and influences many processes in the soil (Soane and van Ouwerkerk 1994). Changes in

microstructure due to compaction mean changes in microporosity and particle arrangement in the groundmass. During compaction, either by cultivation activities or by field traffic, voids are reduced in size and changed in shape, they may become deformed or disrupted, or disappear completely. Consequently, soil properties and soil behaviour change considerably.

One factor influences the compaction of the groundmass is when the soil is subjected to a load such as by farm machinery. Changes occur within the groundmass leading to a collapse in the arrangement of the primary particles, whereby fine material i.e. clay particles will flow and be squeezed between larger sand and silt grains. Another factor is effect of shear when the soil is subjected to shear stresses, during loading, as may be the case during a tillage operation. This may cause shear failure which is characterized by a general realignment of soil particles.

(2) Soil hydraulic properties

The soil compaction process increases soil bulk density and decreases total pore spaces. As a result soil hydraulic properties, infiltration and water retention are significantly altered. Field traffic has a fundamental influence in this context and ponded water in wheel ruts demonstrates an obvious example of the adverse effect on soil permeability of compacted soil. Another effect of loading on a soil is shear without a significant change in volume which, associated with traffic and implement use in wet soils. The direct influences of compaction on hydraulic properties may control infiltration and redistribution of water in the soil profile. This process has many indirect and great effects on plant rooting and growth, such aeration status, soil mechanical resistance to rooting and uptake of water and nutrients.

Measurement and interpretation of the effects of compaction on soil hydraulic properties are often difficult because compaction and soil loosening action usually take place spatially within the same unit implement width. Although a variety of methods are available for in field measurements and subsequent laboratory measurements on undisturbed samples, but there is no direct method to estimate soil water properties from a given tillage system and specified soil properties before tillage. However, soil water properties can be estimated in general from a knowledge of soil structural properties after tillage completed.

(3) Soil aeration properties

Soil aeration is a dynamic soil process which concerns the exchange of gases between the atmosphere and the soil air to support aerobic respiration by plant roots and micro-organisms. Soil aeration is a function of soil structure, water potential, bulk density and soil respiration rate, all of which are affected by soil compaction. There are a number of important indicators of soil aeration in the field, such as air-filled porosity, air permeability and oxygen diffusion rate. Soil aeration appears to be most impaired by compaction near the surface, although compaction of the layers deeper in the soil profile can limit drainage and increase possibility of waterlogging to occur.

Soil aeration is, generally, a problem for plant growth in wet soils where the oxygen supply can not meet the demand and anaerobic zones may develop. This can obstruct or kill growing plant roots, can cause the production of harmful components or the loss of available nitrogen by denitrification.

(4) Soil strength properties

Soil strength is normally defined as the resistance which has to be overcome to cause a given soil deformation. Soil exhibits strength in resistance to volumetric compression and in resistance to linear deformation of soil structural material. In both of these modes of resistance, strength of a particular soil at a given moisture content generally increases with increases in compactness or density of the soil. The major factors affecting specific relationships between soil strength are moisture content, soil texture i.e. particle-size distribution, shear deformation, clay type and cation species. Soil density, however, affects the parameters of resistance to linear deformation including tensile strength, shear strength, penetrometer resistance and pulverization energy (Barnes et al. 1971).

2.6.3 Factors causing soil compaction

Soil compaction can be caused by a number of factors or forces which either are generally manmade or those of natural characteristics of soil formation. These factors might be divided into two broad types, internal and external.

(1) The external factors

External factors or forces are those applied to some boundary of soil mass. Vehicles and tillage tools are the most sources of external forces. Mostly they are mechanical and relatively easily identified and measured. They also are generally within man's control. Increased sizes, weights, and traffic have led to increased applications of these forces to soils.

Today's larger farm tractors, unquestionably comprise the primary source of compaction forces in tilled agricultural soils. Large tyres also have been adopted as an effort to cope with these type of tractors and to keep the nominal ground-contact pressure of wheels nearly constant as tractor weights have increased. Tillage and harvesting equipment also has increased in size. In general, implements which cause the soil to move tend to create localized compaction i.e. blunt cutting edges, high coefficients of friction or adhesion at the soil-metal sliding interface, and improper rake angles can produce compactive forces.

Both distribution of the forces within the soil mass and the sinkage of the surface should be considered eventually to obtain a good understanding of soil compaction. Different relationships are available which predict the surface stress from easily measurable tyre and vehicle characteristics (Soehne, 1958; Vanden Berg and Gill,

1962; Koolen and Kuipers, 1983). However, because of the complex geometry of tyres and farm vehicles, it has been difficult to develop a relationship that will apply to a range of soil and tyre types and vehicles working conditions such as vehicle speed and slip. There are also various models of predicting soil compaction which represent soil stress-strain relationships and the propagation of stresses in the soil profile are reviewed by Soane and van Ouwerkerk (1994).

However, the challenge is still present to link the existing soil compaction models with crop growth models. The latter reference stated that a crop growth model that simulates the soil compaction process starting with the weight of tractors, contact area between the tyre and the soil surface, and soil firmness properties such as wetness and initial bulk density does not exist. The crop growth models generally simulate a compaction event by physically inputting the new bulk density of the soil with no description for how this bulk density was determined, what surface load was applied, or the effect of soil moisture at the compaction time.

(2) The internal factors

Internal factors are those that originate within the soil mass and most of them not easy to identify and measure. The natural agents that may alleviate undesirable effects of soil compaction might be summarised as following (Barnes et al. 1971) :

- The interaction of climatic, biological and management factors.
- Natural events such as freezing and thawing and wetting and drying which produce stresses due to uneven expansion and contraction.
- Soil animals and plant roots employ forces that may compact the soil near their paths. This biological activity results in a decrease in the average bulk density in the long-term.

2.6.4 Methods of measuring soil compaction

Compaction of soil is seldom measured directly. The usual procedure is to determine the change in a parameter or a set of parameters as a consequence of a compacting force. Measurements can be conducted either in a laboratory where the soil is removed or altered in some way or in-place without altering the soil i.e. in a field. Various methods for measuring compaction effect are reviewed by Barnes et al. (1971); Soane (1981); and Soane and van Ouwerkerk (1994). No one method or measurement can be applied universally, since each has advantages and limitations. The one to be used should be selected to provide the most efficient and effective results for the particular task.

The present section represents the most common methods which are reasonably used in many soil compaction studies. These methods might be grouped according to the properties to be measured in compaction assessments as follows :

(1) Soil bulk density

The bulk density is the most fundamental and widely used property to quantify such changes accompanied by an increase of soil compactness by the application of mechanical loads. Soil compaction is usually described in terms of soil dry bulk density to allow soils at different water contents to be compared.

A wide range of methods is available for measuring soil bulk density, but no single one is the most suitable for all circumstances. Methods of soil bulk density measurement generally fall into one of two groups, direct and indirect. Campbell and Heshall (1991) described both of these methods, explained theoretical basis and discussed their use in traffic and tillage research which can be summarized as below :

I. Direct measurement methods

In these methods, both the mass and the volume of a soil sample are determined. Most such methods are long-established and require relatively inexpensive apparatus. Basically, these direct methods differ from each other in the way in which the sample volume is determined which depend largely on the soil type and field conditions, however, all the methods have some limitations. These methods include the followings:

- core sampling
- sand replacement
- rubber balloon

II. Indirect measurement methods

These methods usually are based on radiation methods, in which a gamma rays emitted by a radioactive source are absorbed or scattered by a soil sample. This absorption or scattering radiation is used to give an indirect measurement of soil bulk density. Thus, the radiation methods are either transmission or backscatter gauges.

While direct measurement methods are cheap and simple to use, they have inherent errors and often prove to be very slow and tedious, especially if large numbers of samples have to be taken at different depths in field soils. However, although the use of the radiation methods generally results in more accurate and precise measurements, they too have limitations, including complexity and cost the necessary apparatus. In addition to the need for higher technical skills and safety regulations.

As far as the core sampling method is concerned, in this method an open-ended, metal cylinder pressed or hammered into the soil. The cylinder is then excavated and weighed together with the soil core after the latter has been trimmed flush with the cylinder ends. As the volume of the cylinder is known, the bulk density can be calculated. This method is still widely used, possibly because the equipment required is probably the cheapest and simplest to use. Also it usually the method with which radiation methods are compared when the latter being assessed. In the many comparisons which have been made of the core sampling and radiation methods, the

two methods have been found to be in general agreement. This method is susceptible to error arising from compression or shattering of the core while the cylinder is inserted, therefore more care should be taken when inserting the cylinder to minimise this error. Careful repacking of field soils into containers and calculating their bulk density from sample mass and volume has been shown to be more satisfactory (Soane et al. 1971).

(2) Soil strength

Soil strength varies with change in its moisture content and density, but it also can provide a basis for determining changes in the state of compaction. However, measuring soil strength is not a simple process because of the complex interaction of the stresses of different types applied to the soil during measurements.

Soil strength tests can be conducted on samples that have been extracted from the soil or directly on the soil in the field. Tests in the laboratory usually are complicated and require special equipment, and the procedures are exacting. In addition, it is necessary to obtain good quality undisturbed samples. Therefore, field tests are more desired although they have some limitations. The types of strength test in the field can be placed into two categories as below :

I. Shear tests

Those tests that shear the soil along a surface determined by the geometry of the measuring device. They measure the maximum shear force on an internal horizontal or vertical plan near the soil surface. The most popular test devices for soil strength measurement are discussed in section 2.7.1. Some types of shear test require considerable care in their use which takes time to conduct and more care in obtaining and interpreting the data.

II. Penetration tests

Basically, a test consists of measuring the resistance of soil to penetration of a footing of some kind. Usually, the penetrating elements are either (a) circular or rectangular flat plates or (b) cone shaped tips. The most common penetration device used is the cone penetrometer. The ASAE (1992) specified two standard 30° cone sizes (20.27 and 12.83 mm diameter).

The cone penetrometer is a simple, quick and highly convenient method of measuring compaction to a considerable depth following the general procedure outlined in the Standard S313.2 (A.S.A.E.). The penetration force obtained at a particular depth in the soil is often normalized by dividing by the base area of the penetrometer tip to arrive at the average applied vertical pressure, known as the cone index. This method is applicable to a wide range of soil types. The ease with which a penetration test can be made permits large number of trials and consequently a sufficient amount of data

can be collected in reasonable time, so that an average value can be specified for a particular depth or layer within the soil mass.

The value of penetration resistance that is measured in any soil represents the combined effect of both the cohesive and the frictional characteristics of the soil. This value might also be used in prediction studies of tyre tractive performance as well as in compaction. Freitag (1965) has shown how the cone resistance can be used for purely frictional or cohesive soils to characterize the soil in terms of dimensionless parameters (mobility numbers for clay and sand soils) which are directly related to tyre performance.

(3) Water infiltration rate

A simple method and valuable check on compaction damage to the soil is water entry rate because it is sensitive and closely related to practical problems. This method would be easily understood and carried out by farmers. Quantitatively, infiltration rate is defined as the volume of water passing into the soil per unit of area per unit of time. The rate of water entry into the soil fluctuates widely between soil types and is affected by several factors which the most important include soil type and conditions, biologic and macrostructure within the soil, vegetation cover, slope and surface roughness.

There are several techniques to determine the infiltration rate of soils, however, an appropriate method is used according to a specific task or need. Parr and Bertrand (1960) reviewed various methods that have been used in the characterisation of infiltration rate. One common and simple method is the cylinder infiltrometers which are normally metal and have various types and sizes. Basically, a ring is inserted into the soil to a certain depth to prevent the lateral or divergent flow of water from the rings. In later studies double-ring devices are used so that the divergent flow could be minimized by means of buffer area surrounding the inner ring. Water is added to the rings by means of constant heads or falling heads and the water level in the inside ring is periodically measured with a hook gauge or scaled stick from the top end of the ring. In some circumstances an automatic self recording infiltrometer may be used. It has the advantage of the automatic recording device which permits a continuous record of infiltration.

The limitation to the use of ring devices is the method of placement in the soil. Because most of the methods of placement may cause disturbance to the natural structural conditions or cause seepage planes in the interface between the soil and the ring side which both result in variation in infiltration data. However, this problem could be overcome greatly by careful ring insertion and also by leaving the rings in place over an extended time before or during a set of measurements if it is convenient.

Davies et. al. (1973) used ring infiltrometers to measure water entry rate for estimating compaction in the wheeling path. He found that water entry rate sensitively detected the differences between treatments and was considered satisfactory technique although it is time-consuming method.

(4) Stress distribution

Stress distribution measurements may provide a useful indication of the mechanics of compaction. The basic concept of this method is to insert sensors of some type within the soil before the compaction event. However, it usually requires a considerable amount of instrumentation and care must be taken during placing the sensors in the soil. In addition, the difficulty associated with the interpretation of stress measurements and obtained data in relation to compaction.

(5) Soil surface deformation

Probably the most obvious visual indication of the occurrence of compaction is the rut left by the wheel. Measurement of the depth, width and cross sectional area of the ruts are a quick and effective way of descriptive measurement of compaction. The shape of the tyre rut may also be related to some parameters concerning the wheel, such as contact area, which are otherwise difficult to measure. Davies et al. (1973) considered the depression caused by the wheel i.e. rut depth to be particularly useful indicator of compactive responses to the wheel passage. However, this primary method is limited to the field conditions. If there is plant residue or stubble, it is not easy to distinguish the tyre rut or relate it to a datum level.

2.6.5 Effect of compaction on plant and crop yield

Actual crop growth is considered to reach the maximum potential when, at any time, the uptake of water, oxygen and nutrients from the soil equals the demand of the crop. Actual crop growth is less than potential if the uptake of one or more of these elements is smaller than the demand of the crop. This may be caused by a limited supply from the soil to the root system or by a limited root activity. Crop yield is the cumulative result crop growth during season which is limited by three important factors: length of the growing period; supply of water, oxygen and nutrients; and root activity. Soil compaction by several means influence these factors resulting in the deterioration in the plant growth and crop yield .

Compaction can affect crop production by changing important soil properties, particularly bulk density, soil strength, particle size distribution and the size distribution and continuity of pores. As a result, these changes affect infiltration rate, water availability, drainage, aeration status, root extension and nutrient uptake where all of which can have a direct bearing on plant growth and consequently crop production.

The relationship between soil compaction and crop growth is a complex system of interacting functional relationships between soil characteristics, crop type and weather conditions, therefore no universal index describing the crop response is exist. Thus, this interaction is conceptually represented in the form of Fig. 2.3 to emphasize that crop responses to compaction will not be qualitatively or quantitatively uniform across all areas. In addition, it is indicated that there an optimum level for maximum crop

yields. Crop growth and yield will decline if the level of soil compaction lies either above or below an optimum value which varies with different soils, crops and weather conditions.

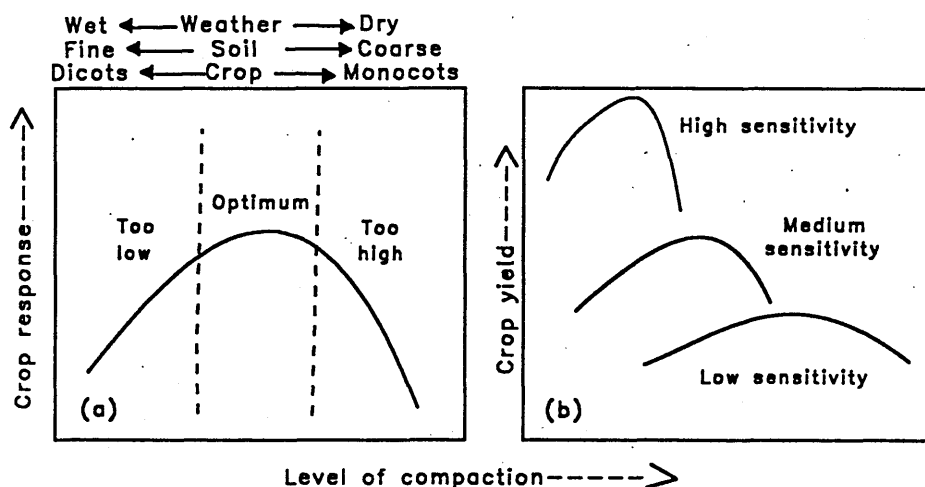


Fig. 2.3. (a). The general relation between crop response and the level of compaction
(b). The influence of crop sensitivity on the variation of crop yield to changes of compaction (from Soane and van Ouwerkerk, 1994)

In some cases when the various soil factors which limit crop growth are available, it can be combined to predict a relationship between compaction in terms of one of soil properties i.e. soil porosity, and crop yield to follow an optimum curve as shown in Fig. 2.4. Although this information indicates the risk of yield losses when soil porosity is outside a specified range but does not provide precise unit value.

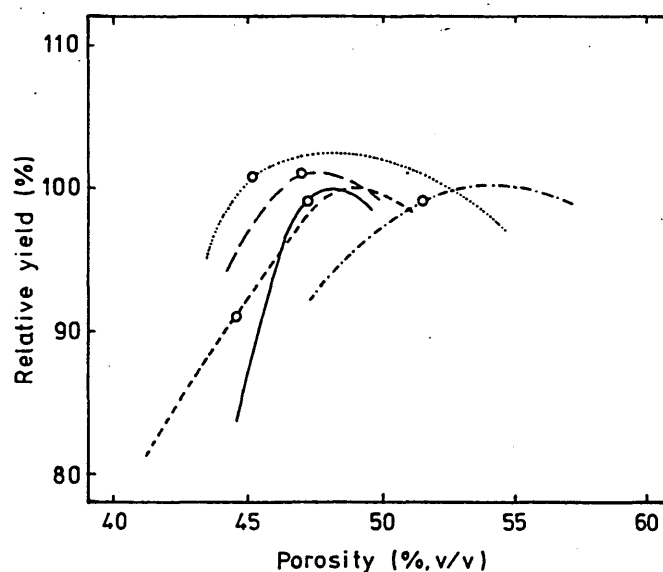


Fig. 2.4. Relative yield of silage as a function of soil porosity in the arable layer of five sandy soils (from Soane and van Ouwerkerk 1994)

Compaction problems have been world-wide importance particularly in North America and most of Europe in which compaction problems have been recognised for a long time. Soil compaction from wheel traffic of modern agricultural machinery and the consequence effects have become one of the major factors affecting yields of cultivated crops in such regions mainly due to:

- the continuous increase in the size and weight of field equipment i.e. primary and secondary tillage operations are undertaken with larger 4WD tractors weighing up to 12-16 Mg and large combine harvesters can have a loaded weight of 24 Mg in the USA.
- the change in cropping systems i.e. row crop culture and continuous crop rotations.
- early crop establishment and used of full season varieties to maximize crop production which often results in field work being undertaken in the spring when the soils are wet and most conducive to compaction.
- the high soil water content in spring resulting from winter rain or snow, particularly in most Europe regions, enhances soil compactability. This has direct effect on soil trafficability, soil workability and harvesting of crops.
- the high clay content and organic matter in such region soils which play an important role in compaction process.
- subsurface compaction below the depth of the normal tillage zone which is a function of the increasing axle load.

Numerous studies and reviews has shown the evidences of the harmful effect of soil compaction on seedling emergence, plant growth, development and yield (Voorees, W.B. 1970; Soane et al. 1982; Soane and van Ouwerkerk 1994 ; ect.). However, most of the information upto now is in the form of a relative effect i.e. descriptive so the plant responses to soil compaction is not quantified in a distinct manner. This is due to the wide variation in crop sensitivity to the compactive effect which implies the need of greater attention to be paid to specify under which site conditions various levels of soil compaction will have a negative or favourable effect on crop production.

Although there are a number of researches trying to link between the soil compaction effect and final crop yield such as that quoted by Soane and van Ouwerkerk (1994) as represented in Fig. 2.5, but it is not quite right to generalized the concept. This figure shows relationship between grain yield of spring barley and soil bulk density in the plough layer for five different soil types. The data indicate that there is very pronounced optimum value, over a wide range of bulk densities, if maximum crop yield is to be obtained. Again these formation applies to a particular type of soil studied under a certain instance which might be not applied elsewhere because the soils i.e. even one type of soil, differs everywhere and the other factors of crop growth are not similar.

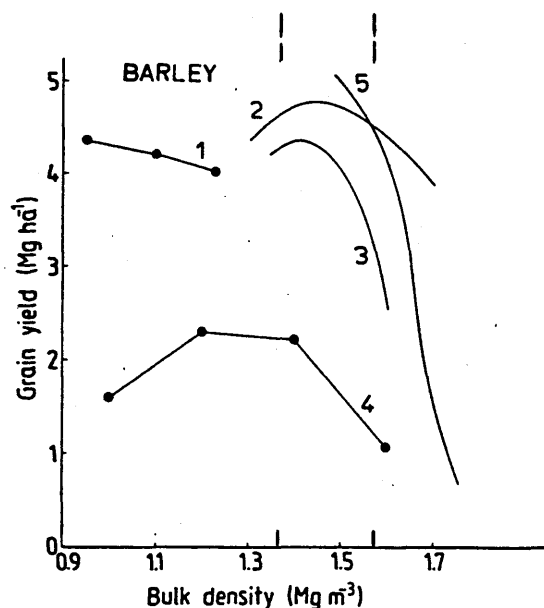


Fig. 2.5. Relationships between grain yield of spring barley and soil bulk density in the plough layer for five different soil types. 1. fine loam, (Russia); 2. loamy sand, (Germany); 3. silty loamy sand, (Poland); 4. light loam, (Lithuania); 5. loam, (former Czechoslovakia) (from Soane and van Ouwerkerk 1994)

Williams (1996) developed a system of movable front weight to reduce the weight variation on a 2WD tractor during the application of Agro-chemicals and fertilizer. Part of his investigation was evaluating the advantage of this system in reducing soil compaction. He found that the system provided a reduction in rut depths of up to 38% over the performance of the standard fixed weight.

2.7 Basic soil properties

2.7.1 Soil shear strength

The amount of traction gained from the tractor and the required draught for the implement in work depend on large on the shear strength of the soil in contact with the traction device. Mostly, the soil strength of soil is evaluated according to parameters of the Coulomb equation (Eq. 2.1) which represents that the limit of soil shear resistance is composed of two components, called soil cohesion c and angle of internal friction.

In most tractive performance prediction of a vehicle moving on soil these two values are considered. In general, soils possess both of these components of shear strength, but there special cases in which only one or the other is observed. The values of c and ϕ vary with the type of soil and its condition. A dry sand, for example, usually exhibits little or no cohesion and is designated as a pure frictional soil having large values of ϕ depending on the density of the sand and the properties of its component particles. Clayey soils are generally cohesive soils with lower values of ϕ , so their strength varies less with normal stress load than sandy soils. Agricultural soils vary within this extremes, having a certain amount of both cohesive and frictional strength because such soils usually contain mixture of course and fine particles and they are partly saturated with water.

Procedures for assessing soil mechanical resistance usually involve the measurement of the force that required to get a given strain, including sudden failure. There are two basic classes of soil strength measurement techniques, namely laboratory and field tests which are well known and standard. Mckyes (1989) described the principle of these methods and discussed their use in soil strength measurement applications.

I. Laboratory tests

Laboratory measurements can in general be controlled more carefully, the amount of water draining from the soil is known more precisely and quantities such as forces and deformations can be measured more accurately. However, it is not easy to assure that the moulded soil sample or that removed from its original location in the field and tested in the laboratory in exactly the same state. In addition, that testing in the laboratory is generally more time consuming and expensive than field mechanical testing. The most common laboratory devices available for measuring soil strength parameters i.e. c and ϕ are :

- The direct shear box
- The triaxial device

As far as the triaxial test is concerned , it is considerably more versatile than the direct shear box test in its ability to control soil strains-stress combinations and the drainage

or measurement of pore water pressure. It provides more flexibility in different measurement applications. This method is based on Mohr circle technique in which the effective principles measured in the test are used to construct sets of Mohr's circles by graphical means i.e. x-y graph. The best fit straight line of the tangent to these circles drawn so that the resulting slope represents the value of ϕ and the intercept is the value of c .

II. Field tests

Measuring soil strength in the field has the advantages of generally speedier results and the possibility of non removal of soil from its natural place. Some field strength tests are suitable for all types of soil, while others are useful only in wet cohesive cases. The most popular field testing devices are :

- Torsional shear box
- Shear plate
- Shear vane
- Sheargraph
- Cone penetrometer

The limitation of the shear vane methods are that they measure the soil shear strength without providing the values of c and ϕ . However, the information received from the penetrometer does not relate the Coulomb soil strength parameters but give an indication of the relative soil strength, density, root penetration, trafficability by vehicles.

2.7.2 Soil deformation modulus

To evaluate vehicle performance in terms of a thrust/slip relationship it is necessary also to consider the strength/deformation characteristic of the soil. When the soil is sheared under a particular normal and shear loads, the shearing strength of the soil increases as it is deformed, up to a maximum value $\tau_{\max}$. After this value is reached no additional strength occurs despite further deformation. The simplified exponential equation (Eq. 2.7) used by Janosi and Hanamoto (1961) of the form :

$$\tau = \tau_{\max} (1 - e^{-j/K})$$

presents the shearing stress/deformation relationship, K being a deformation modulus which varies depending on how rapidly, with deformation, the soil strength reaches its maximum value and j is soil shearing displacement. Theoretically, K is one value for one type of soil but in practical there are different values for K because of the effect of some related factors such as soil variability, moisture content changes and tyre deflection changes. Typical probable value of K (mm) is 12 for compacted soil and 40 for loose one (Crossley and Kilgour 1983).

The evaluation of K may be attempted by the following possible methods.

1. From the results of a sample translational shear test using either :
 - a) translational shear test in conventional laboratory apparatus
 - b) test with a locked track or wheel.
2. From experimental thrust-slip curves.
3. Using the Bevameter.
4. Using Reece' linear shear apparatus.

This method is mainly the approach developed by Komandi (1968) which was described in section 2.2.1. The advantage of such method is that the test could be done with no special measuring instrument (i.e. ordinary load cell) and the values of K are obtained in realistic conditions at typical slip values.

3. THEORY OF STUDY

3.1 Introduction

Various methods of predicting tractor performance and ballast recommendations have been described by various authors (sections 2.2.2 and 2.2.4) , but the approach of Dwyer and Gee-Clough presents a simple and straight forward method more suited for non technical users. This method uses mobility numbers which requires cone penetrometer data form the field. The same information can be used to predict the implement draught requirements (Desbiolless 1994) which can then be used for tractor implement matching (section 7.2.1).

The Dwyer and Gee-Clough equations were based on data collected from many soil types over a number of years. The present study is conducted with the performance on a primarily dry sandy loam soil i.e. frictional soil, so it is necessary to determine if some modification to the theory would find a better prediction to this more closely defined soil type.

3.2 The concept of study

The present investigation aims mainly :

1. to develop a simple prediction methodology based on an existing method which could provide the appropriate combination of the tractor power, weight and forward speed working on a frictional loose soil in particular i.e. sandy loam soil.
2. to validate this prediction approach by comparing the study results with the existing methods to assess the performance of a 4WD tractor operating on such soil.

3.2.1 The existing tractor ballast recommendations

Most of the methods of predicting tractor efficiency tried to develop an proper matching between the tractor power, weight on the driving wheels and working speed to produce an optimum ballast recommendations to optimize the performance of the wheeled tractors. The ballast recommendation usually described as a non-dimensional number R_n and takes the form of :

$$W/P^* = R_n/V$$

This approach has been adopted by a number of workers including Reece (1968), Brixius and Zoz (1976), Dwyer (1978), Gee-Clough et al. (1982) and Bloom et al. (1983) as described in section 2.4. The proposed ballast recommendations of the five approaches are summarised in Table (3.1). They are compared altogether by plotting the relationship between the weight on the driven wheels/tractor power versus the working speed as shown in Fig. (3.1). For the purpose of the comparison, a range of forward speed levels is chosen from tractor catalogue (see Appendix 3).

Table 3.1. The five prediction approaches of ballast recommendations

Worker	Equation	Power (kW)	Weight (kN)	Slip %	COT
Reece	$W^*/P = 0.85/V$	Engine	Total tractor	20	0.865
Zoz	$W/P^* = 1.48/V$	Axle	Dynamic	13	0.5
Dwyer	$W/P^* = 1.79/V$	Axle	Dynamic	10	0.4
Gee-Clough	$W/P^* = 1.26/V$	Axle	Dynamic	20	0.55
Bloome	$W/P^* = 1.4/V$	Axle	Dynamic	20	0.5

Fig. 3.1 shows the variations between the different approaches previously described. As it is seen the curves generated are parallel and have the same trend along with all speed values. However, each approach has a significant difference in the value of the weight per power requirement at any given speed because each of them assumed different values of wheel slip and coefficient of traction.

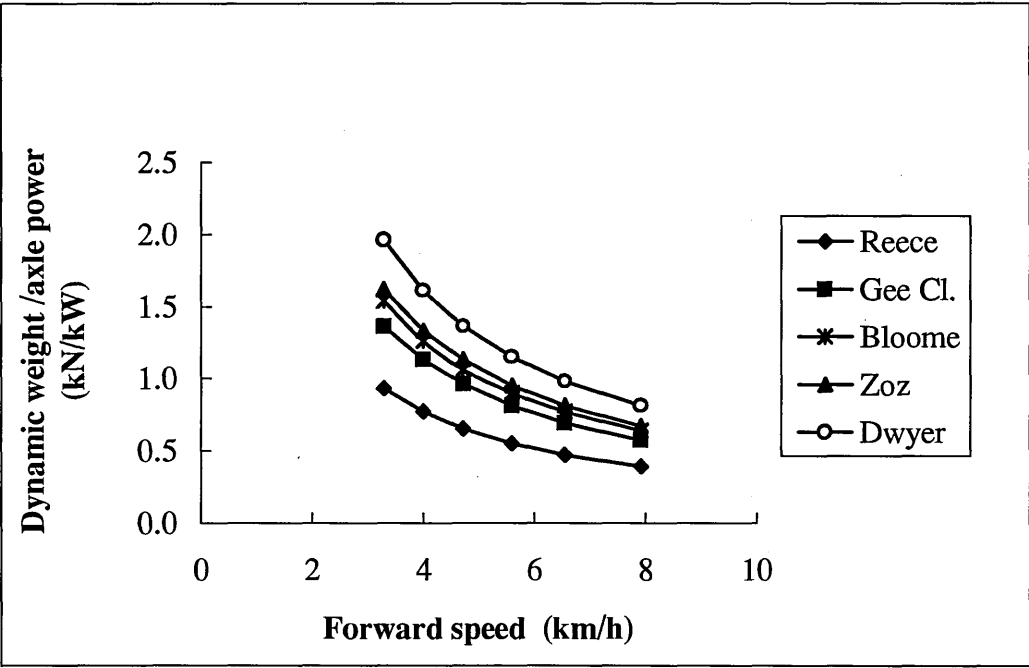


Fig. 3.1. Tractor weight/power & speed relationship for the five approaches

3.2.2 Modification to the ballast recommendations

Theoretically these five relationships should be similar or at least close to each other. However, the variation between these ballasting values are due to each approach suggested an optimum value of slip and coefficient of traction to achieve optimum working condition. In addition, the power figure used in the equations is not constant i.e., engine power and axle power are used, which makes direct comparison of the results difficult.

Therefore, an attempt was made to modify the original formula for each approach so that all of them use similar values of wheel slip and coefficient of traction. This modification was done to hold the slip at two values of 10% and 20%, however the coefficient of traction (COT) was adjusted to be 0.4 as shown in Table (3.2) taking in account that the axle power is used . (see Appendix 3 for modification procedure).

Table 3.2. The five approaches after modification at similar conditions of slip and 0.4 COT

Worker	Equation (modified) at 10 % slip	Equation (modified) at 20 % slip	Power (kW)	Weight (kN)
Reece	$W/P^* = 2.48/V$	$W/P^* = 2.2/V$	Axle	Dynamic
Zoz	$W/P^* = 1.91/V$	$W/P^* = 1.70/V$	Axle	Dynamic
Dwyer	$W/P^* = 1.79/V$	$W/P^* = 1.59/V$	Axle	Dynamic
Gee-Clough	$W/P^* = 1.96/V$	$W/P^* = 1.75/V$	Axle	Dynamic
Bloome	$W/P^* = 1.96/V$	$W/P^* = 1.75/V$	Axle	Dynamic

Again the altered relationships between the dynamic weight per axle available power versus forward speed are plotted as shown in Figs. (3.2 and 3.3). It can be seen that the five approaches, except that of Reece, are very close to each other as was expected. The modified equation of the original formula of Reece is shown to be different from the others because he assumed a high value of coefficient of traction i.e. 0.865 at 20% slip. This value is large compared to the other workers. These workers results are based on many field experiments working on different soil conditions in different countries. Therefore, Reece' equation is excluded in the present investigation.

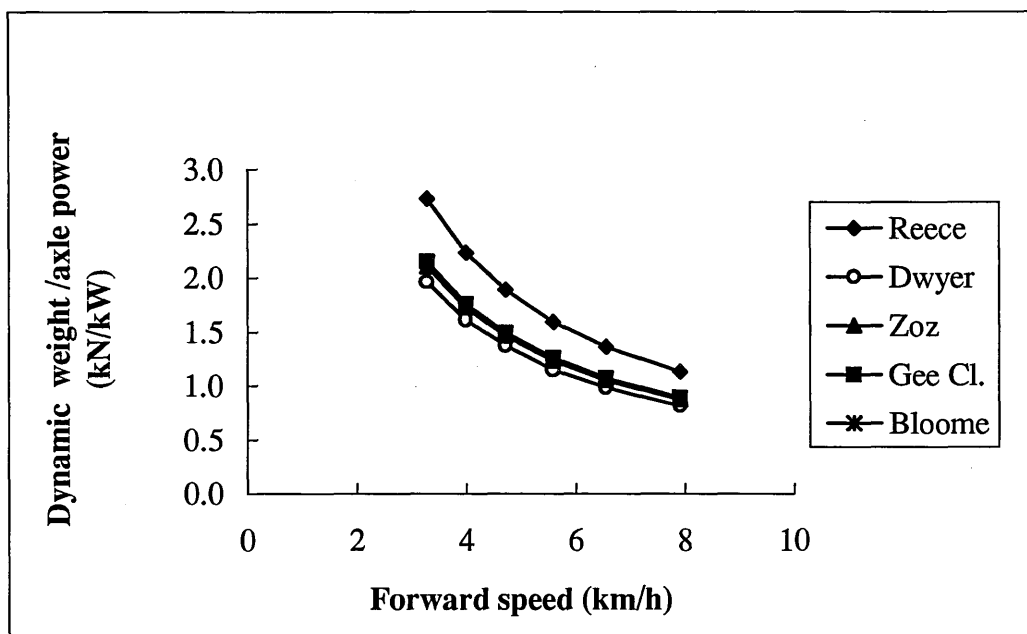


Fig. 3.2. Tractor weight/power and speed relationship for the five approaches at 10% slip & 0.4 COT

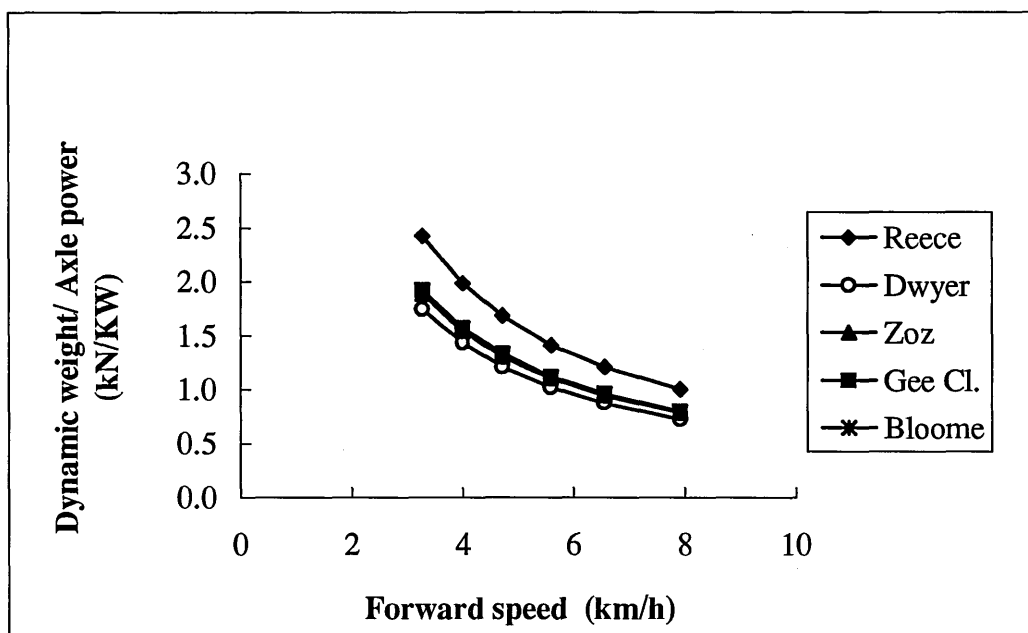


Fig. 3.3. Tractor weight/power and speed relationship for the five approaches at 20% Slip & 0.4 COT

It is found that the average ballast number of the four recommendations when the slip is 20% at coefficient of traction of 0.4 is :

$$W/P^* = 1.7/V \quad (3.1)$$

while when the slip is 10% at coefficient of traction of 0.4 it is :

$$W/P^* = 1.9/V \quad (3.2)$$

The difference between the maximum and minimum recommended numbers among the four relationships after modification is shown in Table (3.3). It is calculated based on the difference between the average value of the recommended number and the highest or lowest one, expressed as a percentage proportion of the average value.

Table 3.3. The percentage difference between the modified approaches

Difference between the average and maximum ballast numbers		Difference between the average and minimum ballast numbers	
At 10 % slip	At 20 % slip	At 10 % slip	At 20 % slip
- 3.2	- 2.9	+ 5.8	+ 6.5

This amount of differences is within an acceptable range normally regarded as satisfactory. However, these average values of the recommended number are taken as a base to compare the measured results with the existing approaches later.

3.2.3 Predicting ballast recommendation for frictional loose soils

The aim here is to predict a new ballast recommendation from field study which could be applied to frictional loose soils in particular. That might be achieved by designing such field experiment involving three variables of tractor ballast weight, working speed and drawbar pull in which the test treatments consist of all possible combinations of the selected levels of the experimental variables. The number of the variables levels are decided based on the field work limitations.

Having measured the variable parameters in the experiment for each test combination, the dynamic weight on the tractor wheels (W), the horizontal draught (H), the actual tractor speed (V) and wheel slip (i) can be determined for each individual test. Accordingly, tractor drawbar power is calculated and a relationship between drawbar power and wheel slip can be produced to determine the best combination which will provide the peak value of tractor power. Consequently, this particular test will propose the optimum matching between tractor weight, speed and pull to achieve the optimum performance.

The measured values of W and V related to the optimum test chosen are taken along with the estimated theoretical axle power P^* (from tractor catalogue) to calculate the value of ballast number R_n which represent the new ballast recommendation number for frictional loose soils where, $R_n = WV/P^*$.

3.2.4 Comparison with the existing data

The next stage in the investigation is to compare the measured results with the existing data to validate study methodology to provide guidelines for optimizing the output for a wheeled tractor performing a draught operation in frictional soils. Three main approaches of comparison may be carried out in this context described below.

3.2.4.1 Comparison with the existing ballast recommendations

The new recommended number R_n will be calculated from the results obtained from the field work and compared with the modified numbers of the different approaches stated previously by plotting them altogether to find out where the recommended value for weak loose soil is relatively located to the theory.

It might be useful for the sake of comparison to assume that the existing approach has two recommendation limits. One is high limit for hard soils and other for soft soils. However, the study prediction is expected to be within the low limit hence the field work will be conducted on mainly loose soil i.e. sandy loam soil.

3.2.4.2 Comparison with the empirical approach

Referring to the work of Gee-Clough et al.(1978) in the literature review, his investigation was based on the work of Dwyer et al. (1974) at S.R.I. (N.I.A.E. previously) in which the tyre tractive performance was assessed on different soil types and conditions including sandy loam soil. Part of the work is investigating the tractive performance of the tyre in terms of the relationship between the maximum coefficient of traction $(C_t)_{max}$ and mobility number M .

It is possible to compare the study field results with the available work data of both of these two workers. It has the advantage of simplicity and the results can be easily interpreted. Such comparison might be done as below :

I. With Gee-Clough et al. (1978) data :

- by determining the value of coefficient of traction C_t from the study field data (i.e. drawbar pull and dynamic vertical load) for each field test conducted.

- calculating the values of both of M and $(C_t)_{\max}$ based on equations (2.16 & 2.28) respectively as stated in Gee-Clough et al. (1978).
- plotting their relationships altogether with Gee-Clough data (i.e. Ge-Clough et al. (1978) Fig. 1) and showing how close the field data is to the existing data.

In addition, equation (2.25) proposed by Gee-Clough et al. (1978) which apply to different soil types and conditions could be modified to be applicable to frictional loose soils in particular and to provide optimum recommendation when a 4WD tractor is operating on such soils.

II. With Dwyer et al. (1974) data

From the available data in this original work, the most relevant information and field working conditions to the current study might be chosen such as tyre size, soil condition and loads used. Similar calculations can be done to estimate the values of M and $(C_t)_{\max}$ based on equations (2.16 and 2.25) and to produce their relationships. Then direct comparison is possible between the field results and the original data to validate the investigation concept. In addition, Gee-Clough data might be also considered in this comparison.

3.2.4.3 Comparison of measured and calculated thrust forces

An alternative way to examine the validity of the experimental results is to compare the measured thrust force H_{mr} with the calculated H_{cal} . The amount thrust of the tractor wheel can exert is given by equation (2.9) referred to Reece (1967) which is rearranged as :

$$H = (Ac + W \tan(\phi)) \cdot [1 + (K/iL) \cdot \{e^{-iL/K} - 1\}] \quad (3.3)$$

However, the total thrust produced by 4WD tractor would be :

$$H = [(A_1 \cdot c + W_1 \cdot \tan(\phi)) \cdot [1 + (K/i_1 \cdot L_1) \cdot \{e^{-i_1 \cdot L_1/K} - 1\}]] \cdot 2 \\ + [(A_2 \cdot c + W_2 \cdot \tan(\phi)) \cdot [1 + (K/i_2 \cdot L_2) \cdot \{e^{-i_2 \cdot L_2/K} - 1\}]] \cdot 2 \quad (3.4)$$

where the subscripts 1 and 2 in the equation refer to the tractor rear and front wheels respectively. To solve this equation all the terms should be known. Therefore, the actual value of each term in the equation could be obtain either from the tractor catalogue i.e. L , b to estimate A or from field measurements i.e. W , i or from laboratory estimation i.e. c , ϕ and K by calculation.

As far as the measurement of c , ϕ are concerned, it was decided to use the triaxial test to estimate the value of c , ϕ because it is considerably more versatile than other laboratory test as was explained in section 2.7.

However, to estimate the value of K there are two approaches:

I. Komandi approach

Komandi (1968) produced a simple method to determine the value of K as it was described in section 2.2.1. Equation (2.13) would be used to calculate K following the suggested procedure.

II. Mathcad calculations

Alternative approach to estimate the value of K is to use equation (3.4). However, because of the complexity of solving this equation it is suggested to use a Mathcad package to simplify the calculations.

The thrust force can be calculated by giving K in the equation a range of values, assuming all the other terms are known, to predict various values of thrust force. Then the measured thrust force for each field test is compared with the calculated one and an appropriate value of K is chosen at the closest values of measured and calculated forces. However, the value of K is expected not to be one value in practice therefore, it is reasonable to take the average of all K values chosen previously and insert it again in the equation. Consequently, the measured thrust force could be compared with the predicted at the corrected value of K .

4. MATERIALS AND METHODS

4.1 Introduction

This chapter represents the detailed information about the design of experimental equipment. It includes the tractor wheel torque/weight transducer developed and other system components. The design considerations selected for the transducers is also given. The gauging, calibration procedure and results are reported. It also includes the developed device for wheel slip and actual wheel speed measurements. The calibration of whole equipment assembly and the operating procedure are described. The data processing system used is explained. In addition, the compaction measurement equipment and methods used are given.

4.2 Design of experimental equipment

Performance data of tractor and implement are essential for farm machinery management as well as for farm machinery manufacturers. The accuracy and dependability of the models and approaches developed for farm machinery depend on the availability and accuracy of data on tractor and implement performance parameters. As one of the objectives of this project, the experimental equipment was developed to measure the vertical and horizontal forces on the tractor wheels as well wheel slip and actual wheel speed. This system enables the evaluation of the coefficient of traction and tractor drawbar power to be calculated directly. Hence, the tractor and implement settings for the best field working conditions can be obtained for the optimum tractor performance.

The designed equipment used for measurement consists of three units for one front wheel and one rear wheel.

1. The modified wheel discs and the transducers located to measure the forces between the wheel and the tractor .
2. The optical sensors and the multi-holes ring to measure the angular position of the wheel and for the determination of the theoretical travel distance.
3. The fifth wheel attachment to measure the actual travel distance to be used in the calculation of actual wheel speed and wheel slip.

4.2.1 Wheel torque and weight transducer

A tractor wheel torque/weight transducer is an alternative technique to measure the torque and forces exerted by the tractor wheels when pulling an implement in a certain field operation. Watt (1991) and Al-Suhaibani et al. (1994) developed and described a transducer that measure the torque transmitted to a tractor wheel, the vertical load on the wheel and the horizontal thrust as mentioned in section 2.5.2. However, their design was too complicated, expensive and difficult to adjust

internally because of its fully protected enclosed design. In addition, it had problems associated with the accuracy.

Therefore, a simple wheel torque/ dynamic load transducer was designed to meet the force measurement requirements in this study. Three transducers were constructed for one rear wheel and another three exactly similar for one front wheel where only one side of the tractor will be equipped and instrumented. The total forces on the tractor are obtained by multiplying the result by two.

4.2.1.1 Design and construction

For the purpose of design, a MF 3065 was chosen as an experimental tractor for the field tests so the developed transducers can be fitted to this type of tractor which is commonly used in Saudi Arabia. The tractor standard wheel disc has been replaced by two flat ring plates for each instrumented wheel, one ring is connected to the wheel rim and the other connected to wheel hub. The outer ring is jointed to the inner one by three transducers i.e. links. Each link has two En 24 T steel pins at each end with two nylatron bushes for each pin serving as bearing unit. The three links are equi-spaced on and tangential to a circle between the rim and the hub.

The transducers were manufactured from a solid block of HE alloy Aluminium and equipped with a strain gauge bridge. The choice of the transducer material is due to the advantage of the following characteristics :

- AL HE 30 has approximately $1/3 E$ (Young Modulus) of steel which will provide approximately 3 times deflection or output of the strain gauges (i.e. more sensitive).
- Relatively cheap and available.
- Easy to manufacture by normal workshop techniques.
- Resistant to corrosion hence, does not require additional protection.

Two types of loading were considered in the equipment design, namely tension forces and side forces. The maximum exerted force through the three transducers of each wheel when they are in tension is assumed to be the combination of the load from the engine torque applied to the wheel plus the load from the vertical ballast weight when operating in the field. However, the wheel transducers may be subjected to a lateral force in certain circumstances such as when the tractor travelling along the direction of a contour line on a slope and /or working with one wheel in furrow (i.e. with mould board plough) .

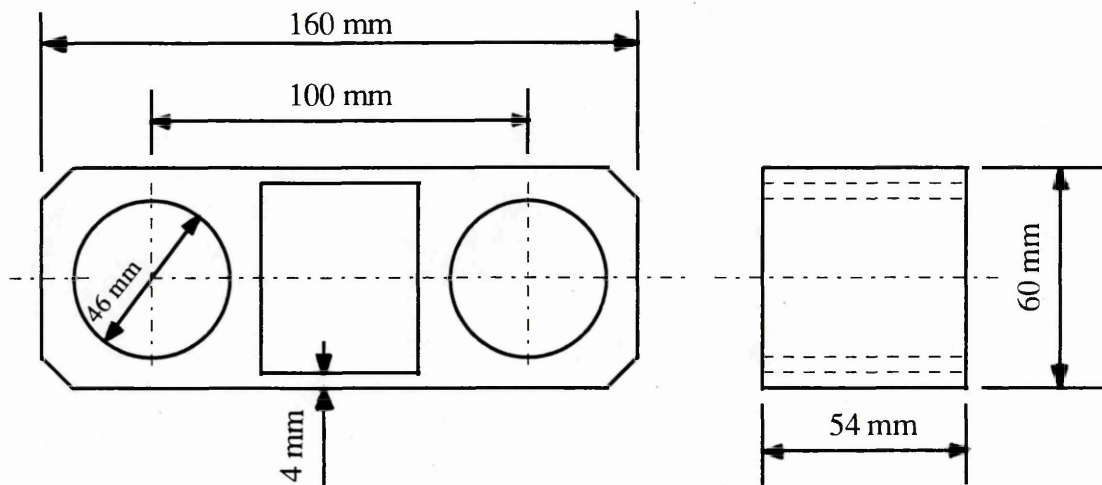


Fig. 4.1. Basic dimensions of the link

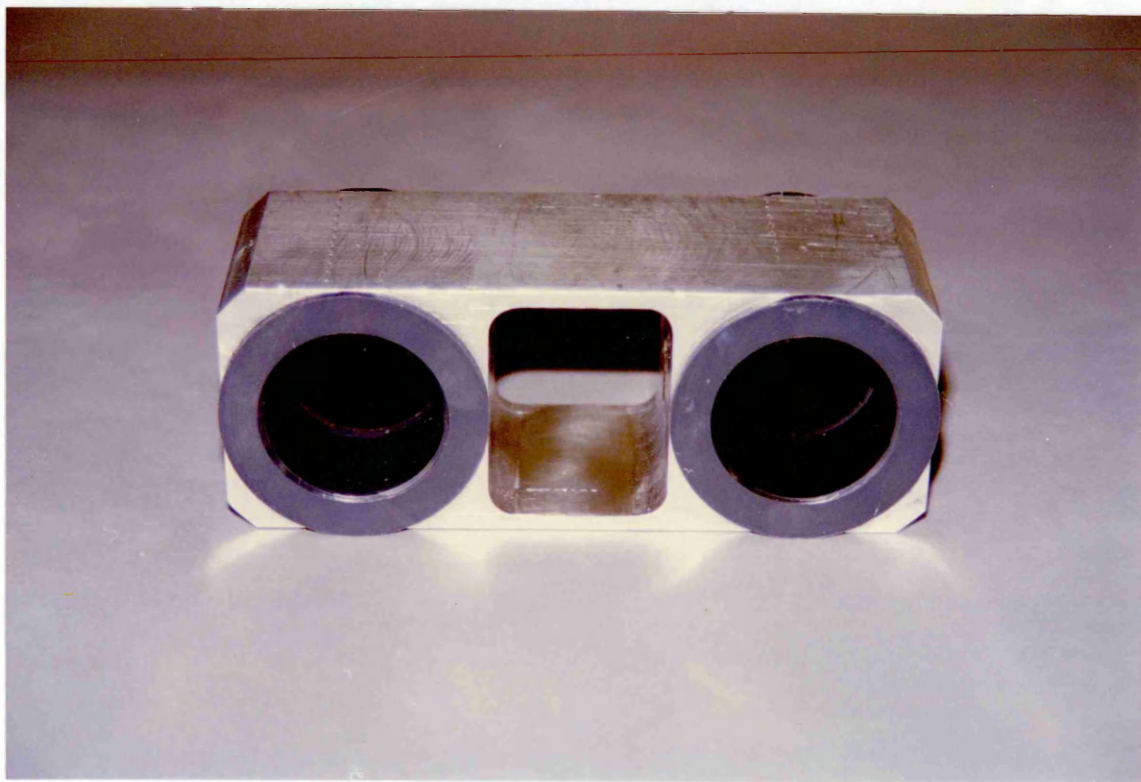


Plate 4.1. The link (transducer) with bushes

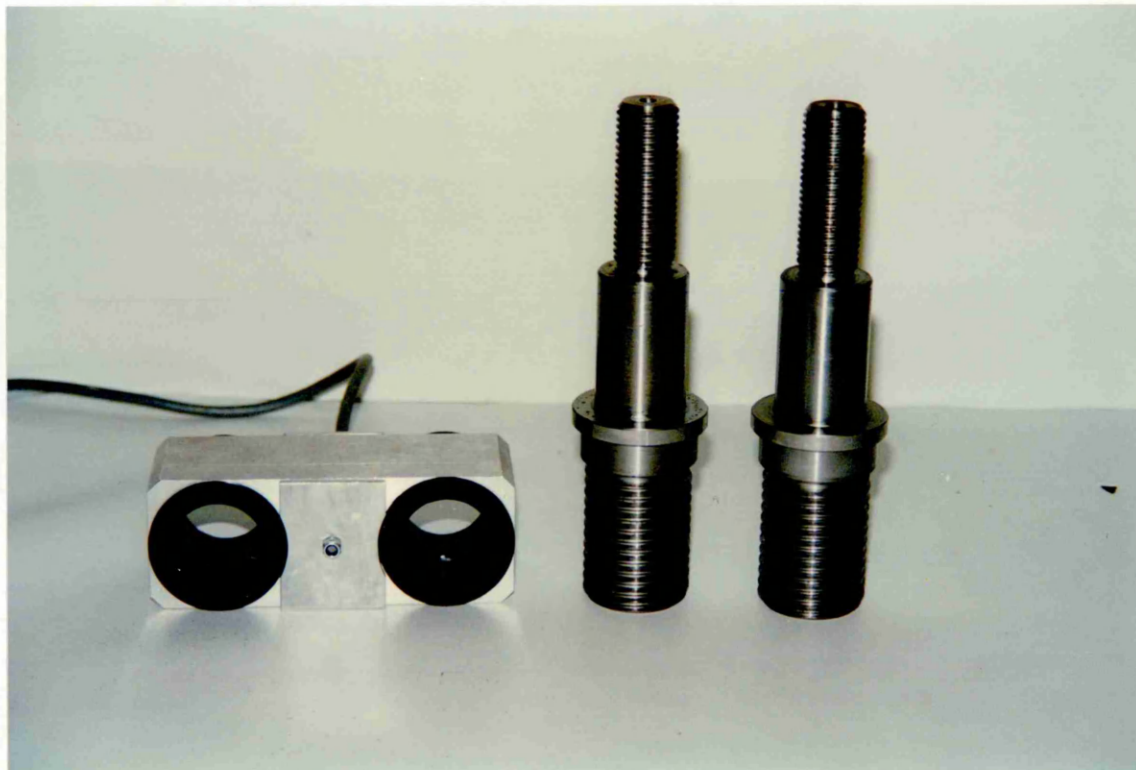


Plate 4.2. The link pins

All calculations relating to the design of links, pins and ring discs and assumptions made are given in Appendix (A4.1) and for engineering drawing see Appendix (8). Technical data for the tractor used is given in Table (4.1).

Table 4.1 Some technical data for the tractor used

Technical data of MF 3065 tractor	
Engine:	
Size (cc)	3860
Max. Power (kW)	62.5
Total static weight (kg)	3840
Tyres:	
Front wheel	11.2 R 28
Rear wheel	13.6 R 38

4.2.1.2 Transducer gauging and preliminary calibration

Each Aluminium link to be used as a transducer was equipped with strain gauge bridge arrangements (Fig. 4.2). The bridge consists of 4 active gauges for a Wheatstone full bridge. Each strain gauge has a resistance of $120\ \Omega$. Strain gauges were selected, bonded and wired on to the links by following "Student Manual for Strain Gage Technology" (Measurement Group 1991). For precise gauge placement and alignment inside the link, a special jig was designed (Plate 4.3 and 4.4). The strain gauges were positioned precisely on the neutral axis of the link to give minimum sensitivity to lateral loads and maximum output for the required loads.

For the purpose of transducer calibration, an universal support frame was designed to provide an axial loading system (Plate 4.5). The transducers were calibrated statically for both tension and lateral loads using the support frame and an Avery Universal Test Machine (Rated to BS 1610) (Plate 4.6).

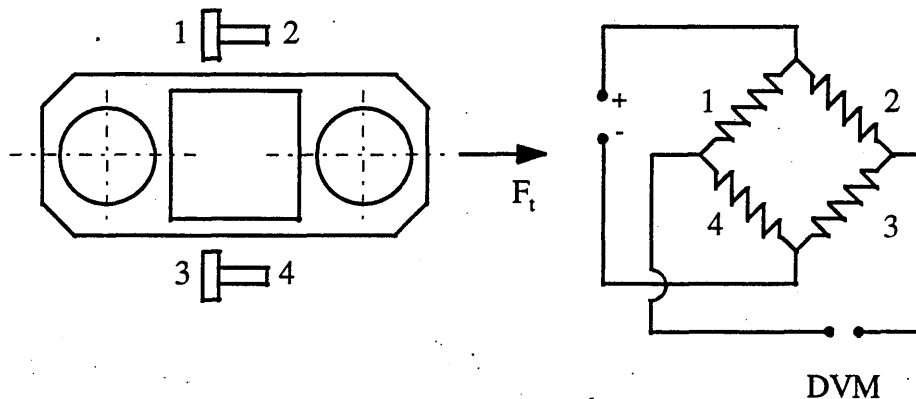


Fig. 4.2 Bridge arrangement for wheel transducer

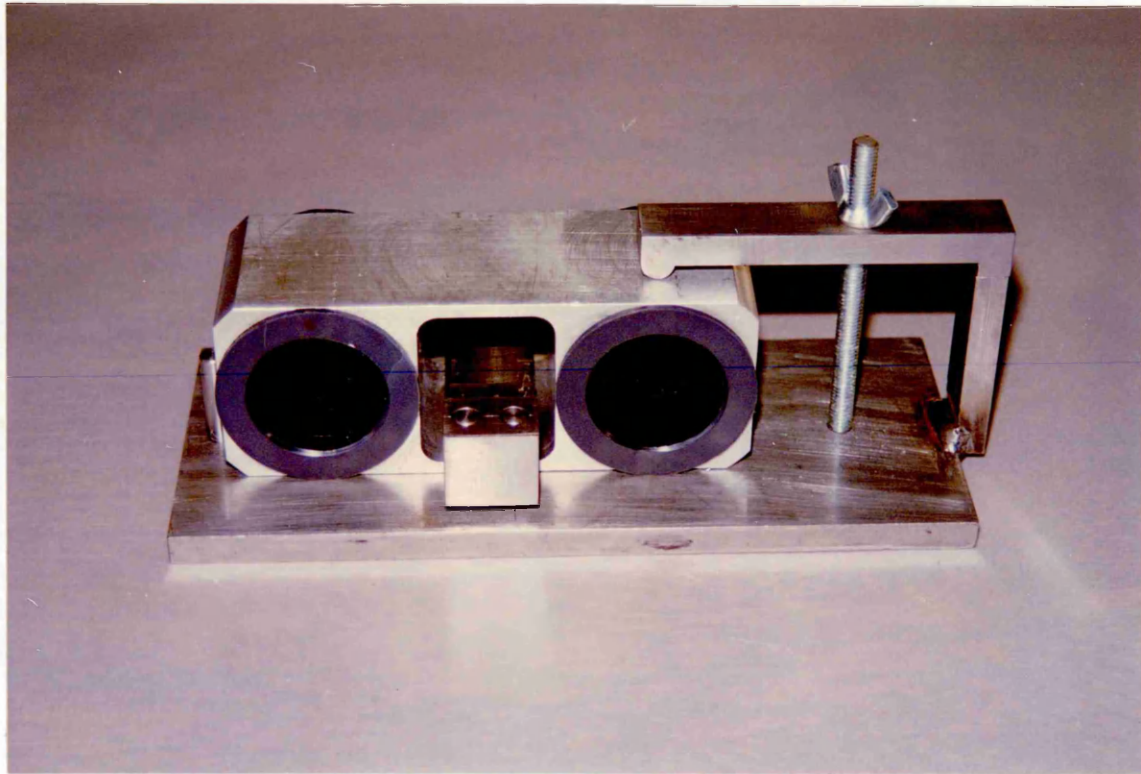


Plate 4.3. The jig unit used for gauge placement on the link

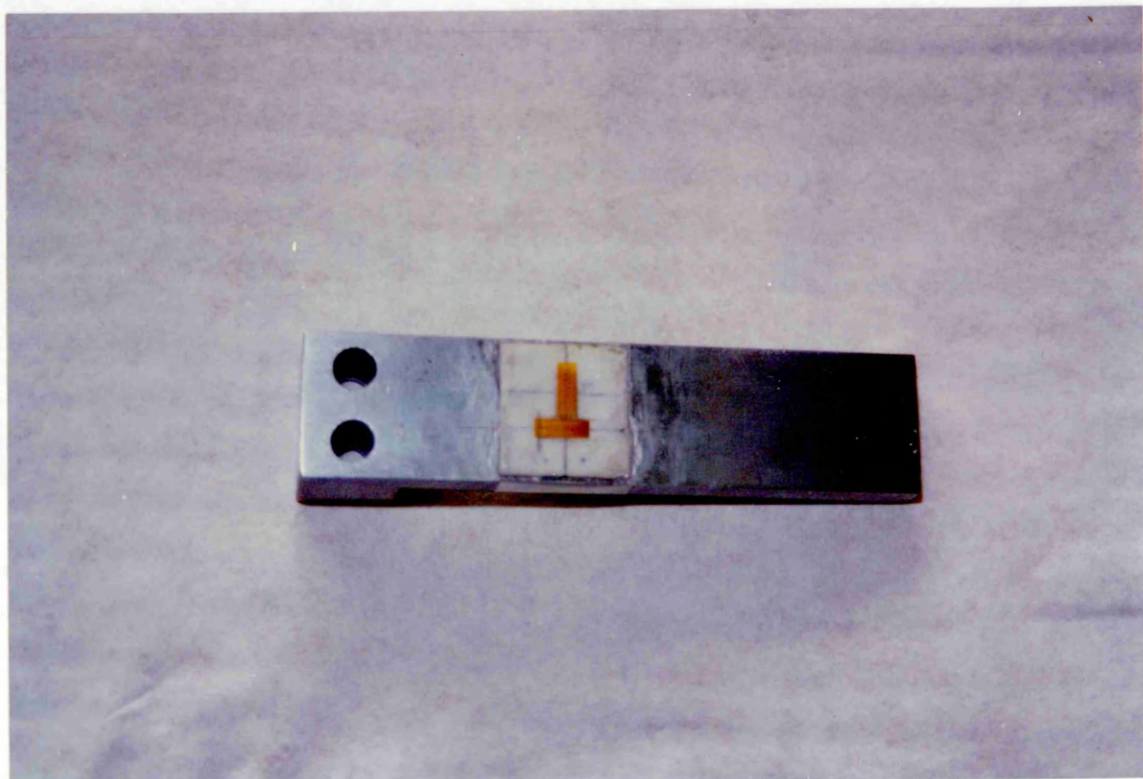


Plate 4.4. The guide block of strain gauge in the jig unit



Plate 4.5. The support frame used with Avery Test Machine

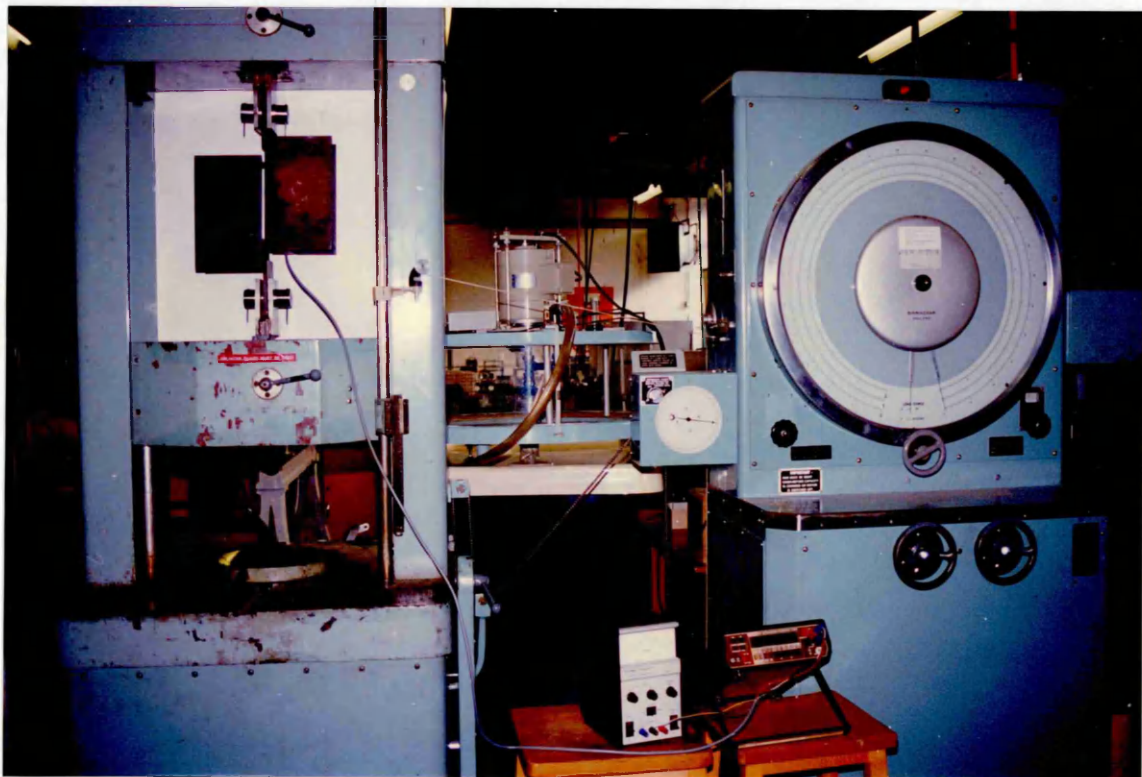


Plate 4.6. Avery Test Machine

In the beginning, Digital Volt Meter (DVM) was used to give general information about signal outputs of the bridges on transducers. The transducers were loaded to 25 kN in tension and 4 kN in lateral direction (see Appendix A4.1 for details). The tests were repeated at least three times to determine the characteristics of the transducer calibrations.

Calibration results by using Digital Volt Meter (DVM) for one of these transducers are shown in Fig. (4.3). The results for the rest of the transducers are presented in Appendices (A4.2 and A4.3).

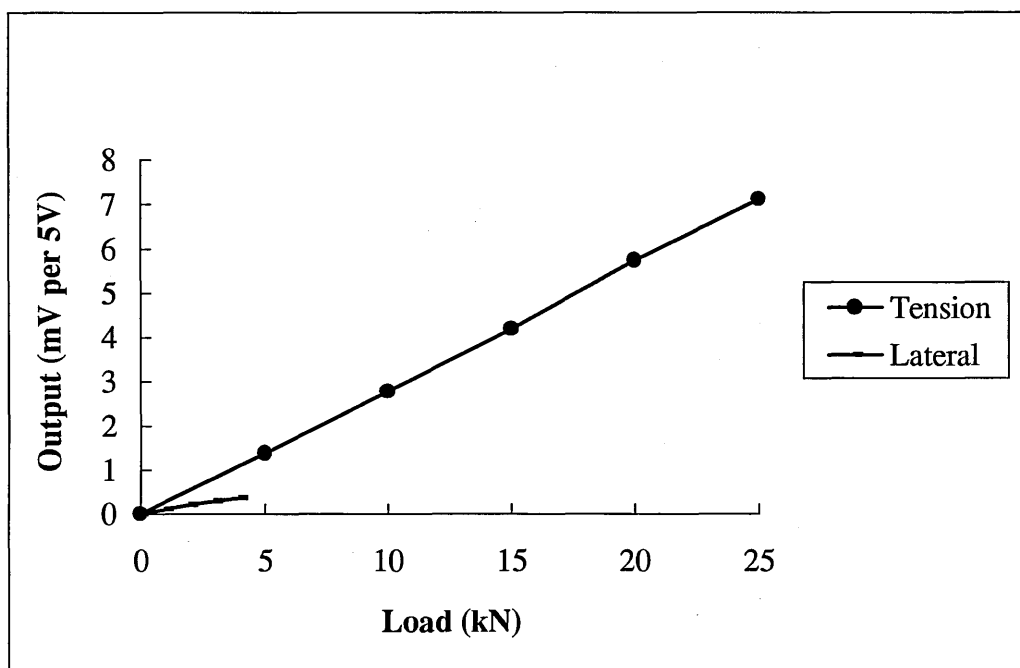


Fig. 4.3. Calibration of transducer No. (1) by DVM

The characteristics of transducer calibrations are summarised in Table (4.2) which can be outlined as follows :

The average tension sensitivity = $0.0562 \mu\text{V V}^{-1} \text{N}^{-1}$.

The average lateral sensitivity = $0.0188 \mu\text{V V}^{-1} \text{N}^{-1}$.

The outputs were linear, with coefficient of determination, $R^2 > 0.9994$.

The repeatability error was practically negligible and the hysteresis effect was not detected.

Table 4.2. The characteristics of transducer calibration

Transducer No.	Tension Sensitivity ($\mu\text{V V}^{-1} \text{N}^{-1}$)	Lateral Sensitivity ($\mu\text{V V}^{-1} \text{N}^{-1}$)	Linearity (R^2)	Repeatability (% f..s.)	Hysteresis (% f..s.)
1. (1-2)	0.0568	0.0181	0.9997	0.21	0.34
2. (3-4)	0.0568	0.0186	0.9998	0.17	0.23
3. (5-6)	0.0568	0.0192	0.9998	0.08	0.17
4. (7-8)	0.0581	0.0187	0.9998	0.12	0.11
5. (9-10)	0.0580	0.0197	0.9998	0.17	0.23
6. (11-12)	0.0506	0.0188	0.9995	0.16	0.55

As far as the application of calibration to a loaded situation is concerned see discussion in Appendix (A4.1) for the predicted loads on each transducer.

From Appendix (A4.3) :

For 2 kN lateral loaded, the average output = ± 0.211 mV depending on the load direction. For 25 kN tension loaded, the output = ± 7.02 mV. For the situation which there is both a tension load and a lateral load applied the output = 7.02 ± 0.211 mV. This represents an error of ± 2.9 % in the worst case.

This study was carried out on non-sloping land with the tractor moving on the flat so this source of error can be neglected. The transducers system would probably be sufficiently accurate in other situations where both tension and lateral loads present.

4.2.1.3 Measurement of wheel angular position and theoretical speed

The equipment system mentioned earlier is expected to measure force along the links so their vertical and horizontal components can be computed and summed. To determine the angular position of the wheel and hence the direction of the forces produced by the wheels, a system consisting of two proximity sensors and a multi-hole ring is used for each transducer system for the front and rear wheels. The ring is made of metal and has two series of holes, 100 and 25 holes drilled in line with each other (Plate 4.7). It was fixed on the tractor axle by means of a special bracket to be parallel and concentric with the modified wheel disc (Plate 4.8). The proximity sensor is an optical fibre type which consists of transmitter and receiver (Plate 4.9).

The principle of this system is that the two sensors are fitted to the inner wheel disc by a L shape bracket and adjusted in a place that when the tractor wheel rotates, each of these sensors is providing one signal or pulse when it faces a hole on the fixed ring per hole. The purpose of the 100 holes is to give 100 pulses per revolution of the tractor wheel by one of the two sensors. However, the 25 holes is to provide a marker pulse per revolution by the other sensor. This marker pulse indicates the synchronized point when the two sensors facing two holes at the same time.

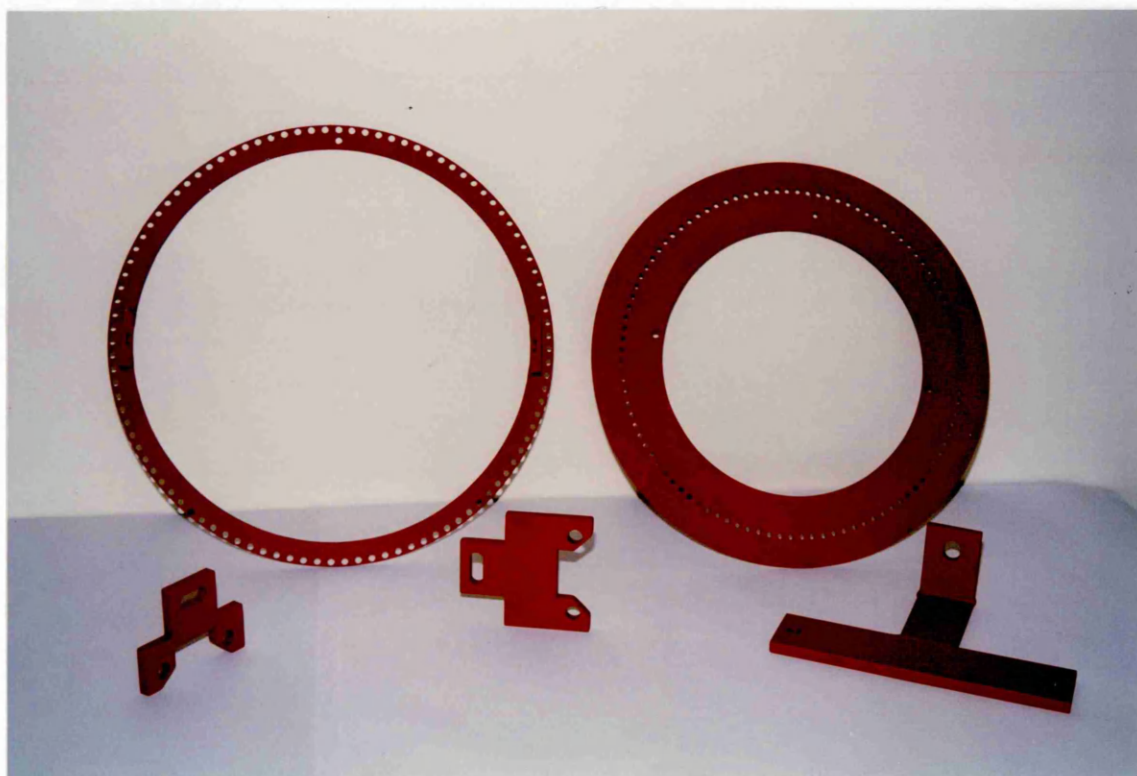


Plate 4.7. The multi-holes rings used with the front and rear wheels

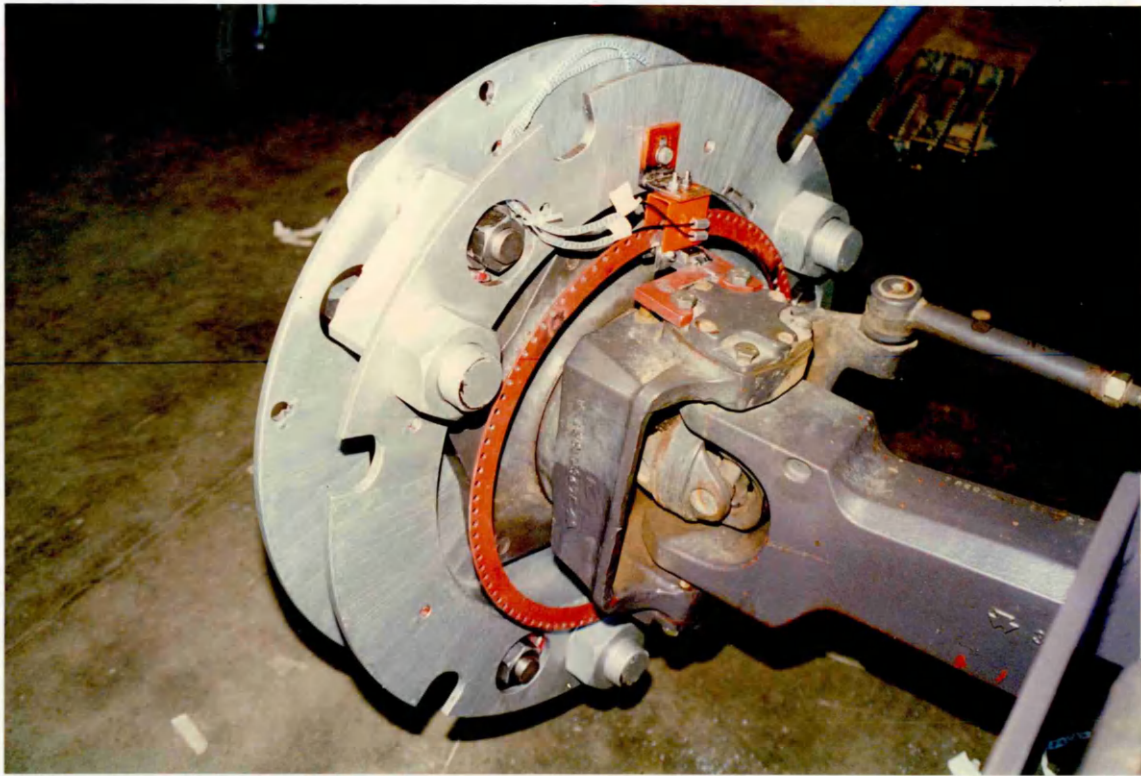


Plate 4.8. The multi-holes ring fitted to the modified front wheel discs

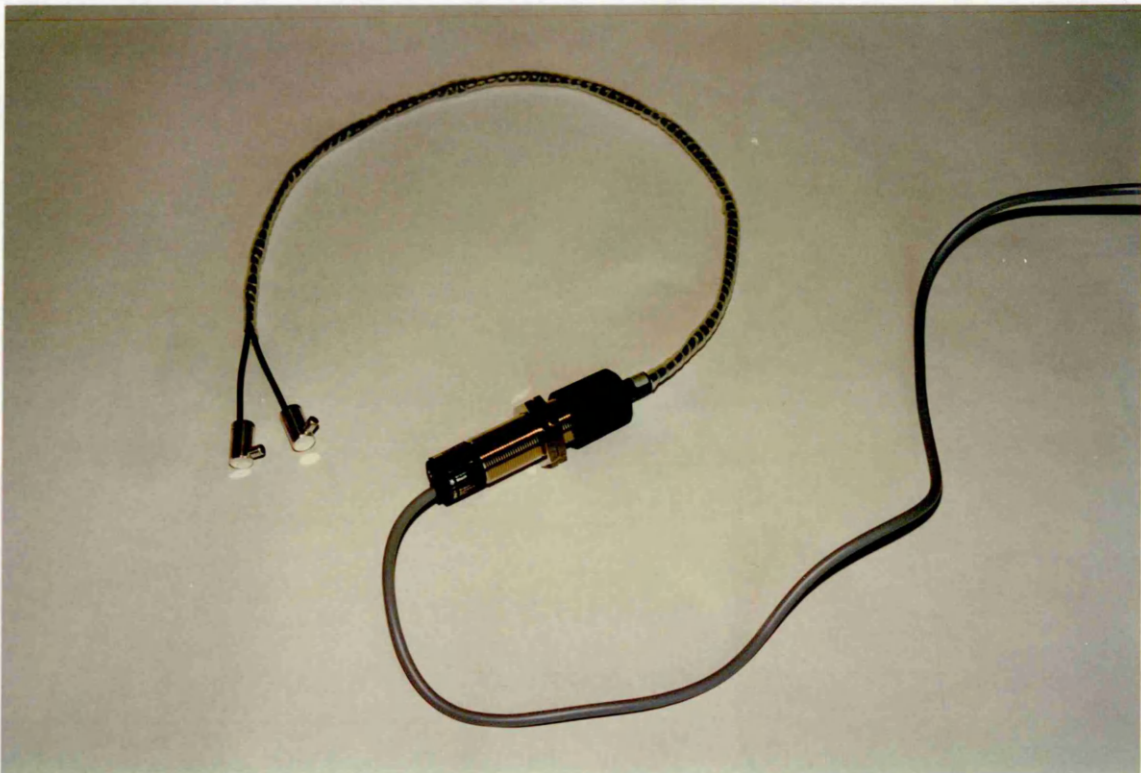


Plate 4.9. An optical fibre proximity sensor used for tractor wheel

4.2.2 Wheel slip and actual wheel speed measuring device

4.2.2.1 The device construction and component

The use of the fifth wheel as a transducer for measuring travelled distances, wheel speed has been an accepted practice for years. This type of measuring device performs well on hard smooth surface where its accuracy depends on the absence slip between the wheel and the surface on which it operates.

With the aim to estimate the tractor wheel slip and the actual wheel speed a 5th wheel attachment has been designed and constructed. Two similar units of the 5th wheel attachment were used. One was connected to the tractor front wheel and the other to the rear wheel because they were instrumented individually (Plate 4.10).



Plate 4.10. A 26 inch bicycle wheel used in the fifth wheel unit

The 5th wheel consists of a 26 inch bicycle wheel i.e. rim and tyre attached to one disc of the instrumented wheel by a horizontal axle shaft (Plate 4.11). The bicycle wheel is attached to this shaft by a support bearing arm which gives the wheel freedom of movement in a vertical plane during tractor motion and to be run in the right hand side of the tractor wheel (i.e. on the undisturbed soil when working in field).



Plate 4.11. The fifth wheel unit attached to a tractor wheel

4.2.2.2 Fifth wheel instrumentation and operation

Each 5th wheel was equipped with a 40 holes ring and an inductive proximity sensor to provide 40 pulses per revolution of the bicycle wheel. The ring was fitted to the wheel axle and the sensor was bolted into the wheel fork by an adjustable bracket so each time the sensor faces a hole it produces one pulse. The data signals from the sensor are scanned and recorded by the datalogger. Because the sensor was attached to the bicycle wheel fork, however the datalogger rotates with the tractor wheel a switch waver unit was used to operate as a slip ring device (Plate 4.12). It was mounted between the wheel fork and the horizontal axle shaft to connect the wiring between the proximity sensor and the datalogger.

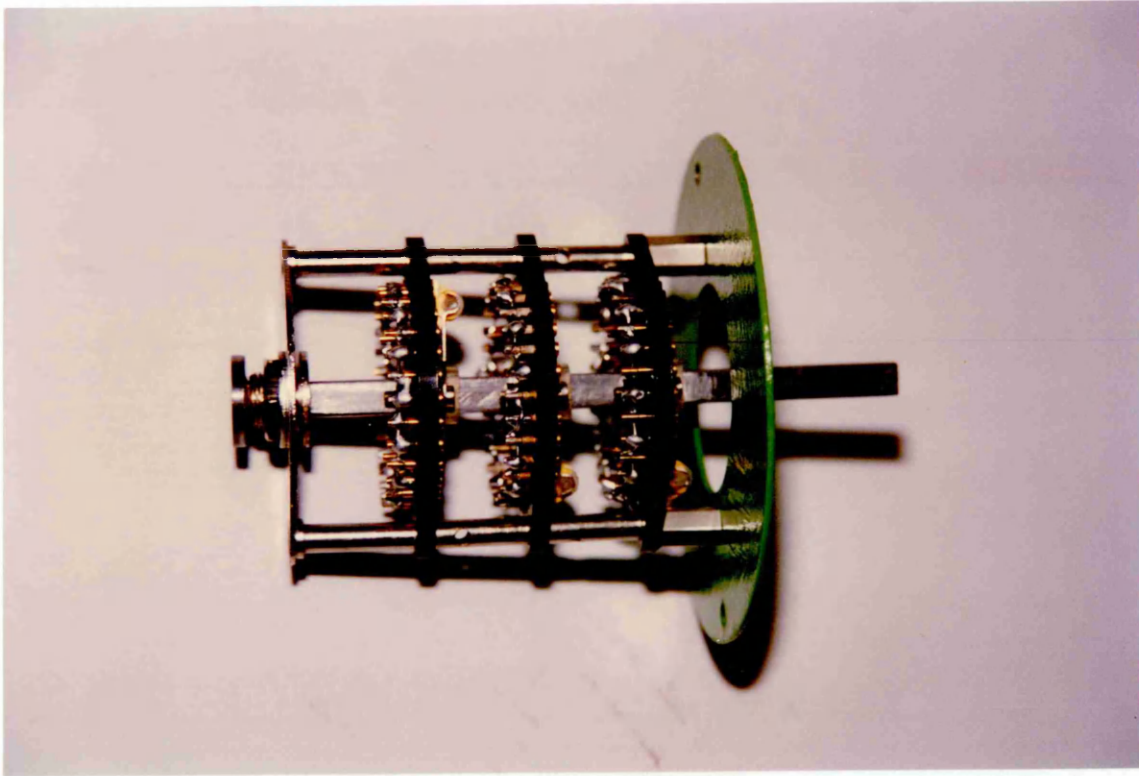


Plate 4.12. Switch wafer unit

4.2.3 The equipment calibration using Datalogger

The real tests for the experimental equipment calibration were conducted by using a datalogger. A Campbell Scientific 21X datalogger (Plate 4.13) was used to scan and record signals from the wheel transducers and sensors. The datalogger has the advantage of providing the excitation for the transducers and proximity sensors which reduced the need for bulky transducer amplifiers, bridge balancing equipment, and 240V AC power supply unit. In addition, it has a wide range of program instructions which gave it great versatility and can be used with a wide range of instrumentation.

Each of the instrumented front and rear wheels is equipped with an individual datalogger set. To avoid the need for a slip ring device and its associated problems, the datalogger was mounted on the tractor wheel to be rotated with the wheel movement. A support frame was designed and bolted to the outer disc of the wheel to hold the datalogger box (Plate 4.14). For the purpose of control the recording of the data and signals from the wheels transducers and sensors and to synchronize the two dataloggers, two types of switches were connected to each of the dataloggers. One is a hand switch to make the datalogger start recording data at the beginning of the test and the other one is a radio control switch, transmitter and receiver, to give a signal to synchronize the two dataloggers recording during the test.

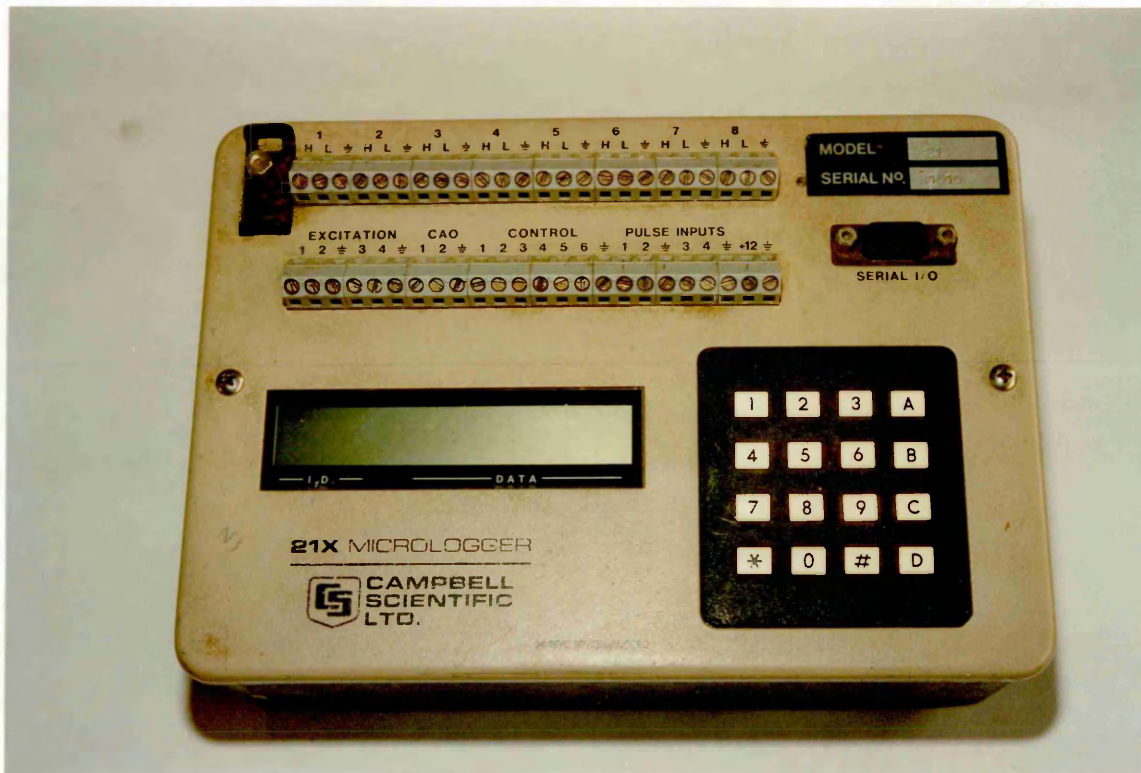


Plate 4.13. A Campbell Scientific 21X datalogger

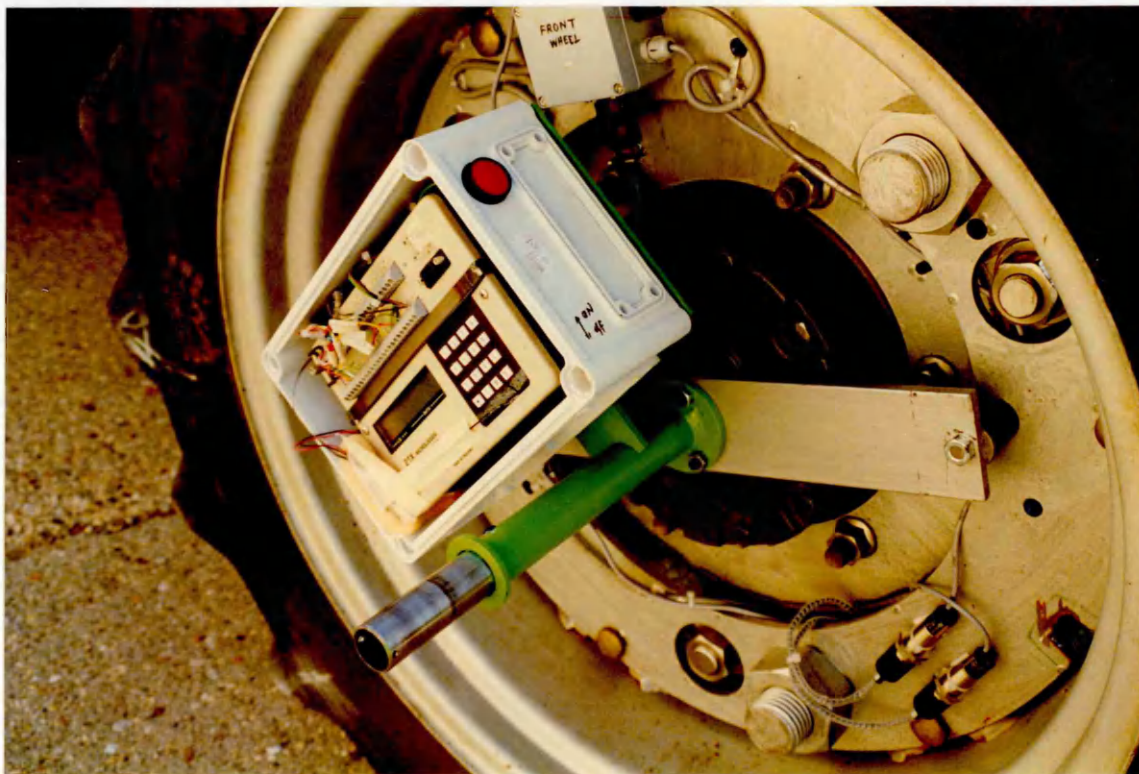


Plate 4.14. The support frame used to hold the datalogger box

A program was developed for the datalogger which would record the data from the gauge bridges of transducers and sensor pulses for both a tractor wheel and a fifth wheel. Each of the instrumented front and rear wheels of the tractor has individual datalogger program having similar instructions but different multiplier and offset values due to their calibration characteristics. The program details are given in Appendix (A4.4). All output from the strain gauge bridges and sensor pulses were sampled at 0.075 sec. (time interval) using instruction "6 Full Bridge" for strain gauges bridges and instruction "3 pulse" for sensors.

4.2.3.1 Calibration of individual transducers

All the bridges from each three transducers belong to one of the tractor wheels were connected in the datalogger instead of the Digital Volt Meter (DVM). Then each transducer was calibrated individually using the Avery Machine. It was again loaded up to 25 kN in tension assuming that this is the actual operating range expected in the experiment study. Each transducer bridge was given an individual value of multiplier and offset in the program to convert the datalogger number into kN output directly as presented in Table (4.4). These multiplier and offset values were derived from the calibration tests.

Table 4.3. The multiplier and offset values in datalogger program

Transducer No.	Multiplier	Offset
1	18.10	-3.32
2	18.00	6.74
3	18.00	-4.06
4	17.30	4.02
5	17.50	-4.10
6	20.20	-6.40

Fig.(4.4) shows the calibration results for one transducer by using the datalogger and the results for the other transducers are shown in Appendices (A4.5 and A4.6).

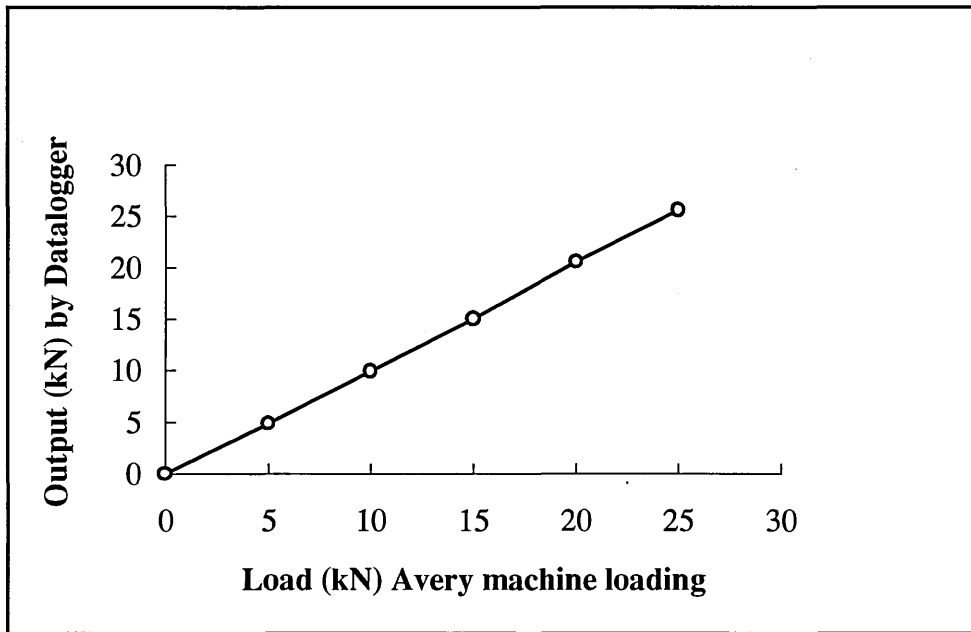


Fig. 4.4. Calibration of transducer No. (1) by datalogger

4.2.3.2 Calibration of sensors

In the beginning all the sensors were tested in the laboratory to make sure they work and give signals. Later, the tractor wheel sensors, i.e. two sensors for each wheel, were fitted on the wheel disc as described previously in section 4.2.1.3. The tractor wheel was jacked up and rotated to adjust the sensor location altogether with the multi-holes ring. Then, both sensors were connected to the datalogger and calibrated to provide 100 pulses and 25 pulses respectively for each one revolution of the tractor wheel (Plate 4.15 and 4.16).

The two sensors are located at an angle to the vertical so the marker pulse indicates the exact vertical position of one of the three transducers of the wheel where the vertical component force produced by this transducer is zero. Therefore, during the test this pulse is used to make the beginning of the count for the wheel angular position pulses. These counts were converted into angles and used to calculate the components of the wheel forces in Equations (2.48 and 2.49) (Watt 1991).

The fifth wheel sensor was also connected to the datalogger and calibrated to produce 40 pulses for each one revolution of the fifth wheel (Plate 4.17). The sensor was adjusted and the wheel was rotated by hand several times to provide the required number of pulses per revolution which can be seen on the computer screen connected to the datalogger.



Plate 4.15. Sensors and multi-holes ring fitted to the instrumented rear wheel

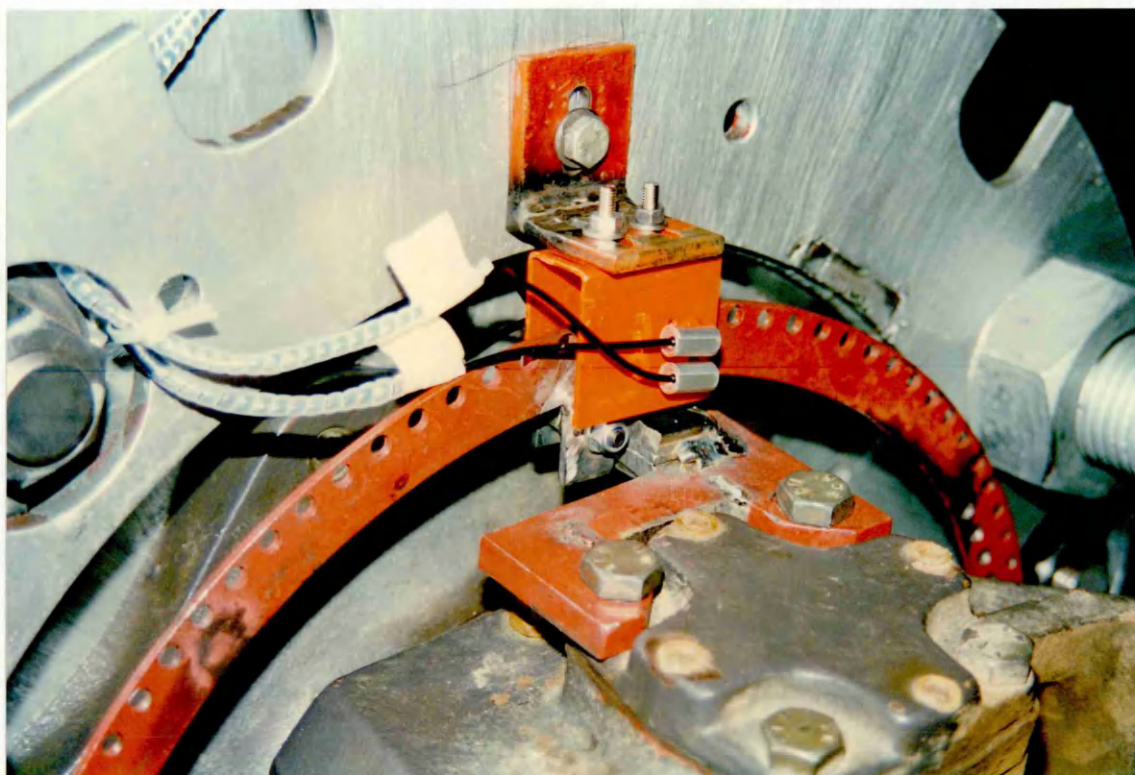


Plate 4.16. Sensors and multi-holes ring fitted to the instrumented front wheel

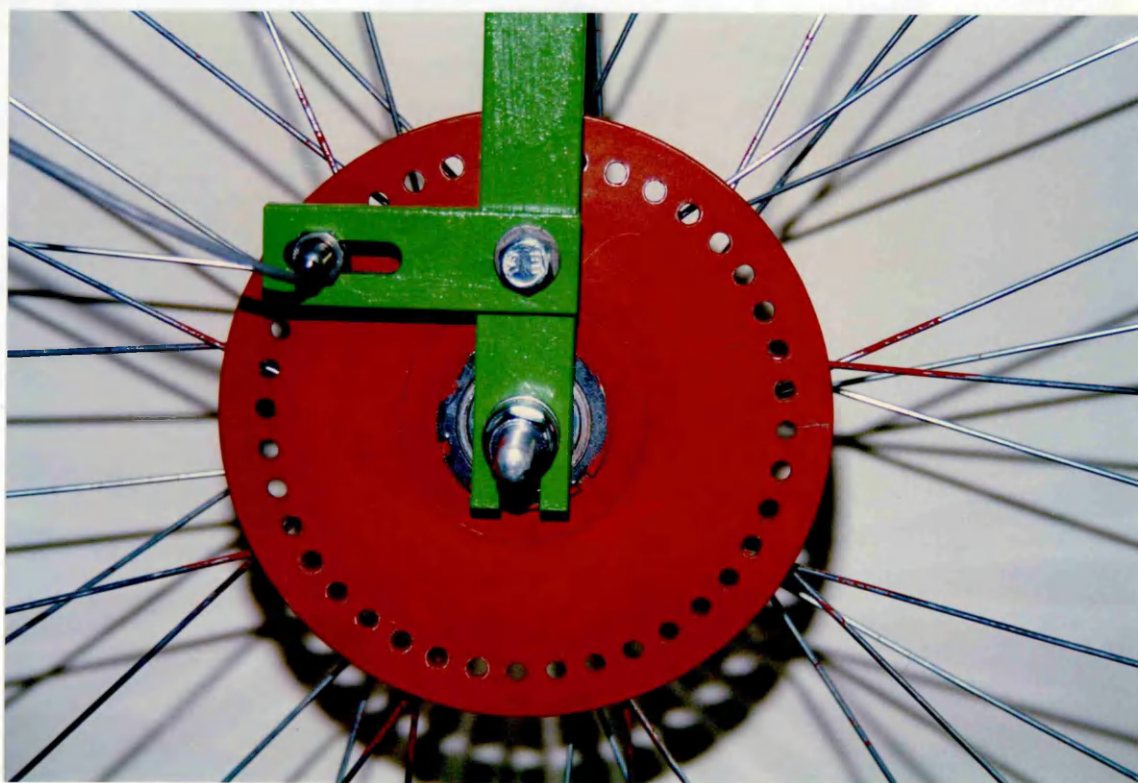


Plate 4.17. The sensor and 40 hole ring fitted to the fifth wheel

4.2.3.3 Calibration of the complete assembly on yard

The equipment components consisted of the wheel modified discs altogether with their transducers, the wheel angular position measuring device and the fifth wheel attachments were fitted to the MF 3065 tractor. The equipped tractor was tested on a hard yard to examine the validity of the system and instrumentation (Plate 4.18). The data recorded by the datalogger was analysed and spread sheet calculations were developed to calculate the vertical and horizontal forces on the tractor wheels and wheel slip and the actual wheel speed as explained below.

To assess the accuracy of the measurement system, the equipped tractor was tested at the beginning on the hard yard at three different nominal speeds 1, 5 and 9 kph in two stages:

- without ballast weight
- with ballast weight



Plate 4.18. Testing the equipped tractor on the hard yard

The system was designed to measure the forces applied on the tractor wheel and hence their vertical and horizontal components can be computed. The wheel slip and the actual wheel speed also can be estimated based on the travel distance measured by the fifth wheel and the tractor wheel. The details of preliminary tractor tests and measurements are detailed next.

(I) Wheel force measurements and calculations

For the purpose of wheel system calibration, the measured vertical load on the tractor wheel by the developed system was compared with the weight obtained by the weigh bridge at the S.R.I. However, the measured travel distance by the fifth wheel was compared with the real distance on the ground.

A method of operating the measurement system on the tractor was developed as outlined in section 4.2.4. This method was followed in testing the tractor on the yard. Consequently, the datalogger data were analysed by converting the data into text files which could be manipulated as required using a personal computer. The developed spread sheet calculations include the following:

1. The summation of vertical forces ΣF_V and the summation of horizontal forces ΣF_H on each of the front and rear wheels using Equations (2.48 & 2.49) respectively.

$$\Sigma F_V = F_1 \cdot \sin \theta + F_2 \cdot \sin (\theta + 120^\circ) + F_3 \cdot \sin (\theta + 240^\circ)$$

$$\Sigma F_H = F_1 \cdot \cos \theta + F_2 \cdot \cos (\theta + 120^\circ) + F_3 \cdot \cos (\theta + 240^\circ)$$

2. The travel distance of the tractor front wheel, rear wheel and the fifth wheel, from which wheel slip was calculated as explained later in this section.

It should be noted that the dynamic vertical load on the tractor wheel measured by the transducers includes the weight of 1/2 axle, part of driver weight and part of the fuel weight, ect.). However, the system does not sense the out side part of the wheel, due to the nature of the design , which includes the tyre, the rim, and the outer wheel disc with its pins and nuts. This part is called the unsensed part. Because the transducers sense the forces between the rim side and the hub side, so the force measured depends on which part is carrying the load and which in rest. Therefore, the weight of the unsensed part was measured separately. The wheel was jacked up just off the ground and rotated for a certain time while the force measurement data were recorded by the datalogger. In this case the out side of the wheel is carrying the load and sensed while the other part of the tractor is at rest.

The weight of unsensed part of each of the front and rear wheels was considered a constant value in all vertical force calculations in the study (Table 4.4). Consequently, the total dynamic vertical weight on the wheel equals the vertical force calculated by Eq. (2.47) plus the unsensed part weight.

Table 4.4. The unsensed part weight of wheel

Unsensed part weight (kN)	
Front wheel	Rear wheel
0.95	1.50

(II) Calculations of wheel slip and actual wheel speed

The measuring method evaluated to estimate the tractor wheel slip and actual forward speed in this project was based on measuring the base (actual) distance travelled by a fifth wheel and the theoretical distance travelled by a given number of revolutions of the tractor driven wheel. The principle of measuring these distances relies upon the determination of the number of sensor pulses produced by the fifth wheel and the tractor wheel, and providing the rolling radius of each wheel is known, the travel distance can be calculated and hence wheel slip as well as wheel speed can be estimated.

Calculations of the travel distance of the tractor front wheel, rear wheel and the fifth wheel, from which wheel slip was determined, as follows

Travel distance of a tractor wheel, TD_t (theoretical) :

$$TD_t = \text{No. pulses} \times \frac{2\pi \cdot \text{Tractor wheel rolling radius}}{\text{No. of holes in the multi holes disc (100)}} \quad (4.1)$$

Travel distance of a fifth wheel, TD_f (actual) :

$$TD_f = \text{No. pulses} \times \frac{2\pi \cdot \text{5th wheel rolling radius}}{\text{No. of holes in the multi holes disc (40)}} \quad (4.2)$$

$$\text{Wheel slip \%} = \frac{TD_t - TD_f}{TD_t} \times 100 \quad (4.3)$$

However, the actual wheel speed was determined based on the time required to travel a certain amount of ground distance. The travel distance is that measured by the fifth wheel in (Eq 4.2) while the time used to travel this distance was calculated from the time interval T_i (sample/sec) in the datalogger program instruction altogether with the number of samples S_n have been read during the measured distance TD_f . Therefore, the travel time T is :

$$T = \frac{S_n}{T_i} \quad (4.4)$$

$$\text{Wheel speed} = \frac{TD_f}{T} \quad (4.5)$$

The tractor weight without ballast (static) and with ballast was determined based on the weigh bridge measurement and is given in Table (4.5), see Appendix (A4.7) for details. The test results of the instrumented tractor on the yard are summarised in Tables (4.6 and 4.7). These results include the comparison between the vertical load on the tractor wheels measured by the developed instrumentation and that measured by the weigh bridge, and the percentage error between the two measurements.

Also the percentage error in the travel distance measured by the fifth wheels, taking the average value of the two distances measured by the front and rear, compared with the real ground distance is shown. Worked examples of calculations are given in Appendix (A4.7).

Table 4.5. The data of tractor weight based on Weigh Bridge measurement

Side	weight without ballast (kN)		weight with ballast (kN)	
	per axle	per wheel	per axle	per wheel
Front	15.20	7.60	16.40	8.20
Rear	25.40	12.70	27.40	13.70
Total	40.60	20.30	43.80	21.90

Table 4.6. Test results of the instrumented tractor on the yard (without ballast)

Nominal speed (kph)	The total vertical load on tractor wheel measured by the system (kN)		Error between the data of the system and weigh bridge (%)		Error in 5th wheel measurement (%)
	Front wheel	Rear wheel	Front wheel	Rear wheel	Ave. of two 5th wheels
1	7.63	12.94	- 0.40	- 1.90	+ 0.05
5	7.70	12.62	- 1.31	+ 0.63	+ 2.40
9	7.95	12.30	- 4.60	+ 3.15	+ 1.75

Table 4.7. Test results of the instrumented tractor on the yard (with ballast)

Nominal speed (kph)	The total vertical load on tractor wheel measured by the system (kN)		Error between the data of the system and weigh bridge (%)		Error in 5th wheel measurement (%)
	Front wheel	Rear wheel	Front wheel	Rear wheel	Ave. of two 5th wheels
1	8.18	14.04	+ 0.24	- 2.50	+ 0.05
5	8.35	13.65	- 1.83	+ 0.40	+ 1.80
9	8.31	13.46	- 1.34	+ 1.75	+ 2.30

Tables (4.6 and 4.7) show the accuracy of the force measurement system. The errors are within the normal accepted range for this type of equipment so it would produce results with the required accuracy.

It should be also noted that the error in measuring the travel distance by the fifth wheel was mainly due to the method used to synchronize the dataloggers of two wheels (i.e. using radio control switch). As mentioned previously, the distance measured depends on the determination of the number of pulses produced by the fifth wheel sensors per a number of wheel revolutions. Therefore, any delay in turning on the radio control switch means missing a number of pulses which will reduce the amount of ground distance measured. Similar, any advance in turning on the radio control switch will add more pulses and the distance measured becomes bigger than the real distance.

4.2.4 The operating procedure of the instrumentation system

The following operating method was developed to operate the instrumented tractor both on the yard and in the field. It is based on driving the tractor a certain distance and taking measurements between two known points using the datalogger. The data recorded from the front and rear wheels were synchronized by using the radio control switch connecting the two dataloggers. The procedural steps are outlined below :

1. Check all the wires and connections between the transducers and sensors, and dataloggers to be correct and all the batteries in charged state.
2. Take the tractor to the yard.
3. Attach the two fifth wheels in their places on the tractors wheels.
4. Measure a known distance between two points A and B say 30m just few meters in front of the tractor.
5. Connect the computer to the tractor battery and to one of the wheel dataloggers, run the computer and turn on the datalogger.
6. Load the developed datalogger program belonging to the wheel (i.e. each wheel has a particular program based on its calibration).
7. Load the other program to the second datalogger.
8. Give the driver a sign to adjust the gear ratio to give the required nominal speed and to be ready.
9. Turn on each of the hand switches on the datalogger boxes to start recording.
10. Give the driver sign to move immediately.
11. Take the radio control switch box and follow the tractor and be sure that you are far away enough from the tractor right hand side (i.e. on the undisturbed land when working in field).
12. When the tractor front wheel centre just passes over point A , turn on the radio control switch.
13. Continue following the tractor and when the tractor front wheel just pass over point B, turn off the radio control switch.
14. Give the driver a sign to stop and after stopping completely, turn off each of the hand switches on the datalogger boxes.
15. Bring the computer and connect it to each of the dataloggers one after the other and load the individual program again for each wheel.
16. Load off the recorded data from the two dataloggers separately, using a floppy disk and give each datalogger data a different file name for each wheel to be recognized.

To operate the tractor in the field, step 2) above is replaced by the following steps :

17. Take the tractor to the field and connect the required implement.
18. Adjust the implement depth to the required setting.

4.2.5 Compaction measurement equipment and methods

One of the aims in this study is to measure the compaction under the tractor wheels in tillage operations. Several measurement methods have been used to estimate soil compaction either in a laboratory or in a field as it reviewed in section 2.6.4. However, three field methods were chosen to measure and assess soil compaction caused by the loading system in the field experiments. These methods are: measurement of soil dry bulk density, penetration resistance and water infiltration rate as explained next :

1. Soil dry bulk density is the widely used property to quantify such changes accompanied by an increase of soil compaction caused by mechanical loads. In addition, soil compaction is usually described in terms of soil dry bulk density to allow soils at different moisture contents to be compared. Soil dry bulk density was determined by using the core sampling method with standard steel ring and following the standard oven drying method procedure.
2. Penetration resistance of the soil was measured by using the cone penetrometer. It is a simple, quick method of measuring soil compaction in a wide range of soil types. The data collection was obtained using a hand-held electronic cone penetrometer with a 12.83 mm cone size, following the general procedure outlined in the Standard S313.2 (A.S.A.E.).

The advantage of using this method is that the value of penetration resistance measured could be used for other research studies such as in tractive performance prediction of tractor tyres which uses the mobility number equations. It may also be used in estimating draught requirement of a given tillage implement working in field conditions (Desbiolles 1994).

3. Water infiltration rate is one of the most important properties and closely related to practical problems of compaction. It is simple method and valuable check on compaction damage to the soil although it is time consuming method. Infiltration rate was measured by using double ring infiltrometers. Two sizes of metal cylinder rings were designed for this purpose. The outer and inner rings have similar length of 20 cm, and diameter of 20 cm, 15 cm respectively (Plate 4.19). Both rings were sharpened at one end to ease ring insertion to soil with minimum disturbance to the natural soil structure conditions.



Plate 4.19. Double cylinder rings used for water infiltration measurement

5. FIELD EXPERIMENTAL DESIGN

5.1 Introduction

Having designed and constructed a wheel dynamic weight transducer and other measurement system components, the next step is to set up the field experiments and to measure the forces on the tractor wheels to predict the optimum tractor performance when applying a particular tillage operation. This chapter is aimed to define the variable parameters considered in field experiment tests. It also includes the pilot study carried out in the field. The field type on which experiments were conducted is represented. The main field experimental plan and test procedure are also given. Further, soil compaction measurement procedure is described.

5.2 Variables in the field experiment

The aim was to demonstrate the principle of the determination of the optimum tractor performance by investigating the best combination of power available, required tractor weight and working speed at which the highest tractive efficiency would occur when working in frictional soils in particular. Hence, the optimum operating parameters could be recommended in such soils for a given tractor size chosen. Therefore, the following parameters were considered as experimental variables :

1. Three levels of tractor ballast weight.
2. Three levels of working speed.
3. Three levels of implement pull setting.

5.3 Pilot test in the field

The tractor and equipment was fully serviced and checked to ensure that their performance met the manufactures' original specifications. Before starting the main field experiments , the variables mentioned previously were specified as the following :

- i. The maximum ballast used to ballast the tractor was decided based on the maximum tyre load capacity and tractor axle limit considered in wheel transducer design, in addition to the physical limitation. The levels of ballast were chosen to be: the tractor with no ballast, tractor with half ballast and tractor with maximum ballast (see Appendix 5 for details).
- ii. Three different gear settings were selected to provide three different nominal speeds, 4, 6, 9 km/h as presented in Table (5.1).

Table 5.1. The tractor gear settings chosen

Nominal speed (km/h)	Gear ratio	Range	Speed shift	Speed Code
4	2B	Tortoise	Slow	Low
6	4B	Tortoise	Slow	Medium
9	1A	Hare	Fast	High

iii. Because the prediction method in this study investigation deals with traction performance, one type of tillage implement i.e. disc harrow is used to exert pull forces on the tractor (Plate 5.1). This type of tillage implement has the advantage of providing a uniform operation and steady draught force.

The implement pull setting i.e. depth setting calibration was determined by using another tractor to find out the maximum pull the equipped tractor can manage. Therefore, the equipped tractor with the implement connected was towed by a MB trac 1300 to measure both tractor rolling resistance and implement draught by using a shear load cell connected by chain between the tractors (Plate 5.2). This was done with different forward speeds and implement depth settings. Later, the tractor was drawn alone to determine its rolling resistance (Plate 5.3). The implement depth settings were adjusted by altering the hole position on the depth control bar of the implement as shown in plate (5.4). Table (5.2) summarised the three designation settings used.

Table 5.2. The implement pull settings

Pull setting	Hole position on implement
Low	B2
Medium	A1
High	A2



Plate 5.1. Disc Harrow (the implement used)



Plate 5.2. The measurement of the draught and rolling resistance



Plate 5.3. The measurement of the tractor rolling resistance



Plate 5.4. The implement depth settings (hole positions)

A pilot field tests were carried out with the aim of assessing the variability in system measurements. The equipped tractor was operated in the field with the implement engaged at certain depth at different working speeds, following the operating procedure described in section 4.2.4. Data were analysed and calculations of wheel forces were done by using calculation procedure explained in section 4.2.3.3.

The study tests represented a reasonably repeatable overall average readings. The results showed the average coefficient of variances of the mean C.V. for the vertical ΣF_V and horizontal ΣF_H wheel forces were 2.61% and 6.42 % respectively. However, the average C.V. was 0.94 % for the travel distance TD_f measured by the fifth wheel. The details of results are presented in appendix (A5).

5.4 Location of the experiments

The field experiments were done in Downing Field on Silsoe College Farm. This field soil is mainly sandy loam which represent nearly the type of soil required for the study. The mechanical analysis determined by the Pipette Method is given in Table (5.3). The field was covered with stubble (Plate 5.5) and the average moisture content was 15% .

Table 5.3. Mechanical analysis of the soil of Downing Field

Fraction	Rep. 1 (%)	Rep. 2 (%)	Rep. 3 (%)	Average (%)
Coarse sand	10.05	5.38	10.35	8.59
Sand	45.43	48.39	45.12	46.31
Fine sand	17.04	19.36	17.93	18.11
Total	72.52	73.13	73.40	73.01
Slit	17.27	14.28	14.01	15.19
Clay	10.21	12.59	12.59	11.80



Plate 5.5. Downing Field on Silsoe College Farm

5.5 Field test design

A factorial experimental design with 3 replications was developed for the layout of the experiment tests as shown in Appendix (5). The aim was to carry out a range of field tests having the variables outlined previously to achieve the investigation objective and in addition a full statistical analysis could be done. However, due to the following reasons :

- the agricultural limitations such as the land availability for short period due to requirements for other activities.
- the pilot tests showed that the measurement equipment has an acceptable accuracy and good repeatability.
- the whole system calibration was satisfactory.

Therefore, the theoretical design plan was modified to hold one replication to fit the time scale for the study experiments and to achieve realistic field results by comparing these results with the existing data as a part of this project aim.

The adapted field experimental plan is shown in Fig. (5.1) which applied to the field tests conducted. These tests consist of the combination of the three variables of ballast, working speed and implement pull setting (i.e. 27 different combinations).

B1P2 S2	B2P1 S3	B3P3 S1	B1P3 S2	B2P3 S3	B3P2 S2	B1P1 S3	B2P2 S2	B3P1 S1
B1P2 S1	B2P1 S2	B3P3 S2	B1P3 S3	B2P3 S1	B3P2 S3	B1P1 S1	B2P2 S3	B3P1 S2
B1P2 S3	B2P1 S1	B3P3 S3	B1P3 S1	B2P3 S2	B3P2 S1	B1P1 S2	B2P2 S1	B3P1 S3

Fig. 5.1. The adapted field experimental layout

Where :

B = Ballast weight

P = Implement pull setting

S = Tractor speed

5.6 Experimental procedure

The field tests were conducted by taking all the measurements between two known points along each plot in the plan, following the operating procedure described in section 4.2.4. The plot size allowed space for tractor manoeuvring and effective run length of 15m (Plate 5.6). At the end of each test, the data recorded were off loaded onto floppy disk and then the implement was raised up before transferring to the next plot to avoid disturbing the path of tractor rear wheel in which soil compaction was measured.

For the purpose of tractor ballast weights two types of carrying frames were designed. One was to be fitted to the front of the tractor and the other to be mounted to the rear wheel disc i.e. each wheel was fitted by one wing frame (Plate 5.7 and 5.8). The arrangement of the ballast weight on these frames are shown in Plate (5.9 and 5.10).

The arrangement of down loading the datalogger program to the system at the beginning of each test is shown on Plate (5.11). Plates 5.12 show the equipped tractor with the implement pulled on a typical test plot.



Plate 5.6. Preparing the plot size



Plate 5.7. Front head ballast frame



Plate 5.8. Rear wheel ballast frame (both sides)



Plate 5.9. Front tractor ballast



Plate 5.10. Rear tractor ballast



Plate 5.11. Arrangement of down loading the datalogger program to the system



Plate 5.12. Arrangement of the equipped tractor in some field tests

5.7 Parameters measured and computed

5.7.1 Parameters measured

The system measured the following parameters in each test run :

- The applied forces on the equipped front tractor wheel.
- The applied forces on the equipped rear tractor wheel.
- The pulse signals from the sensors of these two wheels and from the fifth wheels.

5.7.2 Parameters computed

The experimental data collected were analysed and by using the calculation method described in section 4.2.3.3, the following parameters were calculated for each test :

- Summation of the vertical forces ΣF_V on each of the front and rear tractor wheel.
- Summation of the horizontal forces ΣF_H on each of the front and rear tractor wheel.
- Travel distance of each of the front and rear tractor wheel.
- Travel distance of the fifth wheel.
- Wheel slip.
- Actual wheel speed.

Consequently, the other parameters also were calculated including :

- Tractor drawbar pull.
- Tractor drawbar power.
- Coefficient of traction.
- Tractor rolling resistance.

The tractor drawbar pull F_X was calculated according to the following equation :

$$F_X = H - R \quad (5.1)$$

where H is the gross draught force measured by the system which equals to summation of the horizontal forces ΣF_H on the instrumented front and rear tractor wheels multiplied by two. R is the rolling resistance of the tractor which was measured by driving the equipped tractor alone on several places in the field and the average value was taken as presented in Appendix (A6.2).

The tractor drawbar power P_d was determined from the product of the drawbar pull F_X and actual tractor speed V_a as :

$$P_d = F_X \times V_a \quad (5.2)$$

The coefficient of traction was calculated as :

$$C_t = \frac{F_x}{W} \quad (5.3)$$

where W is the total vertical load on the wheel.

5.8 Compaction measurement procedure

As described in section 4.2.5, three different field methods were used to estimate the soil compaction for the particular traction situation. These methods are: the measurement soil bulk density, penetration resistance and infiltration rate. All measurements were taken on the same day after each field test has been conducted. Measurements were made in two locations :

- In the centre of wheeling of the rear tyre path, in the space immediately between the right rear tractor tyre and the implement head (Plate 5.13). It was titled as a "wheeled location". It should be noted that the right wheel of the implement has a different path than the right rear wheel of the tractor and providing the implement was raised at the end of each test any disturbance to the later was avoided.
- In the undisturbed soil at about 100 cm away from the tyre path centre line. It was titled as an "undisturbed location".

Measurement procedure

1. Soil density samples were taken at three depths of 5 cm, 20 cm and 40 cm using two samples each, using steel rings to take soil cores. These data were also used to determine the moisture content for all the locations.
2. Penetration resistance was measured with the cone penetrometer, recording resistance at every 3.5 cm vertical interval to a depth of 49 cm up to 8 places per experiment. Penetrometer readings were taken in both wheeled and undisturbed locations in parallel along the tyre path of the rear wheel.
3. Water infiltration rate was estimated by using double ring infiltrometers. The rings were inserted 4 cm into the soil and filled with water. The water entering the soil in the rings, fixed in the undisturbed and wheeled places, was recorded at each 5 minutes by measuring the water level in the inner ring from the top end. Rings were refilled with water from time to time manually.

However, compaction assessment was made at only one level of tractor speed so the dynamic effect of speed were not consider in this study. The effect on soil compaction would be by the other two variables in the experiment i.e. ballast weight and implement pull.

Plate 5.13. Compaction measurement in wheeled location
(Right) the centre of wheeling ,
(Down) in space between the
right rear tractor tyre and the
implement



Plate (5.14) shows the field condition after conducting a certain test and the measurements of soil compaction using double-ring infiltrometers in particular. The details of this plate is drawn in Fig. (5.2) which is a sketch showing the explanations of the photograph. It describes the arrangements made to allocate the location of compaction measurements on the path of the tractor rear wheel after a particular force measurement test.



Plate 5.14. Compaction measurements by the infiltration rate method

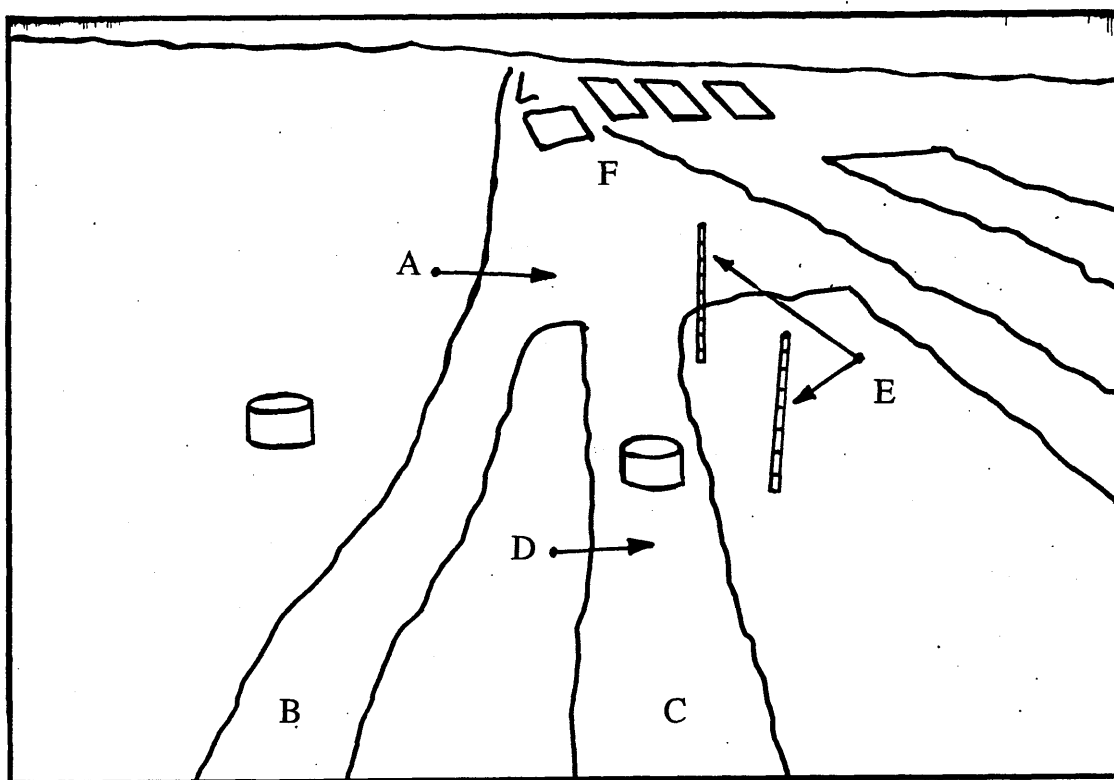


Fig. 5.1. Sketch showing the explanation of Plate (5.14)

- A = where the implement lifted
- B = the path of implement depth control
- C = the path of tractor wheel
- D = position of tractor wheel at lift initiation
- E = two sticks to define the wheeled location place
- F = cultivated soil

5.9 Basic soil properties

For the purpose of evaluation of the thrust gained from the tractor at work, three basic soil properties were determined. These properties include the soil cohesion (c), the angle of soil shearing resistance (ϕ) and the soil deformation modulus (K).

The values of c and ϕ were measured for the field soil on which experiments conducted. Soil sample was taken from at least 12 different sites on the field. It was chosen from the depth of first top ten centimetres to represent the depth of the tyre rut which was noticed after the test. The triaxial test apparatus was used following the standard method procedure. The value of K was estimated by using both Komandi approach and Mathcad calculations explained in section 2.2.1.

6. RESULTS AND DISCUSSIONS

6.1 Introduction

This chapter represents the laboratory and field test results. The traction field performance of the instrumented tractor is given. These results are compared with the existing work data. The tractor thrust force is also calculated and compared with the measured. In addition, an assessment of soil compaction for particular traction circumstances is presented.

6.2 Basic soil properties

6.2.1 Laboratory results

The values of soil strength properties c and ϕ were determined at similar soil bulk density and moisture content when the field tests were carried out. The laboratory results are presented in Appendix (A6.1). The average values were found as :

$c = 9.1 \text{ kN/m}^2$
 $\phi = 24^\circ$

However, the determination results of the soil deformation modulus K are presented in section 6.3.2.3.

6.2.2 Comparison with existing data

The estimated values of c and ϕ were compared with two existing data. The first is the data available at the soil laboratory on Silsoe College which they are an average of many tests results obtained for a relatively similar soil type. The second is the data of Desbiolles (1994) who worked on a field of similar type of soil. Table (6.1) shows the comparison between the values of c and ϕ determined by the three sources. Generally, they have good agreement and the differences between them are due to the variation in soil density and moisture content at the time of measurements. Also because of the variation in preparing the soil sample.

Table 6.1. Values of soil mechanical properties determined by the three sources

Soil property	The study	Soil laboratory	Desbiolles
$c \text{ (kN/m}^2\text{)}$	9.1	11.5	8.9
ϕ°	24	27.2	23.3

6.3 Traction performance

The following table represents the definitions of the experimental variables and the test code numbers used in the study.

Table 6.2. The definitions of the experimental variables and the test code numbers

Field Test No.	Tractor nominal speed	Ballast setting	Implement Pull setting
1	4	None	Low
2			Medium
3			High
4	6	None	Low
5			Medium
6			High
7	9	None	Low
8			Medium
9			High
10	4	Medium	Low
11			Medium
12			High
13	6	Medium	Low
14			Medium
15			High
16	9	Medium	Low
17			Medium
18			High
19	4	Maximum	Low
20			Medium
21			High
22	6	Maximum	Low
23			Medium
24			High
25	9	Maximum	Low
26			Medium
27			High

6.3.1 Predicting ballast recommendation for frictional soils

The results of the field tests conducted including the tractor drawbar pull, drawbar power, wheel slip and actual speed are given in Appendix (A6.2).

The tractor drawbar power was plotted versus wheel slip for each of the tests to determine which of these tests gives the peak value of the drawbar power as shown in Figs. (6.1 to 6.3). It was found that only few tests showed this value, however, in the other tests the tractor did not reach its maximum power performance. This is because the various variable parameters were not matched properly so the tractor wheels can not transmit all the available power at these particular test settings. Also it was observed that in some tests particularly at high speed and high implement pull the tractor can not pull, once starting to move it stopped suddenly due to the poor matching between the operating variables.

However, from those few tests the one which showed the highest value of drawbar power at optimum slip was picked to represent the best test result providing the highest performance of that tractor size at that particular combination of ballast weight, working speed and implement pull setting. Wheel slip is about 10% and coefficient of traction is 0.31.

This combination is when the tractor working with maximum ballast at nominal tractor speed of 6 kph and medium implement pull setting (Fig. 6.3).

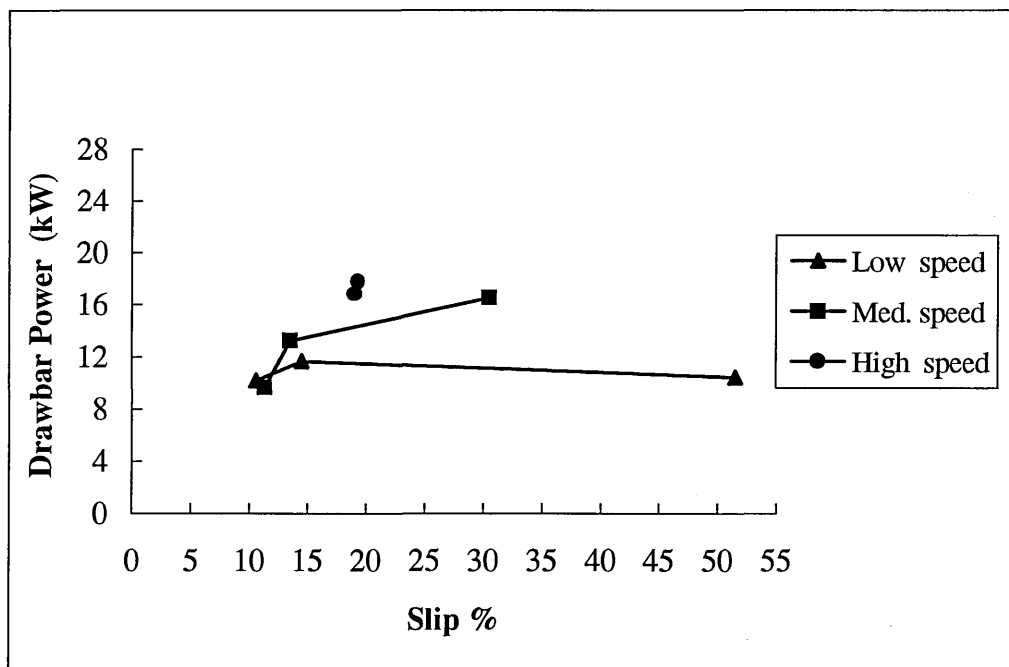


Fig. 6.1. Tractor drawbar power Vs. slip at No ballast weight

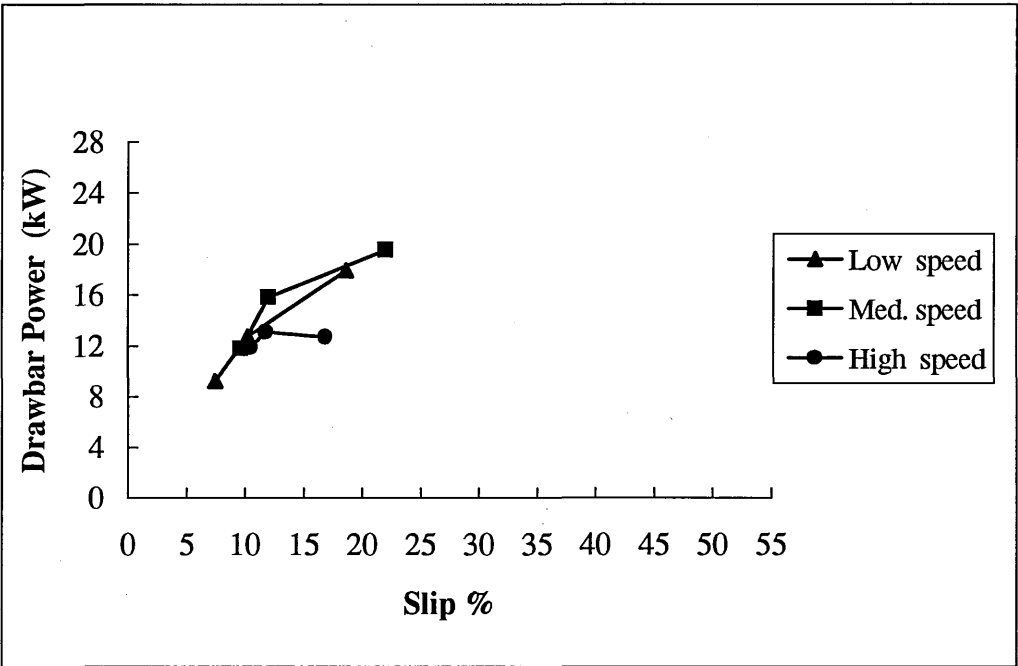


Fig. 6.2. Tractor drawbar power Vs. slip at Medium ballast weight

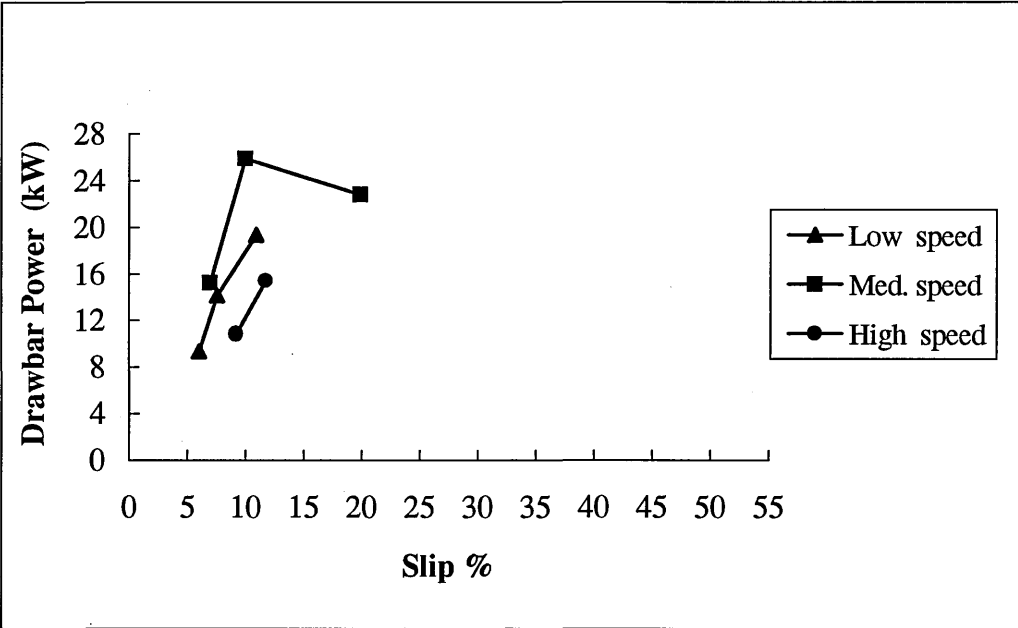


Fig. 6.3. Tractor drawbar power Vs. slip at Maximum ballast weight

The next important step was to predict a new ballast recommendation number, from the field experiment measurements, which could be applied to the frictional soils. Therefore, the dynamic tractor weight W , and the actual tractor speed V were calculated for each individual test using the following expression as was explained in section 3.2.3.

$$W/P^* = R_n / V$$

It was found that there are different ballast numbers, but the most important one is that related to the test which gave the highest tractor performance. The ballast number developed is of the form :

$$W/P^* = 1.62/V \quad (6.1)$$

This number is expected to be the ballast number when working in semi dry frictional loose soils with medium size tractor at wheel slip of 10% and 0.31 coefficient of traction (see Appendix A6.3 for the details of the method of calculation).

As far as the wheel performance is concerned, the rear wheel showed always better tractive performance than the front wheel in terms of thrust-slip relationship as is shown in Fig. (6.12) in section 6.3.2.3. The front wheels have less tractive efficiency not only because their size are smaller and the vertical load on them is lesser but also there is weight transfer from the front wheels to the rear wheels during the field operation. The amount of this weight transfer in may reach up to 40% of the total vertical load which is available on the front wheels.

6.3.2 Comparing the measured results with the theory

One of the major concerns of the study concept was to compare the field results with the existing work to examine the validation of the study results and give guidelines for the optimum performance of the 4WD tractor working particularly in frictional soils.

6.3.2.1 Comparison with ballasting recommendation approaches

It was explained in section 3.2.2 that four approaches of prediction of tractor ballast recommendation were considered. These different approaches became nearly very close to each other when their equations modified to provide the ballast number at the same value of wheel slip and coefficient of traction (Fig. 3.2 and 3.3). The average ballast number of these approaches at wheel slip of 10% and coefficient of traction of 0.4 (i.e. Eq. 3.2) was chosen for the current comparison which is of the form :

$$W/P^* = 1.9/V$$

However, the developed ballast number (i.e. Eq. 6.1) was also adjusted to have similar working conditions of wheel slip and coefficient of traction mentioned above (see Appendix A6.3). Thus, the study ballast number would be as:

$$W/P^* = 1.3/V \quad (6.2)$$

This new relationship was compared with others by plotting them altogether as shown in Fig. (6.4). From this figure it can be seen that the new relationship is below all the others. If it is assumed that the theory has a high limit for hard soils and low limit for soft soils, the study prediction is assumed to be located at or within the lower limit because the study work has been done on mainly soft sandy loam soil.

Therefore, the high and low limits at 95% confidence level were determined for both of the average ballast recommendation relationship of the four approaches chosen and for the new developed one as well. Then, they were plotted together again as shown in Fig. (6.5).

Figure (6.5) shows that the higher limit of the study recommendation relationship is close to the average lower limit of the theory as was expected. However, if only the work of Gee-Clough et al. (1982) is considered in particular and similar comparison as above is done, the study result becomes more closer to the lower range of the theory as represented in Fig. (6.6) which reasonably validates the above assumption. These results show that the tractor ballast recommendation in terms of weight-power ratio should be not increased for frictional loose soils and it is expected to be about 70% of the amount of ballast recommended by the existing work for the frictional-cohesive soils.

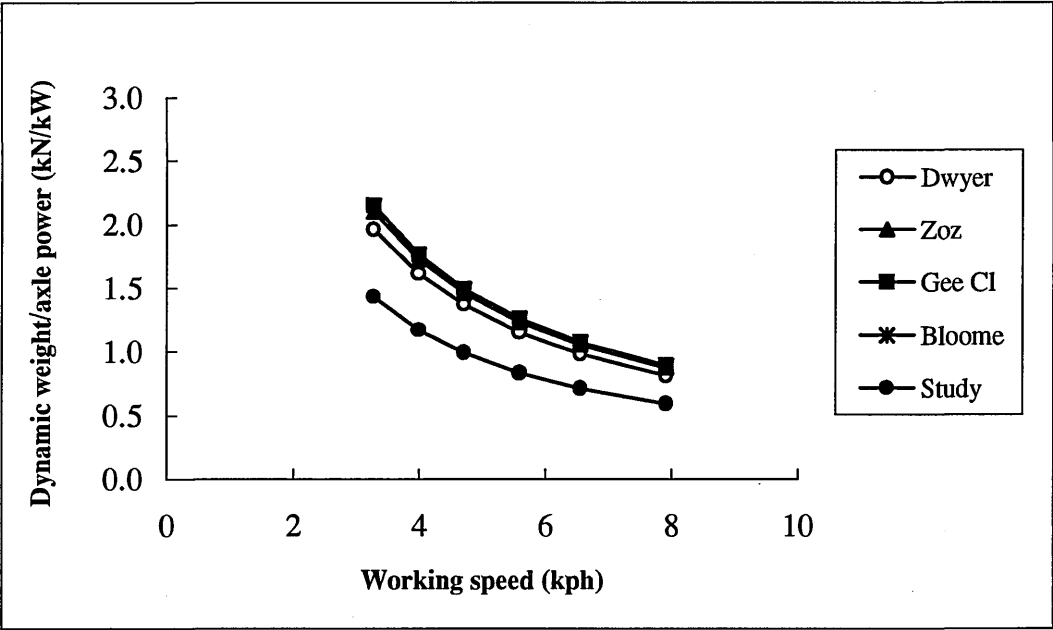


Fig. 6.4. Recommended tractor weight/axle power Vs. speed by Theory and Study at 10% slip and 0.4 COT

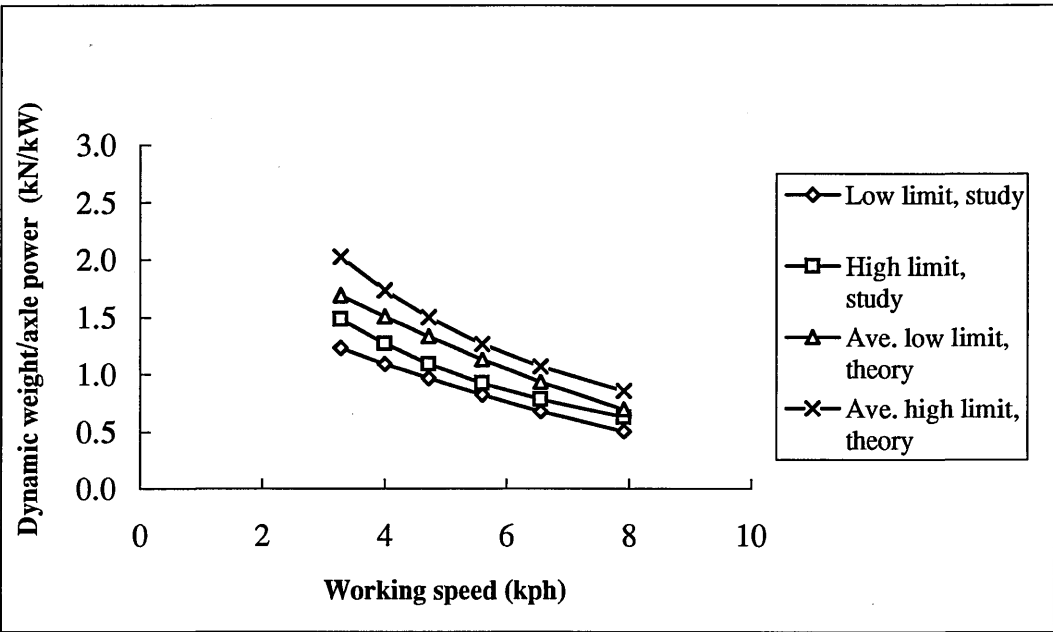


Fig. 6.5. Comparison between Theory high & low limits with those of Study at 95% confidence level at 10% slip and 0.4 COT

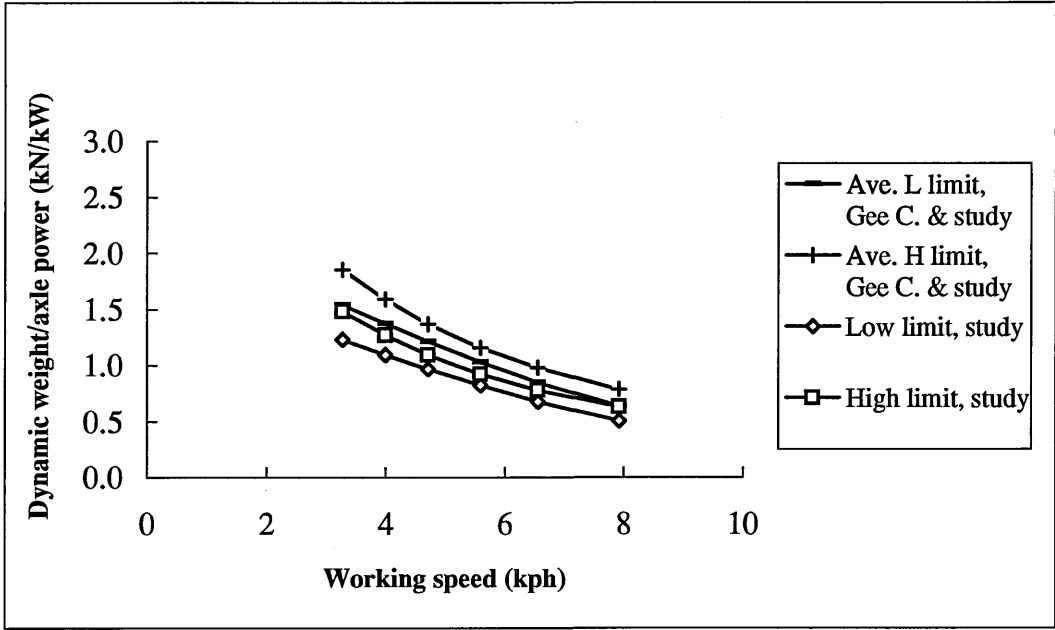


Fig. 6.6. Comparison between the work of Gee-Clough and Study at 95% confidence level at 10% slip and 0.4 COT

6.3.2.2 Comparison with the empirical approaches

The aim here to compare the study results with the work of Gee-Clough et al. (1978) and Dwyer et al. (1974) who are recognised leaders in this aspect of traction mechanics.

Gee-Clough et al. (1978) represented different empirical relationships to describe the tractive performance of a tyre in off-road conditions. One of them is the relationship between mobility number M and coefficient of traction $(C_t)_{\max}$ at maximum efficiency as shown in Fig. (6.7) which has been chosen as a base for the current comparison. His graph showed a considerable scatter data which came from re-analysing experimental data have been assembled originally by Dwyer et al. (1974). However, he tried to demonstrate a good fit to the data.

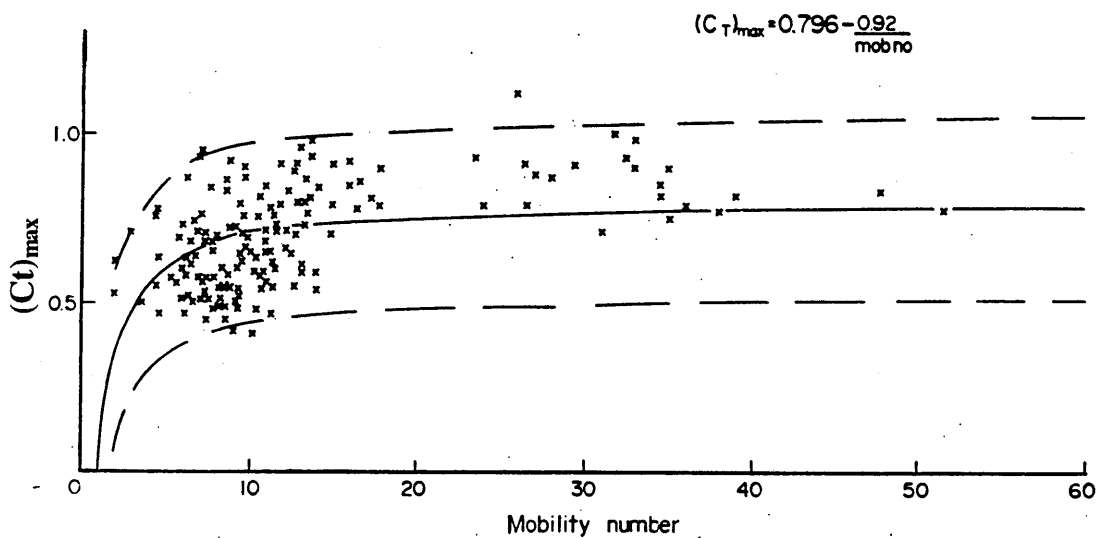


Fig. 6.7. Relationship between maximum coefficient of traction and mobility number (from Gee-Clough 1978)

He stated that the central curve in this figure is the empirical relationship between the mobility number and the maximum coefficient of traction which is in the form of :

$$(C_t)_{\max} = 0.796 - 0.92/M \quad (6.3)$$

and the two flanking curves are the 95% confidence limits for the data analysed. He pointed that this expression is valid for stubble, ploughed and cultivated fields only and for other fields with some restrictions. Since, these data obtained from many different soil conditions, it is expected that the data related to the loose weak soils to be between the average curve and the lower limit line. On other hand, it is assumed that as the soil becomes loose the mobility number becomes smaller and hence the coefficient of traction reduces.

Therefore, attempt was made to allocate the current study data on the Gee-Clough graph to determine their places between the existing data. From the study experimental data and information of both tractor front and rear dimensions of the tractor is used, the M and $(C_t)_{\max}$ were calculated from the following equations used by Gee-Clough et al. (1978) as described in section 3.2.4.2 :

$$M = C_{bd}/W \cdot \sqrt{\delta/h} \cdot [1/(1+b/2d)]$$

$$C_t = (C_t)_{\max} (1 - e^{-k_i})$$

The calculation results are given in Appendix (A6.5). From the results of the present study the relationship between the M and $(C_t)_{\max}$ were plotted alone on the Gee-Clough graph as shown in Fig. (6.8), however the existing data points were hidden to avoid the confusion between the data points.

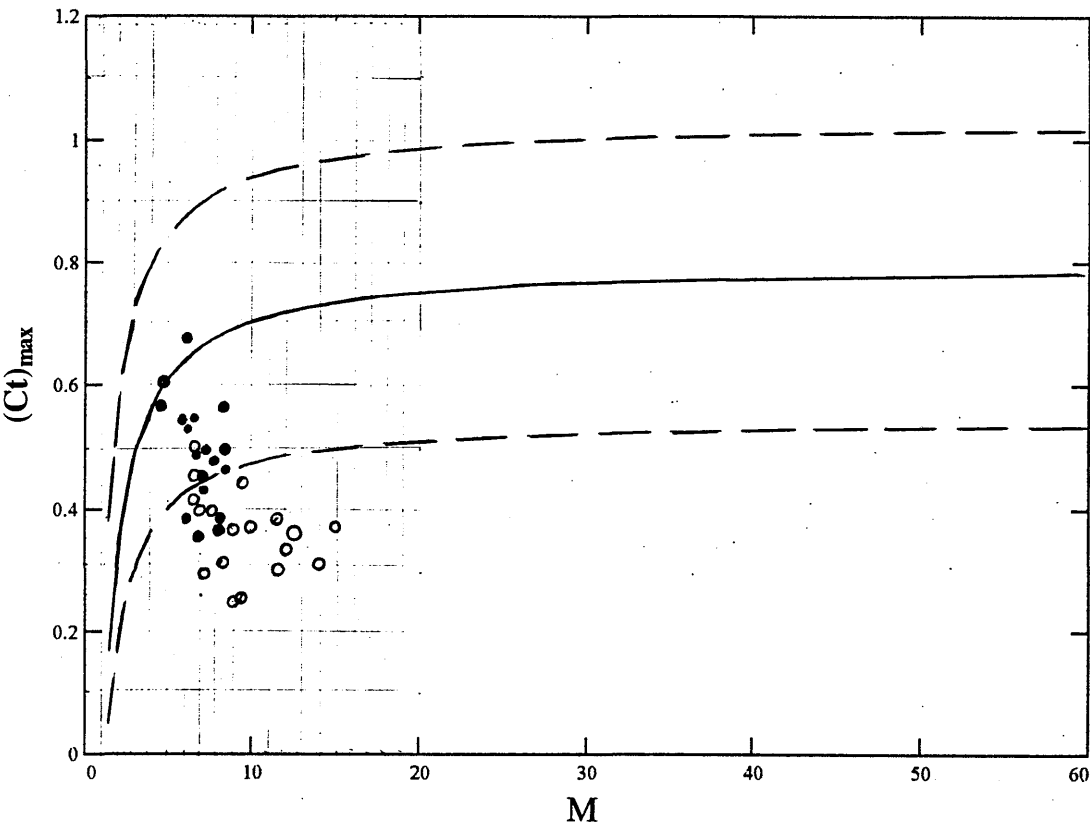


Fig. 6.8. The Gee-Clough graph with the study field results located on

Condition	Symbol
Gee Clough average data curve	————
Gee Clough low limit curve	- - - - -
Gee Clough high limit curve	- - - - -
Study Rear Data	•
Study Front Data	○

Fig. (6.8) illustrates that the study results are scattered and condensed in an area in similar way of the existing data. In addition they are located within and just below the lower limit of the exist data having low mobility number values which mean that the current study proves the concept and this investigation can be valid for the frictional soils as was assumed.

However, only the study results at low and medium tractor speed were used in the above investigation because it was observed that the results at high tractor speed appeared to be affected by the limited sampling speed provided by the datalogger used in the wheel force measurement system. The limited sampling (i.e. low sampling capacity) means that the wheel transducers may miss sensing some peak force values applied on the wheel during its rotation particularly at high speed, which represents the worse case, and result in some errors in force measurements. Such a problem could not be avoided with the available instrumentation.

As far as the work of Dwyer et al. (1974) at S.R.I. they assessed five different tyre sizes at a wide range of inflation pressure and vertical loads by means of the single wheel tester in many field conditions. A further step in this study was to select, from these original data, the most related data and information to the tyre tractive performance operating on sandy loam soil in particular in order to be compared with the study results obtained from the field experiments.

One of the parameters considered in their prediction to define the tractive performance was the relationship between mobility number M and coefficient of traction at maximum efficiency $(C_t)_{\max}$. Therefore, the following information were extracted from the original work (see Appendix A6.6 for details) :

1. Tyre size : 13.6/12-38
2. Soil type : sandy loam soil.
3. Soil conditions : stubble and ploughed fields.
4. Different vertical loads on the wheel and inflation pressures.

However, even some of this information is not exactly similar to that used in the study but it has been chosen to produce more reasonable data from which the value of M and $(C_t)_{\max}$ was calculated based on equations (2.16 and 2.25) respectively using similar prediction accuracy which was quoted by Dwyer et al. (1974). Then the relationship between M and $(C_t)_{\max}$ was allocated again on the Gee Clough graph alone without the existing points as shown in Fig. (6.9).

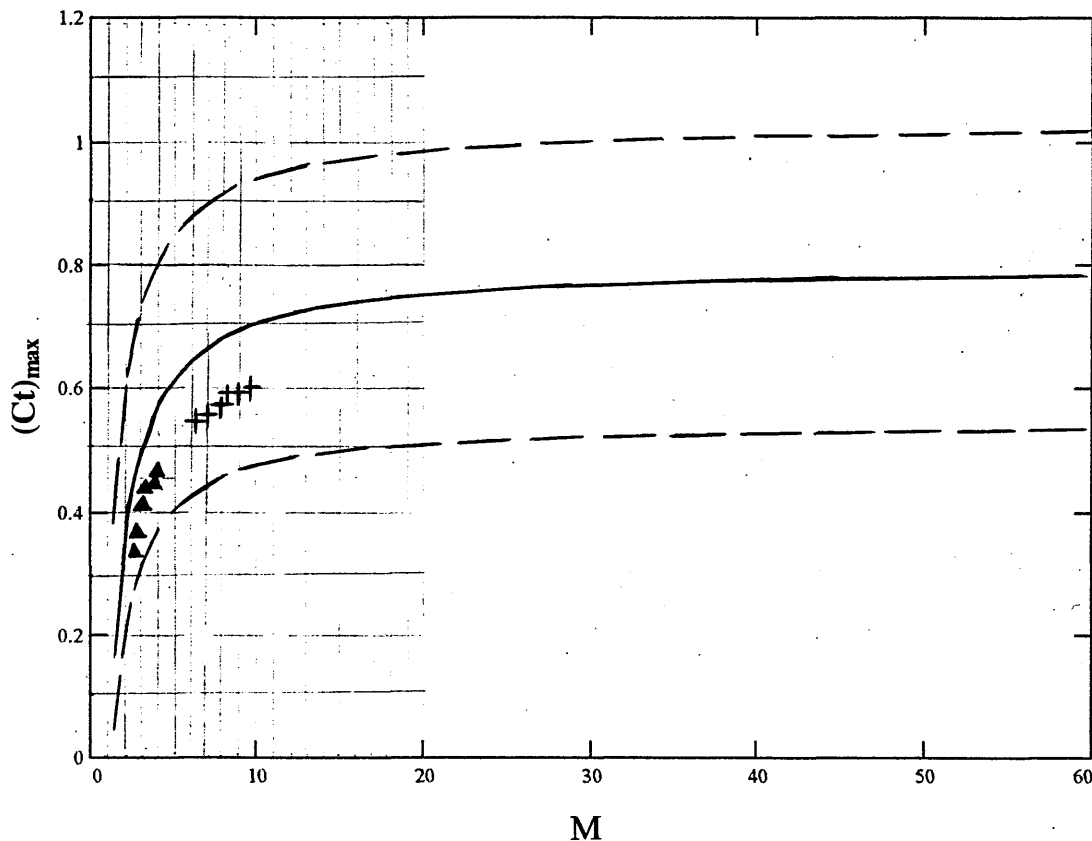


Fig. 6.9. The Gee-Clough graph with some data of Dwyer et al. (1974) located on

Condition	Symbol
Gee Clough average data curve	————
Gee Clough low limit curve	- - - -
Gee Clough high limit curve	- . - .
Dwyer data (Stubble field)	+
Dwyer data (Ploughed field)	▲

It can be seen the results determined from the pervious work for the tyre performance on sandy loam soil are located below the average curve. Also when these results compared with the study results for the rear wheel and plotted altogether as shown in Fig. (6.10), the data are nearly coincident which gives a favourable correlation between the study and the theory. In general, the current comparison has demonstrated that the study investigation has realistic results which could be applied to the frictional soils in particular since the study results were obtained from the real data collected from the field experiments.

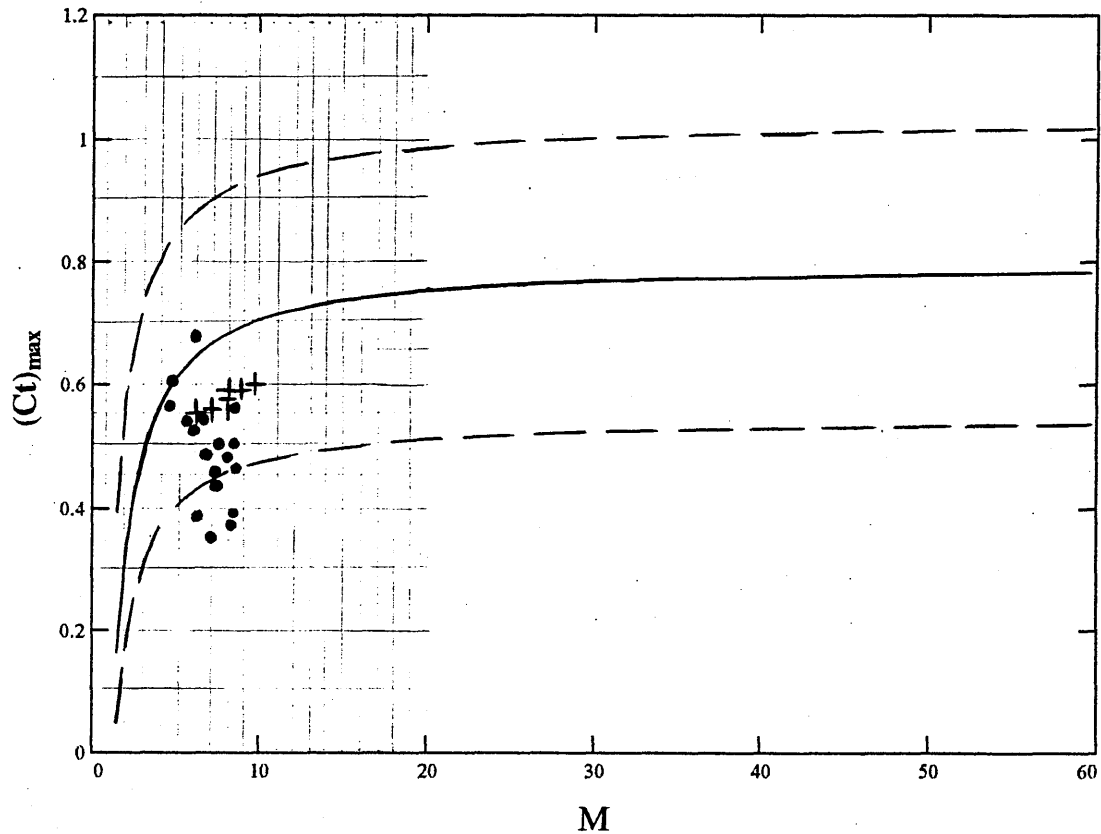


Fig. 6.10. The Gee-Clough graph with both the study and Dwyer data located on

Symbols are as on previous graphs.

A completely accurate comparison can not be made due to some or all of the reasons listed below :

- The large amount of data collected by the previous workers over a number of years.
- The wide range of variation in these field data.
- Although relatively similar soil type and condition were selected from the existing data for the sake of the comparison but still there is a variation in soil characteristics such as soil moisture content, c and ϕ .

As a result, equation (6.3) could be modified to be valid for the loose soil conditions in particular. That can be done by taking the average value of the study results on Fig.(6.8) which came from tractor rear and front wheels measurements. Then, the mentioned equation can be adjusted into two new equations, each of one can validates the average value of the rear and front wheel performance respectively in the same manner that Gee-Clough equation validates only the average value of his data. They are:

$$(Ct)_{\max} = 0.62 - 0.82 / M \quad \text{for rear wheel} \quad (6.4)$$

$$(Ct)_{\max} = 0.42 - 0.52 / M \quad \text{for front wheel} \quad (6.5)$$

Consequently, two new curves may be drawn from equations (6.4) and (6.5), one represents the performance of the rear wheel and the other represents the front wheel performance. They are plotted altogether with the average data curve of Gee-Clough as shown in Fig.(6.11).

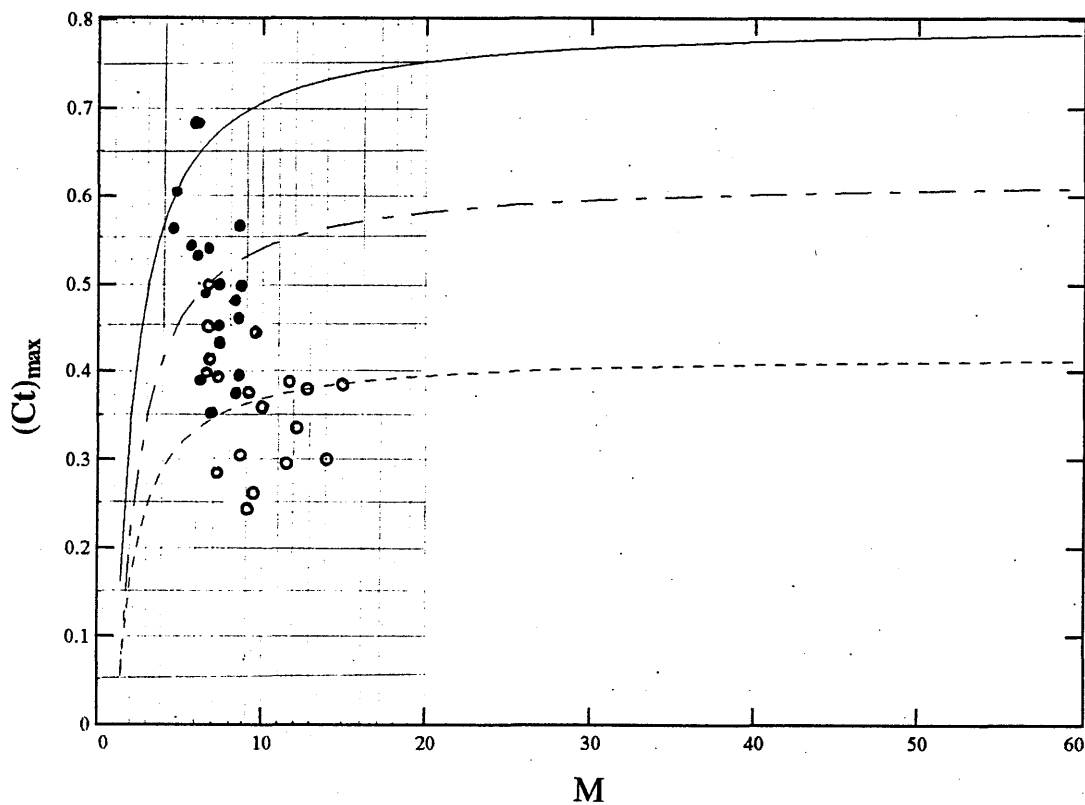


Fig. 6.11. The new performance curves of the tractor rear and front wheels

Gee Clough average data curve	————
Study rear wheel data curve	-----
Study front wheel data curve	- . - . - .

6.3.2.3 Comparison of Measured and Calculated thrust force

An attempt was made to examine the validity of the experimental results by comparing the measured thrust force with the calculated force. The thrust force H_{cal} was calculated by using Eq. (3.4) which referred to Reece (1967) and has the form shown for wheeled tractors :

$$H = [(A_1 \cdot c + W_1 \cdot \tan(\phi)) \cdot [1 + (K/i_1 \cdot L_1) \cdot \{e^{-i_1 \cdot L_1/K} - 1\}]] \cdot 2 \\ + [(A_2 \cdot c + W_2 \cdot \tan(\phi)) \cdot [1 + (K/i_2 \cdot L_2) \cdot \{e^{-i_2 \cdot L_2/K} - 1\}]] \cdot 2$$

All terms in the equation, except K value, are known as explained in section 3.2.4.3. However, the value of K was estimated by following two methods :

I. Komandi method

The value of K was estimated by following the Komandi approach described in section 2.2.1. In this regard some of the thrust-slip curves established for from field measurements for the rear and front tractor wheels were used. Fig (6.12) represents one of these curves.

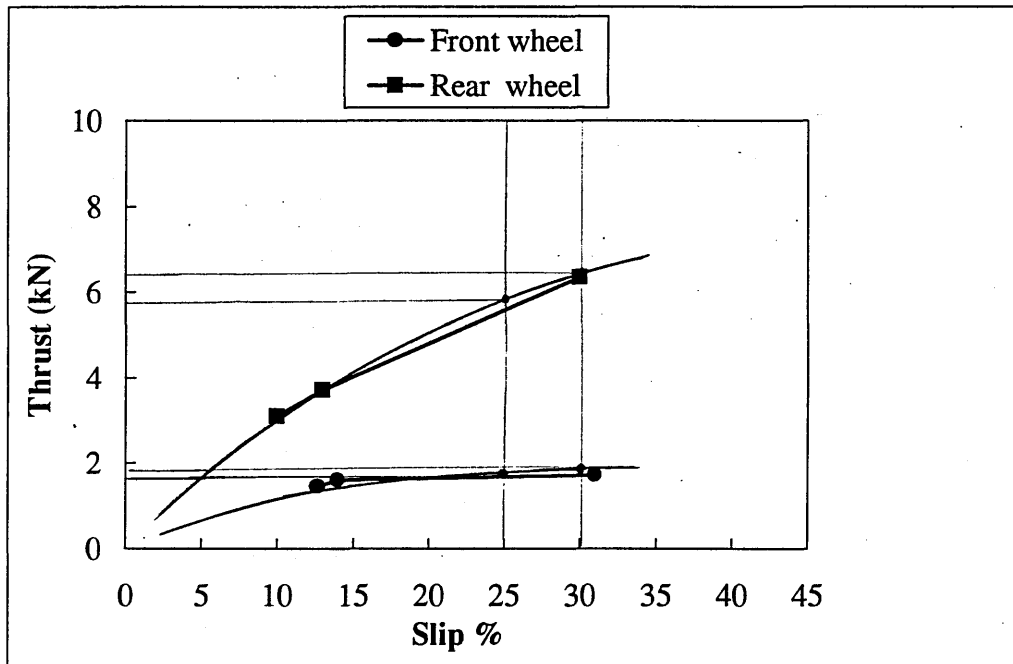


Fig. 6.12. Thrust-Slip relationship for test of No ballast at 6 Nominal speed used to estimate K value

Hence, K value can be calculated from the simplified equation established by Komandi (Eq. 2.13) as :

$$K = i_1 i_2 \ell(1 - \lambda) / [i_2 - (i_1 \lambda)]$$

Table (6.3) shows some of the K values established from different field test results. There are a few tests which showed slip values above 20% (recommended by Komandi). So this calculation method can only be used in a few situations for this study.

Table 6.3. The values of K determined based on Komandi approach

Field test condition	Wheel	K value (mm)
No ballast & Med. speed	Rear	47
	Front	37
Med. ballast & Med. speed	Rear	34
	Front	39
Max. ballast & Med. speed	Rear	36
	Front	33

II. Mathcad calculations

In this method K value was evaluated from Eq. (3.4) using a Mathcad Package to simplify the calculations. At the beginning, K was given a range of values and providing the other terms are known various values of thrust force were calculated. Then the measured thrust forces F_{mr} were compared with the calculated ones F_{cal} and a suitable value of K was chosen at the closest values of the measured and calculated forces as presented in Table (6.4). An example of this calculation is shown in Appendix (A6.7).

It should be noted that theoretically, K has one value for one type of soil, however, in practice there are different values for K as it can be seen in Table (6.4). This because K is influenced by some factors such as the changes in soil condition including the moisture contents, homogeneity and initial state, and also due to the changes in tyre deflection. The typical probable value of K (mm) is 12 for compacted soil and 40 for loose one (Crossley and Kilgour 1983).

Table 6.4. Evaluating K value using Mathcad calculation method

Field test No.	H_{mr} (kN)	H_{cal} (kN)	K (mm)
1	10.88	10.81	33
2	12.78	12.70	32
3	19.64	19.67	19
4	9.10	9.04	46
5	10.62	10.60	42
6	16.14	16.12	37
7	10.60	10.63	65
8	9.98	10.01	69
9	----	----	----
10	10.00	9.96	34
11	13.74	13.78	28
12	20.10	20.02	21
13	9.60	9.55	46
14	12.56	12.58	38
15	19.20	19.23	28
16	7.00	7.04	77
17	8.86	8.88	63
18	15.40	15.45	38
19	10.26	10.13	32
20	14.64	14.65	23
21	20.36	20.19	18
22	11.86	11.81	29
23	19.04	19.14	18
24	24.58	24.45	18
25	6.96	7.00	74
26	10.02	10.08	64
27	----	----	----

(----) means the tractor proved not capable of working at this combination of speed, weight and pull setting.

Therefore, the average value of K could be determined and chosen. The average value obtained by Komandi approach and Mathcad calculation is $K=38\text{mm}$ and $K=40\text{mm}$ respectively. The later value was reinserted again in the equation. Consequently, the calculated thrust force H_{cal} was compared with the measured H_{mr} as shown in Table (6.5).

Table 6.5. Comparing the measured and calculated thrust forces
at an average value of $K = 40 \text{ mm}$

Field test No.	H_{mr} (kN)	H_{cal} (kN)
1	10.88	9.54
2	12.78	11.23
3	19.64	17.76
4	9.10	9.94
5	10.62	10.93
6	16.14	15.70
7 *	10.60	14.01
8 *	9.98	13.77
9	----	----
10	10.00	8.82
11	13.74	10.99
12	20.10	15.45
13	9.60	10.99
14	12.56	12.18
15	19.20	16.70
16 *	7.00	11.52
17 *	8.86	12.24
18 *	15.40	15.04
19	10.26	8.51
20	14.64	10.01
21	20.36	20.92
22	11.86	9.31
23	19.04	12.09
24	24.58	18.40
25 *	6.96	11.32
26 *	10.02	14.04
27	----	----

From Table (6.4) it can be seen that the predicted (calculated) thrust force is always higher than the measured value at field tests of high tractor speeds (*) because of the problem associated with the data collection system explained in last section. Therefore, the results at these speeds are not taken in account in the present comparison. A regression analysis was done to evaluate the calculated values (Appendix A.6.8). The results showed that there is no significant difference between the measured and calculated thrust values at 95% confidence level which indicated that the classical theory of traction mechanics can predict the study results in this aspect adequately.

A source of error which influences the current comparison is that it was assumed that most of the terms in the equation used are constant for all field tests. However, practically, tyre deflections vary from one test to another which affects the values of tyre contact area and length of contact values. Also, the soil shear properties c and ϕ is expected to vary across the field. Furthermore, K value was selected as an average value for all the thrust forces calculated.

6.4 Soil compaction assessments

The results of field measurements are given in Appendix (A6.9). In this section, soil dry density and penetration resistance were plotted against depth and infiltration rate against time to determine the effect of the ballast weight and implement pull setting on soil conditions (i.e. in undisturbed and wheeled locations).

It is found that soil conditions in the undisturbed places which represent the initial case were not consistent which shows that the field soil is not quite homogenous. There was also variation in soil moisture content during the days of the field tests due to rainfall. Therefore, the ratio of the measured value in wheeled location to that in the undisturbed location i.e. the final condition to the initial condition was used for the current comparison between the different treatments.

Figs. (6.13 to 6.15) summarized the change of soil dry density, as a ratio of the final to the initial case, with the depth as a result of ballast and pull effect. It can be seen that at a particular ballast amount as the pull increases the soil density increases through the depth. Similarly, at a particular implement pull there is an increase in the density ratio with the increase of tractor weight.

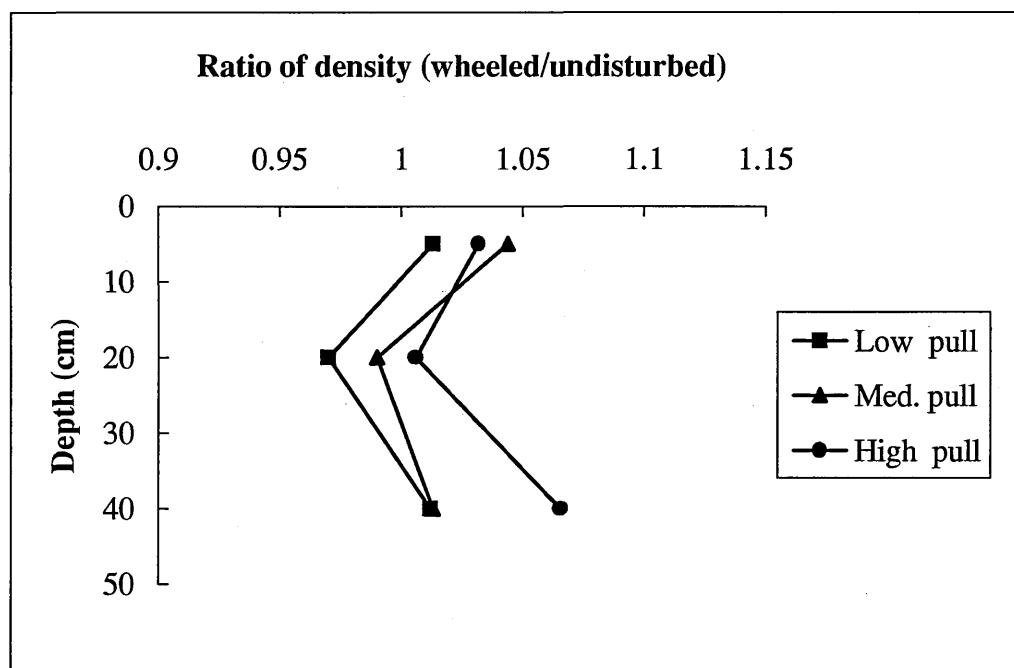


Fig. 6.13. Change in soil dry density ratio with the depth at No ballast

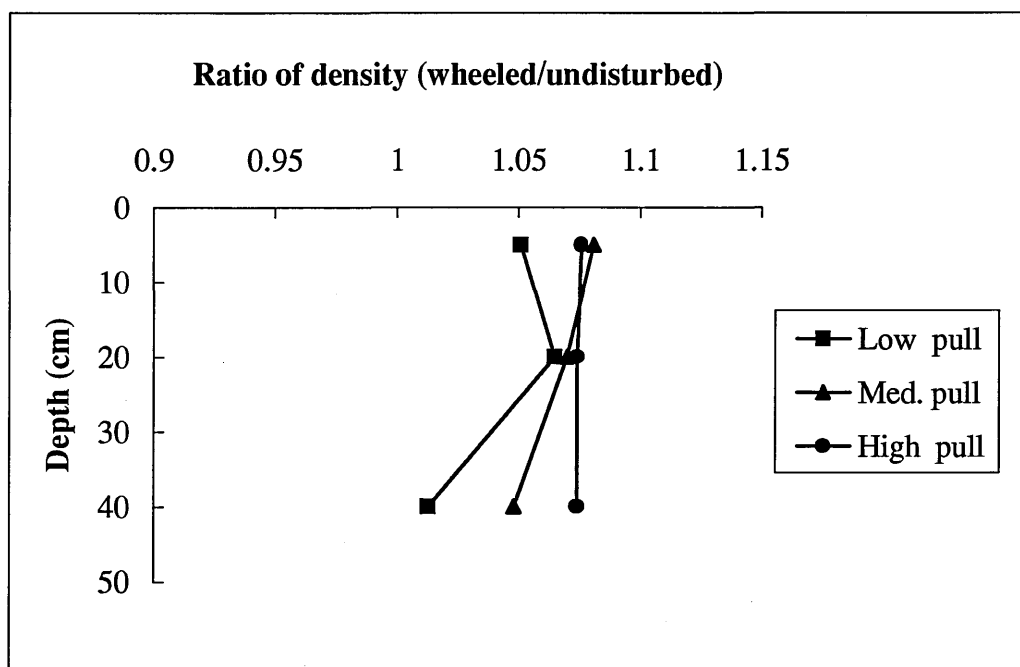


Fig. 6.14. Change in soil dry density ratio with the depth at Medium ballast

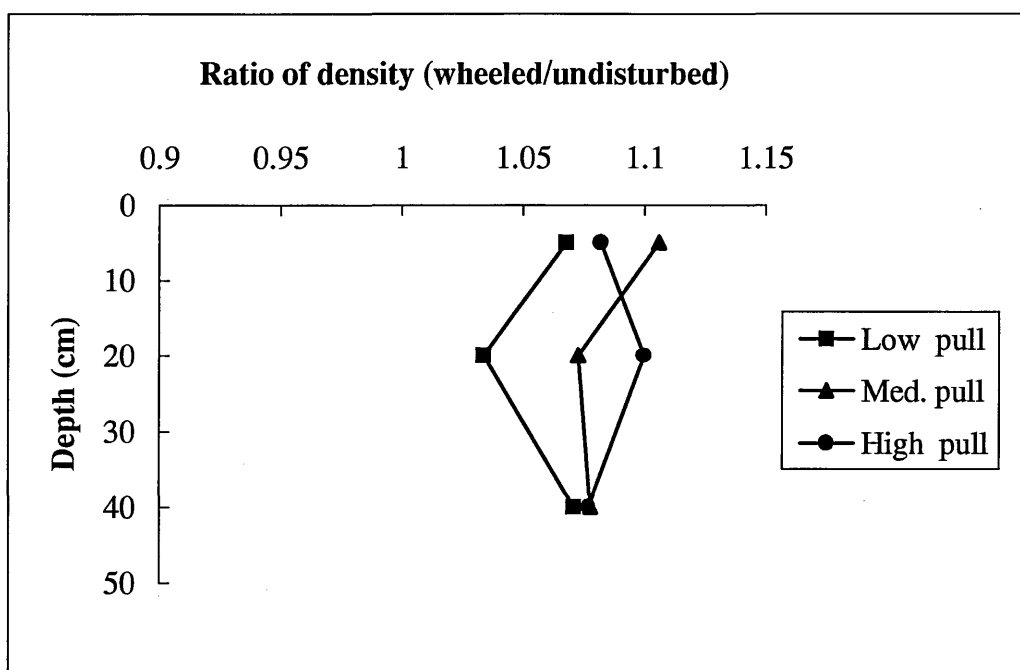


Fig. 6.15. Change in soil dry density ratio with the depth at Maximum ballast

The change in penetration resistance through the depth is shown in Fig. (6.16 to 6.18). It is observed, generally, that penetration resistance ratio is greater at a depth below 15 cm and this effect increases with the increase of ballast amount and pull value. However, the upper zone showed to have some loosening effect by tractor wheel particularly at high pull.

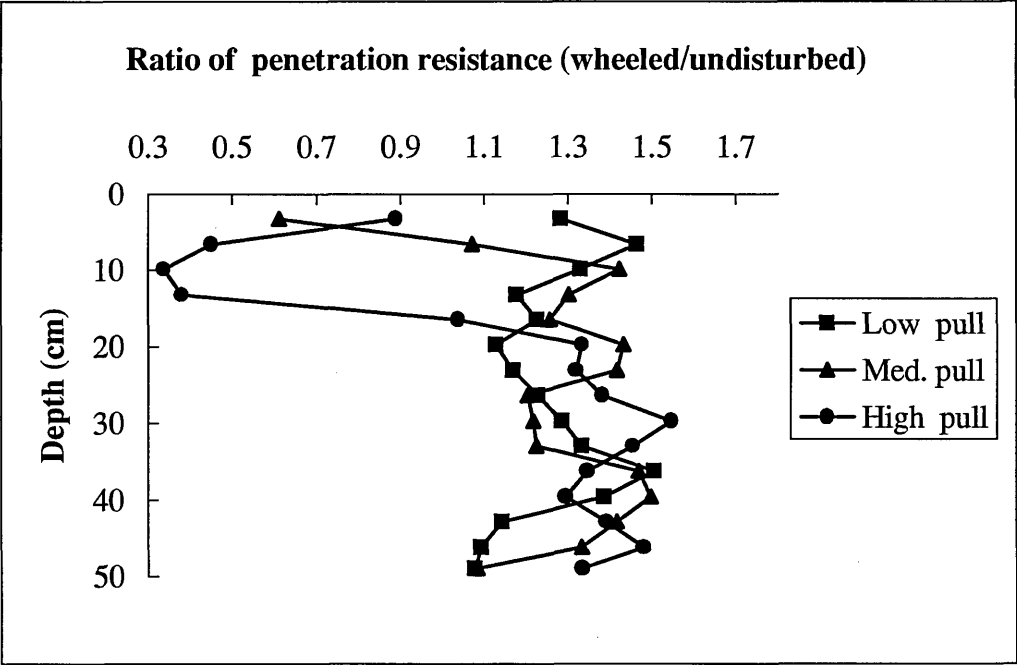


Fig. 6.16. Change in penetration resistance ratio with the depth at No ballast

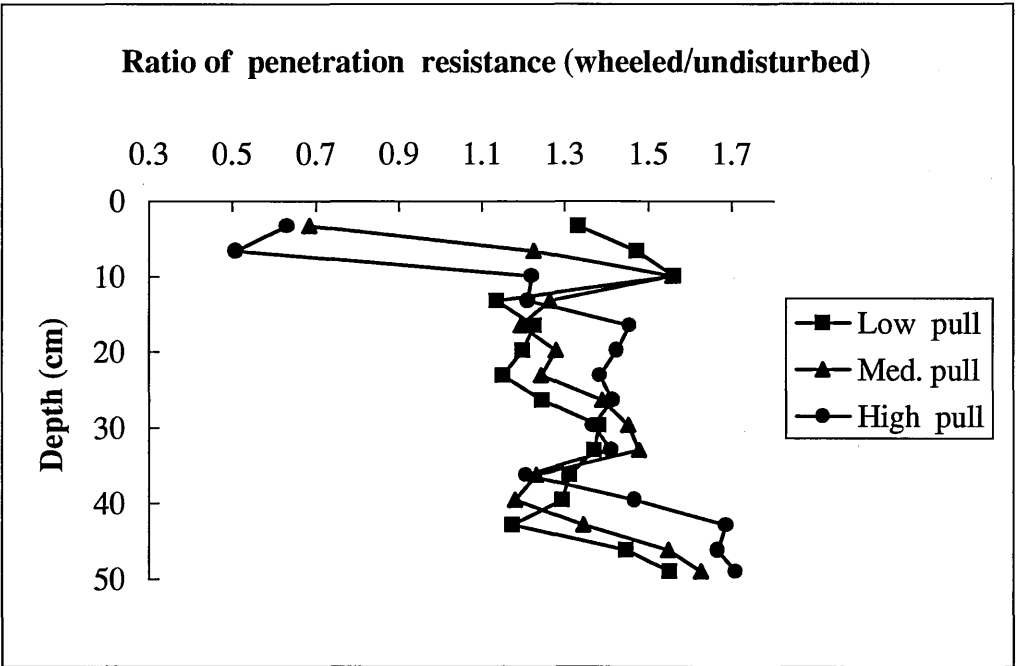


Fig. 6.17. Change in penetration resistance ratio with the depth at Medium ballast

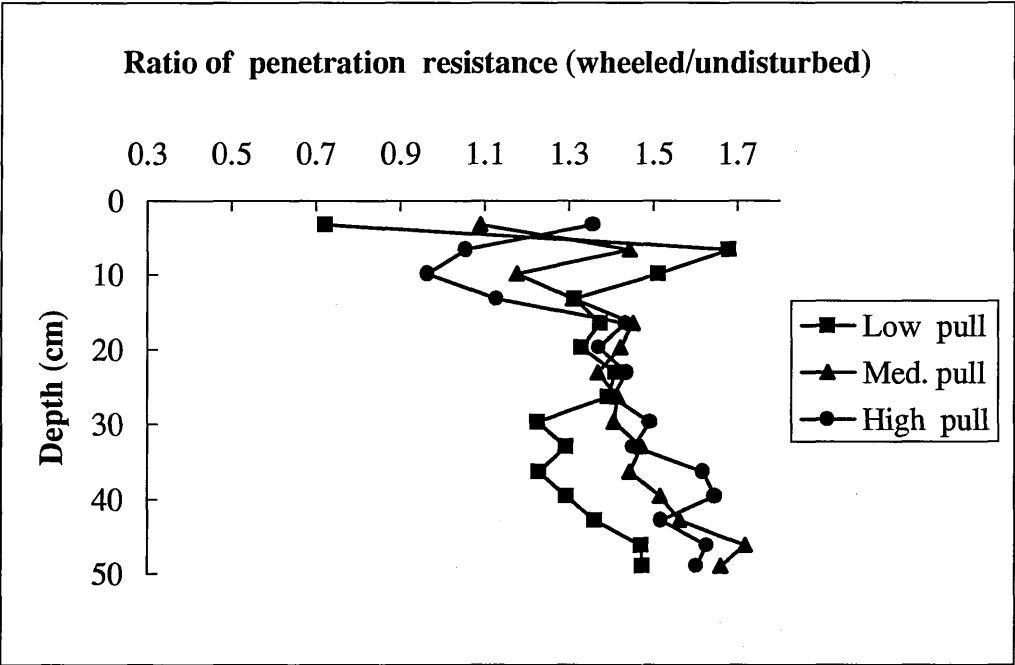


Fig. 6.18. Change in penetration resistance ratio with the depth at Maximum ballast

The simple method of measuring water entry rates at different combination of ballast weight and pull showed clearly that there is a large effect as a result of the tractor wheel passage. It is found that the variations in infiltration rate between the different treatments are more comparable when using the measured results in the wheeled locations rather than using the ratio between the values of wheeled and the undisturbed location. Figs. (6.19 to 6.21) represent the measured infiltration rate with time in the wheeled locations for the different treatments. The results show that the infiltration rate at no ballast and medium ballast conditions is not much affected by the increase of the implement pull but at maximum ballast weight condition as the pull increases the infiltration rate becomes worse. The condition of maximum ballast and high pull shows the worse case where the infiltration rate decreases substantially (Fig. 6.21).

For the purpose of determining the effect of compaction on the undisturbed places, the value of infiltration rate after about 50 minutes from the beginning of recording time was chosen. It was observed that this value started to be constant with the time as shown in Tables (A6.15 to A6.17). On average, the results from the different tests appeared that the undisturbed soil was compacted almost 5 times excluding the worse case.

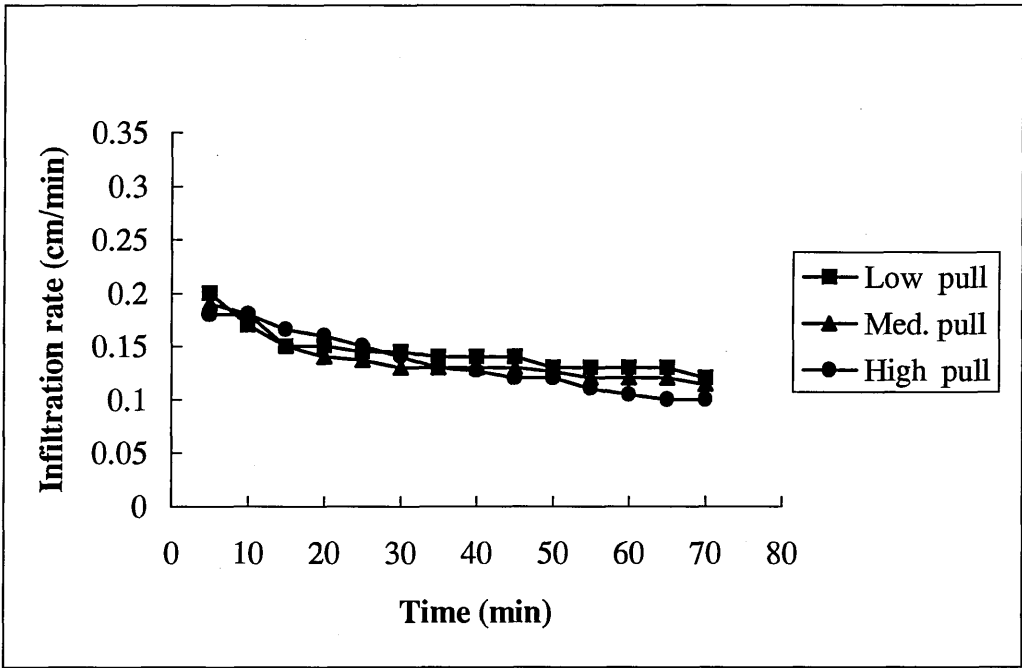


Fig. 6.19. Change in infiltration rate with time (in the wheeled location) at No ballast

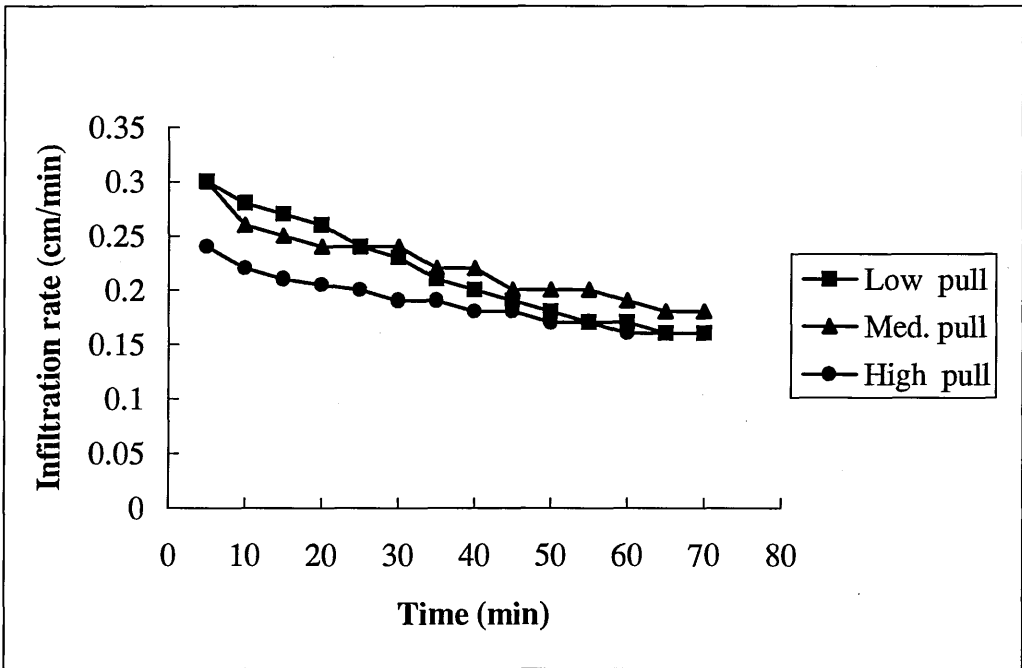


Fig. 6.20. Change in infiltration rate with time (in the wheeled location) at Medium ballast

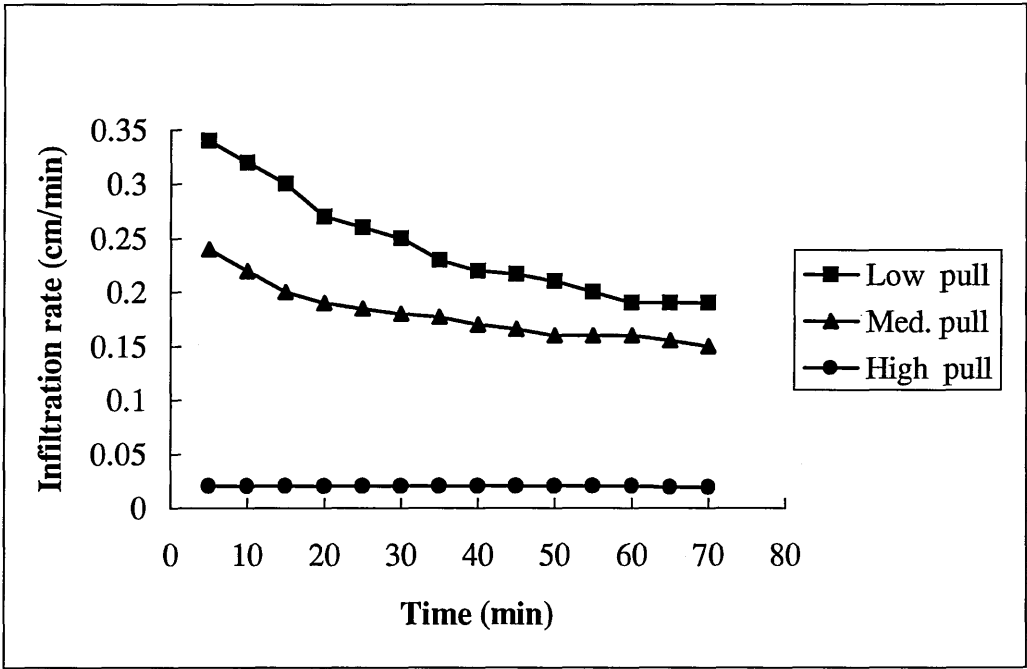


Fig. 6.21. Change in infiltration rate with time (in the wheeled location) at Maximum ballast

The effect of tractor weight and slip on soil compaction

An attempt was made to find a link between the soil compaction and the tractor performance tests discussed previously in section 6.3.1. Therefore, the measured values of soil density, penetration resistance and infiltration rate were plotted versus the tractor wheel slip at different ballast weight conditions. The results of the soil density, penetration resistance are presented at three different depths.

Figs.(6.22 to 6.24) show the effect of slip in increasing soil compaction at the depths of 5, 20, 40 cm respectively at different tractor ballast weights. In all cases, there is a little increase in density ratio with the increase in wheel slip or tractor weight except in the top layer in which the density ratio rises with slip up to a certain maximum, then reduces with subsequent increase in slip.

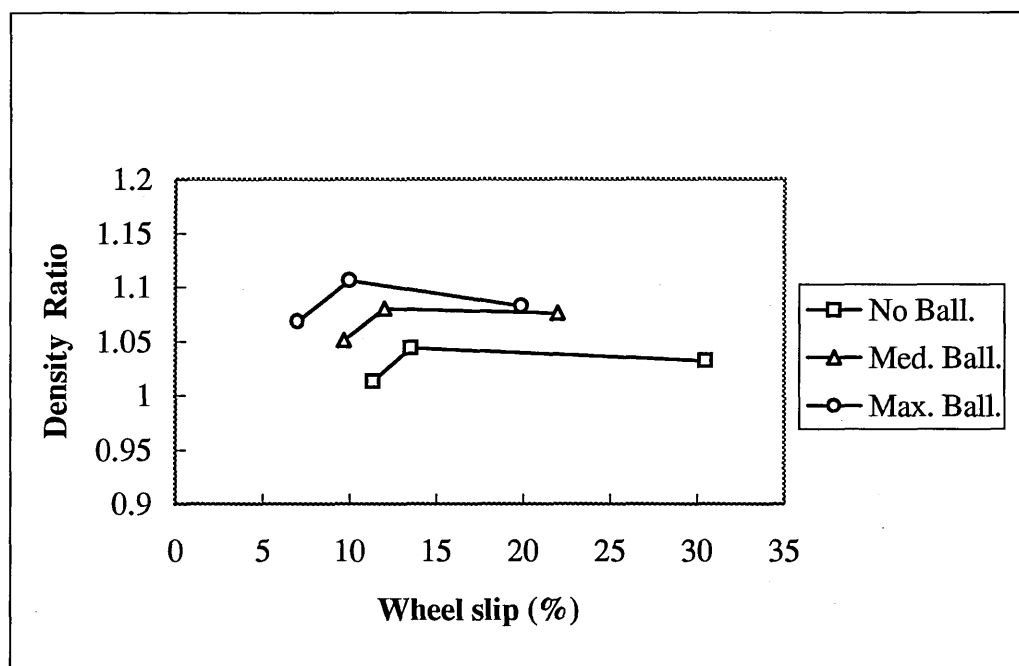


Fig. 6.22. Change in soil dry density ratio with the slip at 5 cm depth

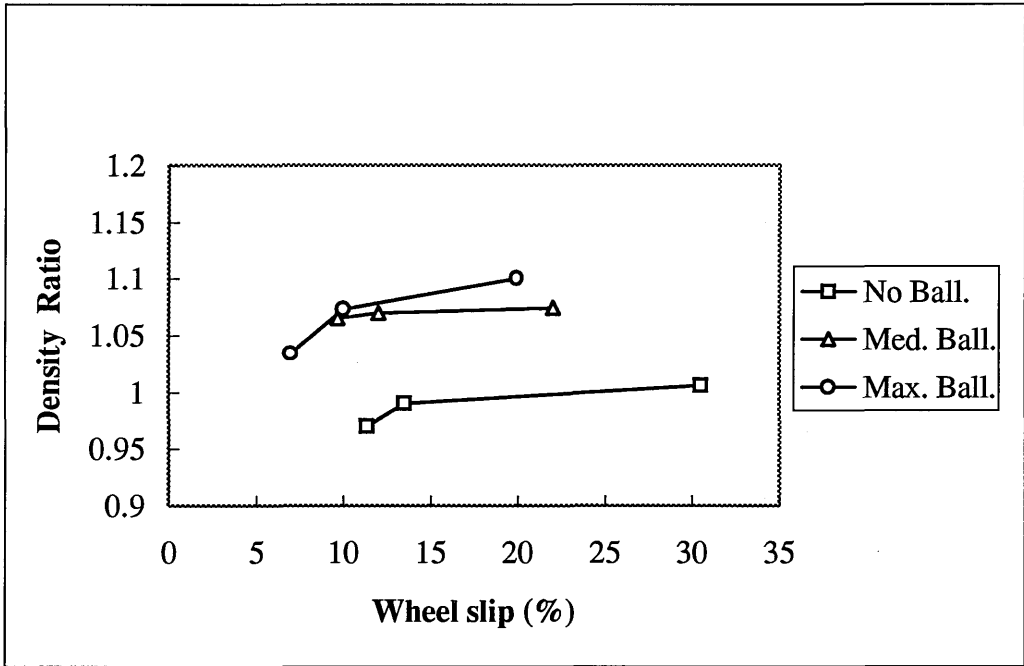


Fig. 6.23. Change in soil dry density ratio with the slip at 20 cm depth.

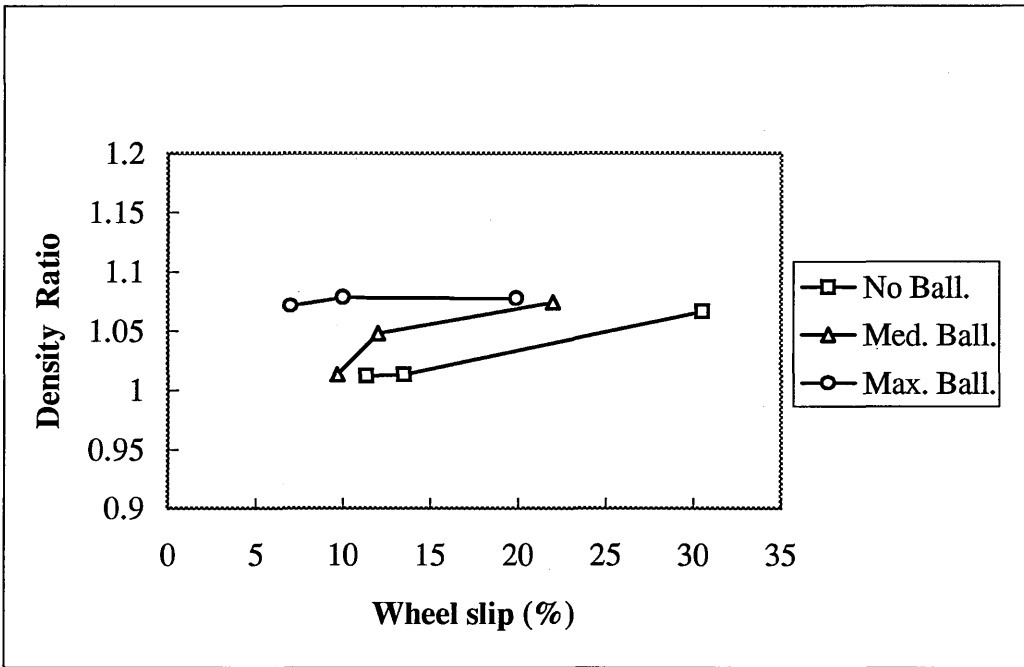


Fig. 6.24. Change in soil dry density ratio with the slip at 40 cm depth.

The effect of slip on penetration resistance ratio at the average depth of 0-15 cm, 16-35 cm and 36-49 cm was determined at different tractor ballast weights as shown in Fig. (6.25 to 6.27). The surface layer indicated a sudden decrease in the penetration resistance ratio with slip. That can be referred to that the soil is disturbed and the tyre starts to throw the soil backwards resulting in loosening effect particularly at high slip (Fig 6.25). However, at depth below 15 cm the wheel slip and tractor weight caused a remarkable increase in penetration ratio particularly at maximum tractor ballast (Fig. 6.27).

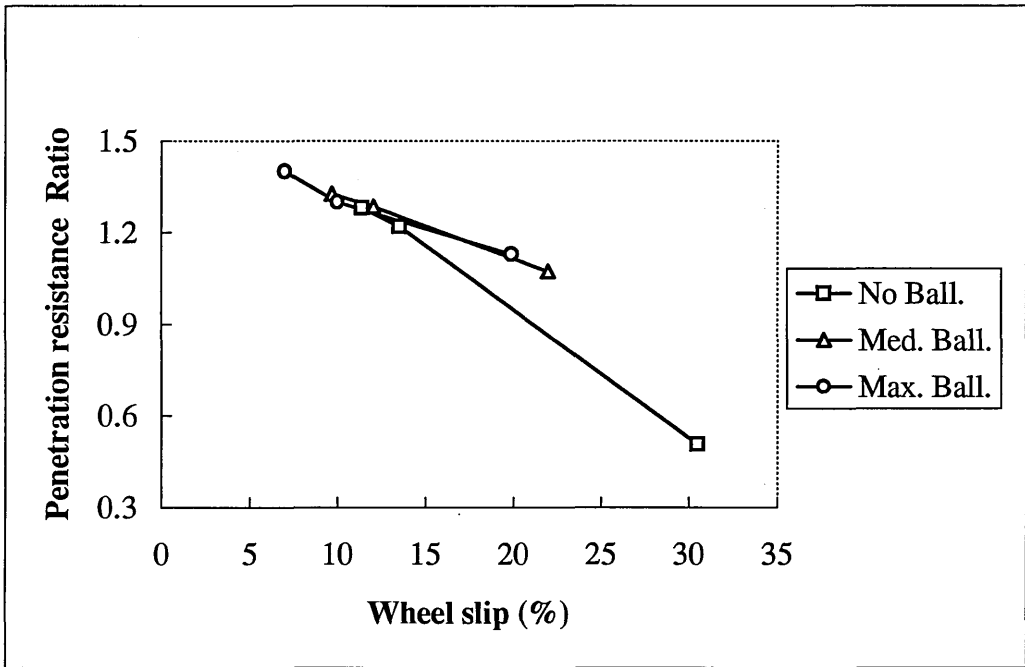


Fig. 6.25. Change in penetration resistance ratio with the slip at average of 0-15 cm depth

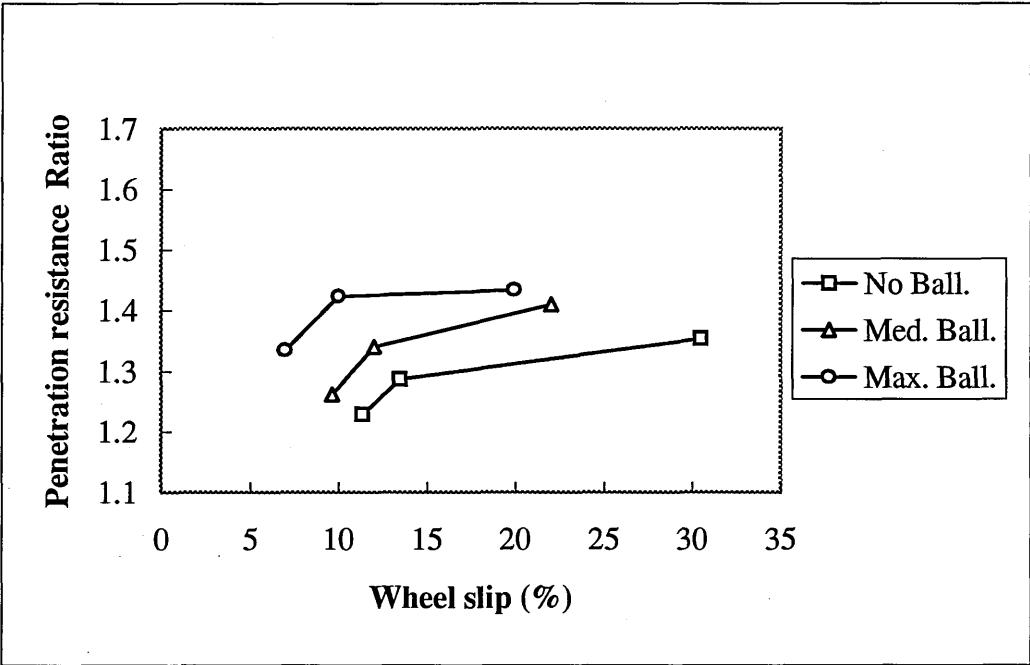


Fig. 6.26. Change in penetration resistance ratio with the slip at average of 16-35 cm depth

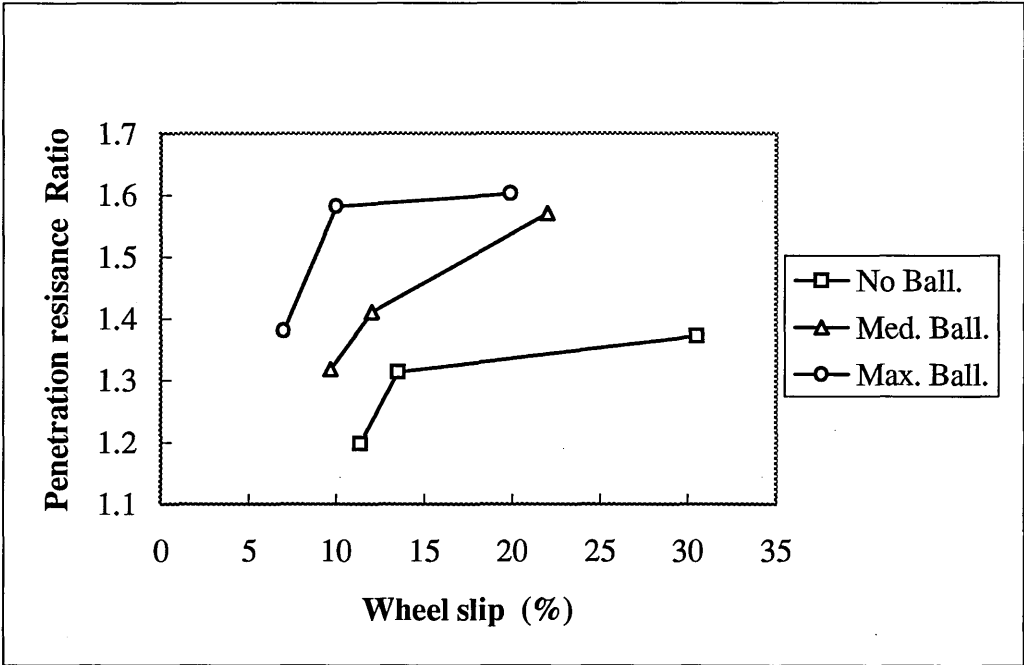


Fig. 6.27. Change in penetration resistance ratio with the slip at average of 36-49 cm depth

The average infiltration rate measured at the last twenty minutes of the measurement time (i.e. became nearly constant) was plotted against wheel slip as presented in Fig. (6.28). The results indicated there is a reduction in water entry as wheel slip or tractor ballast increases. The maximum reduction reaches up to 80% when the tractor ballasted to its maximum and working at high implement pull, probably because of the smearing effect occurs under the tyres.

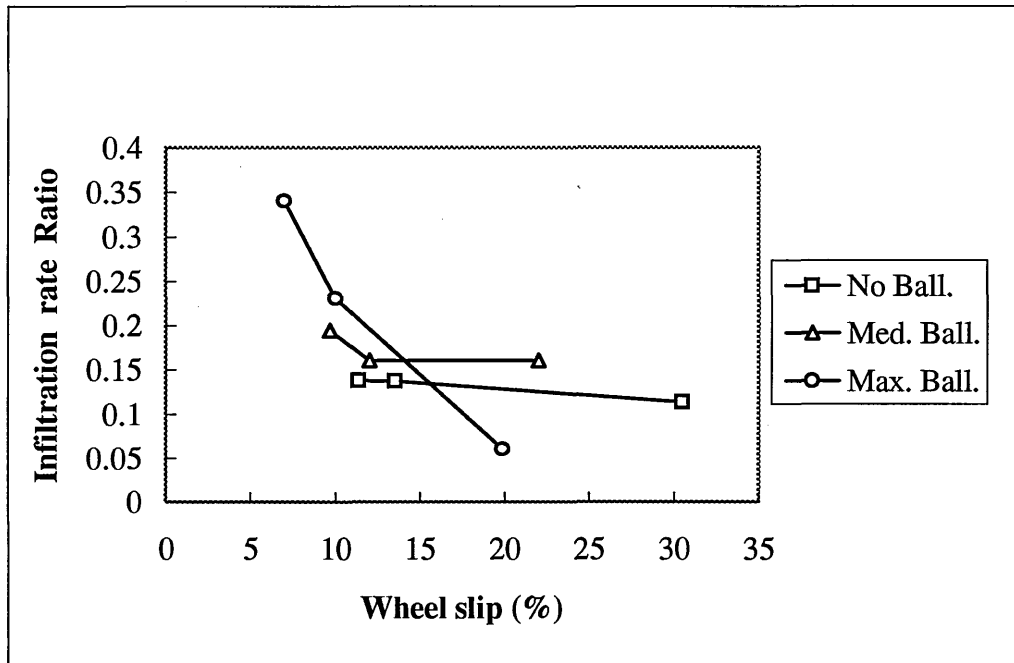


Fig. 6.28. Change in infiltration rate ratio with the slip

The investigation results used to evaluate compaction characteristics can be summarised as the following :

1. From soil density measurements, both tractor ballast weight and implement pull cause compaction through the depth, however, the former has more effect.
2. Penetration resistance measurements showed a loosening effect in the upper zone and more compaction at depth below 15 cm.
3. Infiltration rate measuring method is the most sensitive one to demonstrate soil compaction which showed clearly that the worse case of compaction occurred when the tractor operating at maximum ballast and high pull.
4. Results indicated that the worse effect of wheel slip occurs when the implement pull is maximum and combined with the extra ballast Fig. (6.27 and 6.28).
5. The field test chosen to represent the highest tractor performance in section 6.3.1, did not cause the critical compaction and the infiltration rate could be used as a base of this assessment.

7. APPLICATION OF THE RESULTS

7.1 Introduction

In this section an attempt is made to demonstrate the possible application of the study results. It provides a method of correlation between the present work and some other studies with the aim to provide useful advice. It includes also the final soil compaction assessment and discussion on the difficulty of showing particular relationship between soil compaction and plant growth.

7.2 Engineering and agronomy recommendations

7.2.1 Matching tractor performance to implement size

This section aims to show how to link between different research studies to provide information for practical use. In addition, an integrated application can be achieved.

A semi-empirical approach developed by Desbiolles (1994) can be used to estimate the optimum draught required for a tillage implement with combination of the results of the present study. The first source gives the draught required for a single tool of implement and the second source provides the optimum tractor drawbar pull at a certain condition. An optimum operating combination can be achieved in terms of a proper matching between tractor available power, weight, operating speed and implement draught needed to work efficiently in frictional soil (i.e. sandy loam in particular).

The approach of Desbiolles relies upon using the cone index field data to estimate the draught requirement of a given tillage implement working in field conditions at a depth (d) by following the procedure he proposed as below :

1. Relate the tool type of implement to its closest equivalent one among the several tools used in the study of Desbiolles (1994).
2. Read from the chart Fig. (A7.1) the related Tool-Index value (I) at the appropriate working depth (Appendix 7).
3. Establish the mean Cone-Index (C.I.) characteristics (in bar units) of the field soil condition at regular intervals down to the intended depth of work, following the general procedure stated in the ASAE standard S313.2.
4. Estimate the area under the C.I. down to the required depth of work (AreaCI). This value may be approximated by multiplying the average cone-index over the soil profile by the intended work depth.
5. Specify the moisture content of the soil (% on dry bases) in the working zone.
6. Read from the chart of Fig. (A7.2) the F_{mult} value at the appropriate depth and moisture content (Appendix 7).

7. Estimate the standard-tine draught D (in kN) at a depth d (in metre) as follows:

$$D = F_{\text{mult}} \times \text{Area C.I.} \times (0.0495 + 1.2247 \times d) \quad (7.1)$$

8. Estimate the single tool draught as follows:

$$D_{\text{tool}} = D \times I \quad (7.2)$$

The present study results give the optimum available drawbar pull of the tractor (i.e. draught). Consequently, the implement size of n single tools can be determined by :

$$n = \frac{\text{Tractor drawbar pull}}{D_{\text{tool}}} \quad (7.3)$$

A worked example can be given (based on data selected from the present study) using a mould board plough as follows :

Feature	Value
working depth d	0.25 m
Tool Index I	1.55
Mean Cone-Index	7.3 bar
(AreaCI)	1.83 bar-m
Moisture content	15.5 %
Multiplier Factor F_{mult}	2.25
Optimum tractor drawbar pull	17.24 kN

Then,

The standard-tine draught $D = 1.46$ kN

Draught required for a single tool $D_{\text{tool}} = 2.26$ kN

The optimum implement size of n tools $= 7.62 \Rightarrow 7$ furrows

The value could be adjusted to exactly 7 furrows by changing the working depth slightly. Further, if the width of cut and field efficiency (η) are known at the recommended actual speed the optimum work rate can be determined as :

$$\text{Work rate} = (\text{no. of furrows} \times \text{cut width}) \times \text{working speed} \times \eta \quad (7.4)$$

Machine cost calculations can also be done to show the advantage of operating at optimum tractor-implement performance when appropriate values and assumptions are available. This information could be then used by the management for control of the farming enterprise.

7.2.2 Soil compaction implication

The results of soil compaction measurement presented in details in section 6.4 show there is change in soil state because of the wheel loading and wheel slip effect. Due to the non consistency of the initial state of the soil, the ratio of the measured value in wheeled location compared to the undisturbed location was used.

The general trend from the present results of soil compaction shows that as the tractor weight and /or wheel slip increases the soil compaction also increases. Comparing the results of three ways of measurement presented in Fig. (6.13 to 6.21), the infiltrating rate method provides the most sensitive indicator of soil compaction effect because it avoids the confusion in measured results through the soil profile. Therefore, it is suggested to use this method in the current assessment of soil compaction and to provide a useful conclusion.

Fig. (7.1) represents the general trend of the effect of wheel slip on the infiltration rate combining the effect of all the tractor ballast weights values together. It shows that as slip increases so the infiltration rate ratio decreases, indicating that compaction is more at high slip values. Fig. (7.2) shows infiltration rate against slip for the maximum ballast situation. Under these conditions maximum power can be obtained at maximum ballast weight at wheel slip of 10%. The power is less at high slip but the compaction is more severe, so it is advantageous to work at the maximum power point to minimize the effect of compaction.

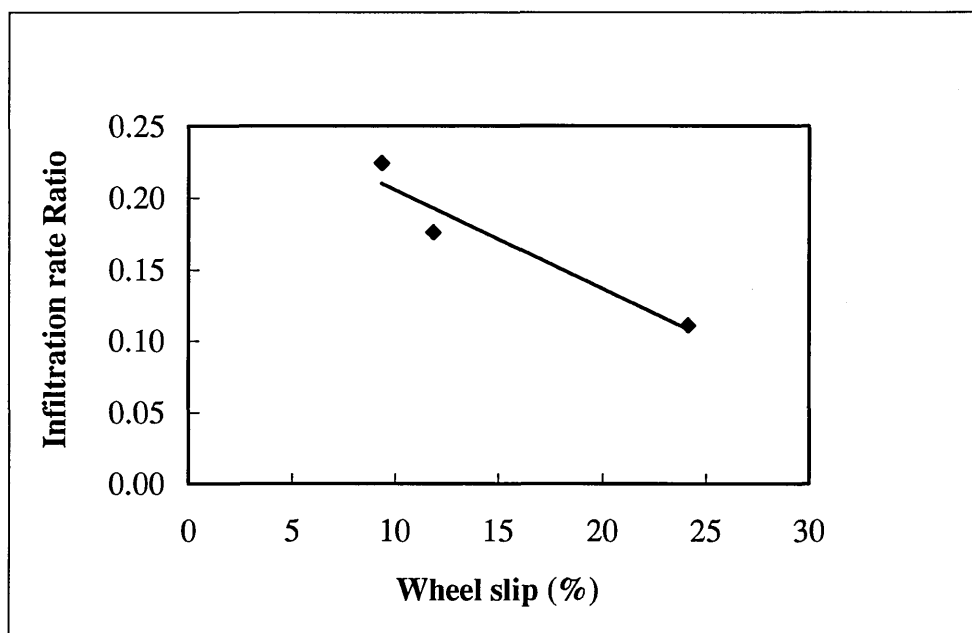


Fig. 7.1. The general trend of the effect of wheel slip on infiltration rate (using average of all the ballast weight values)

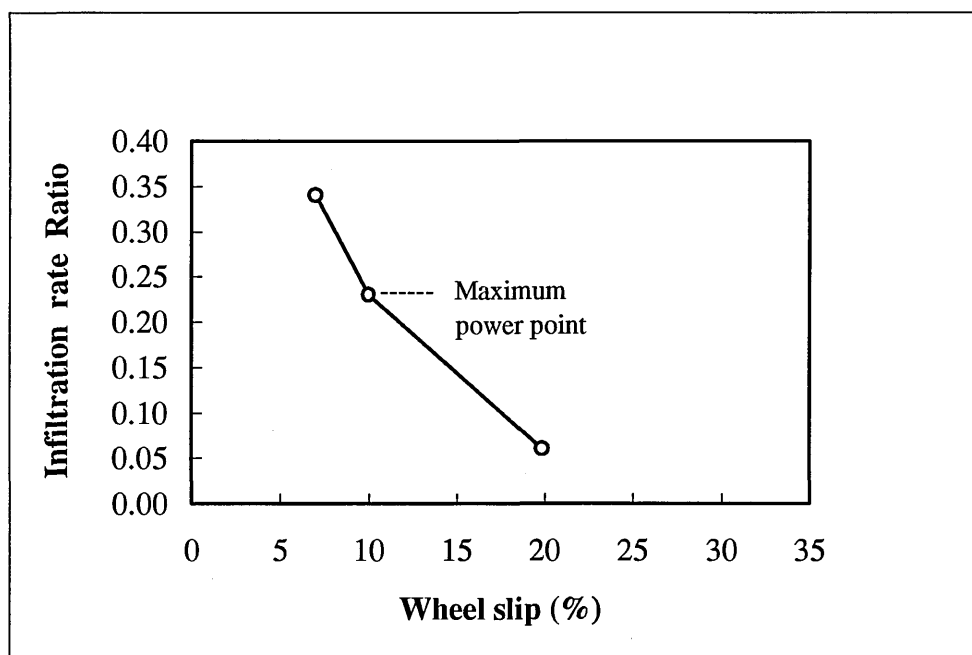


Fig. 7.2. The effect of wheel slip on infiltration rate at Maximum tractor ballast condition

In practice, if there is a sufficient consolidation of optimum plant establishment additional compaction increases the risk of not only of reduced or delayed seedling emergence but also of loss in final yield. As explained in section 2.6, the relationship between soil compaction and crop growth is a complex process of interacting functional relationships between soil characteristics, crop type and weather conditions, so no universal or direct index exists to describe the crop response. This interaction is presented in general concept as shown in Fig. (2.3) without quantities. However, it suggests that the state of soil should be maintained at an optimum level if maximum crop yields are to be obtained.

It is not easy to link between the effect of soil compaction measured in the current study and crop yield. However, the data showed the optimum field test condition is working at the right hand end of the optimum level of the compaction curve shown in Fig. (2.3). This expectation may be supported by two reasons :

- 1) The optimum field test did not cause the worse compaction effect. In addition, there is a significant difference between the infiltration rate measured for the optimum test and the test which caused the worse compaction effect either in the wheeled location where the infiltration rate is 0.16 and 0.02 cm/min respectively or as a ratio of the final to the initial condition where it is 0.23 and 0.06 for both tests respectively (Figures 6.19 to 6.21 and Tables A6.16 to A6.18).
- 2) Referring to Fig. (2.5 soil 2) with assumption of that this graph data is the most relevant condition found in the literature in this context, it shows an optimum range of soil dry density of 1.36 to 1.58 g/cm³ for maximum grain yield (ton/ha) of barley. The study data show an average of 1.60 g/cm³ soil dry density measured after the

optimum field test was performed. It could be said that under our test conditions the optimum tractor performance occurs near to the optimum compaction condition for plant performance.

Whether or not these results are precise depends on the complex interaction of several factors but the important aim is still to minimize the causes of soil compaction when carrying out all field operations on the land.

The results of the traction and compaction relationship could be represented graphically as in Fig. (7.3) showing that the maximum power occurs at a slip value which give a lower compaction effect than at a higher slip.

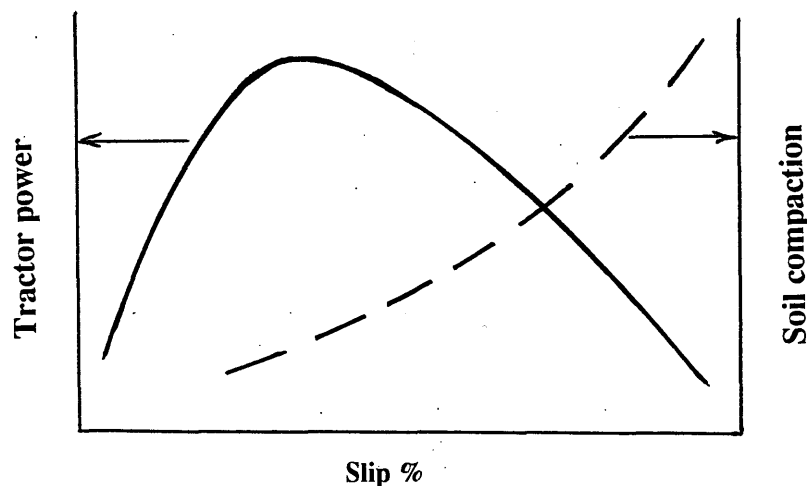


Fig. 7.3. Traction and compaction relationship

From the relationship between soil compaction and crop growth which is conceptually represented in the form of Fig. 2.3, this implies that the likely position on this compaction curve moves towards the optimum compaction value (Fig. 7.4). There is insufficient data to numerically link all these factors at this point in time but it should be possible to develop a mathematical link from further experimental data.

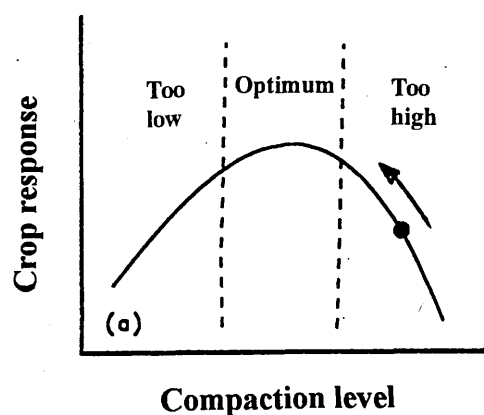


Fig. 7.4. The position of optimum power on the compaction curve

7.3 Implication for 4WD tractors

7.3.1 Movable front weight system

The trend in the recent years is for farmers to buy high power tractors particularly 4WD tractors. They are looking for better traction and work rate for their investment. The 4WD tractors have also the advantage of stability and the front wheels can be fitted with a wide and large diameter tyres which could improve their potential performance. However, there is still a need to ballast the tractor to the correct level and to overcome the variation in the weight distribution between the front and rear axle to achieve the maximum performance to help offset the extra cost of such tractors.

It is common practice for farmers to add ballast to the tractor rear and front according to the recommended amount of weight, so in static position both of the axles are ballasted to the maximum required limit which usually includes any weight carried from the implement in the transport mode. However, when the tractor is at work in field pulling a tillage implement there is weight transfer from the front to the rear wheels resulting in a reduction in the actual weight on the front wheels. This in turn decreases the tractive performance of the front wheels which will operate at low coefficient of traction compared to the rear wheels. The result obtained from the present study experiments as shown in Fig. (6.11) in section 6.3.2.2. is evidence of this problem. The rear wheels are usually not a problem as in work there is less vertical load from the implement than on transport but increased weight transfer due to traction so the two effects probably cancel each other out.

Such problem of front wheel is not associated with performing a certain tillage operation but also occurs during the applications of agro-chemicals and fertilisers working in particular with 2WD tractor. Travelling with a full hopper or tank, weighing in excess of 2500 kg, requires an equivalent counter balancing weight at the front end of the tractor to obtain sufficient stability. The problem here appears when the weight at rear of the tractor reduces, however the front end balancing weight remain constant so significant amounts of unnecessary weights are being carried on the front wheels. This problem becomes serious during early spring time when such field operations have to be conducted in wet conditions. This excessive static weight on the front is a major contributor to soil compaction and deep tyre ruts compounded by the fact that the front wheels are small and narrow with a relatively low load capacity. It also causes numerous problems such as excessive tyre wear, increased rolling resistance and loading the power steering components (Williams, 1996).

Currently, the only way a farmer can ballast his tractor on the front is by using manual static ballasting techniques. The common method is bolting cast iron weights into a frame on the tractor head.

Williams (1996) demonstrated the use of an effective method to reduce the above mentioned problem. He developed an experimental movable front weight system mounted to the front of a 2WD tractor (Plate 7.1). This design is capable of moving a 240 kg weight in a fore and aft motion over a distance of 1.5m ahead of the front of the tractor when it is fully loaded. The movement of the weights is determined by the tractor operator in the cab. He compared the system with a standard fixed weight using a hopper of 1100 kg capacity weight considering two situations. One is a loading position when the hopper is full and the other is unloading position when the hopper is empty. The possible advantage to be gained from this method is evaluated by comparing the weight on the front and rear axle at different load configurations and movable front weight positions.

He found the system is effective in maintaining the desired, safe vertical reaction on the front axle resulting in efficient ballasting under both loaded and unloaded rear axle conditions.

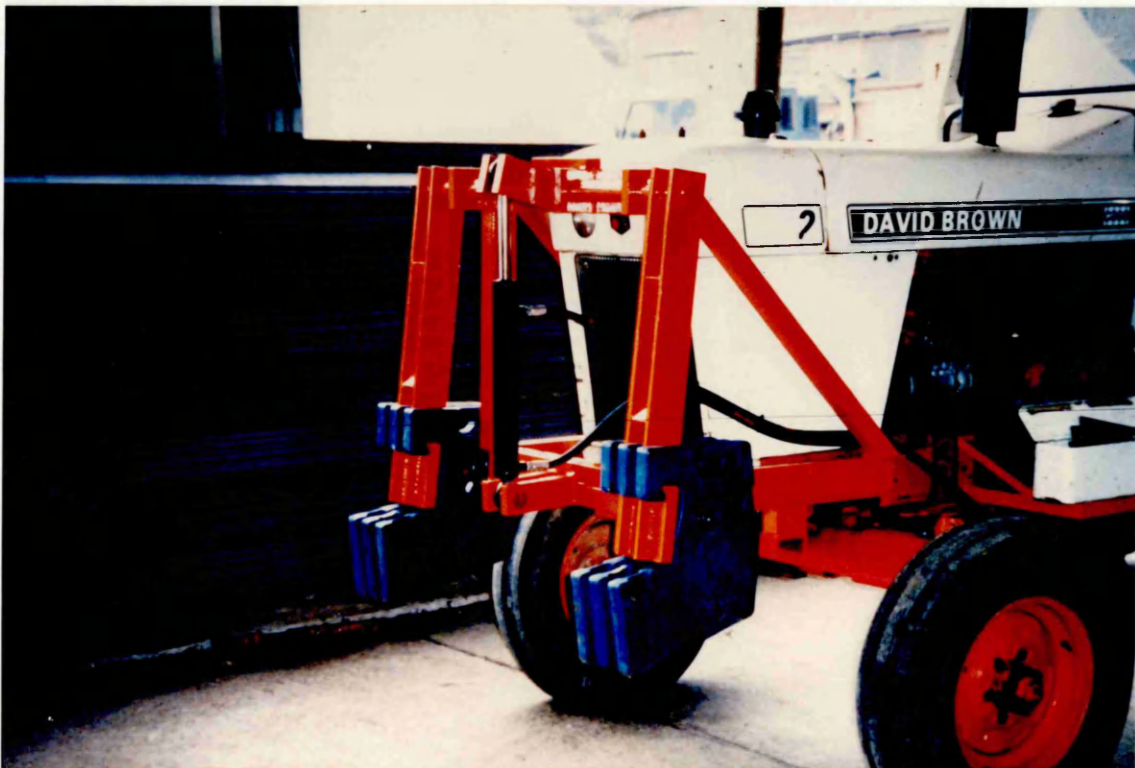


Plate 7.1. The suspended swinging weight system proposed by Williams (1996)

A similar principle of the movable front weight system can be used to minimize the problem associated with draught implements mentioned earlier. Such a system is required to provide the operator a quick way to control the effect of weight variation on the tractor wheels to optimize the tractor ballasting to improve the front wheel tractive ability and to gain more traction from the 4WD tractor.

In this manner, the front wheels are ballasted statically to the maximum allowed limit recommended by the manufacturer. When the tractor works in field, as it begins to pull and the implement draught increases the movable weight system should move the front weight ahead of the tractor gradually by means of an automatic control system. So at a maximum draught position, i.e. maximum weight transfer, the front ballast would be moved ahead to a maximum acceptable distance. The moment effect exerted by the movable front weight will maintain the desired vertical load on the front wheels during the field operation. Once the tractor lifts the implement and the draught is removed, the front ballast returns back to its original position.

This proposed technique maintains the required weight on the front wheels in both static and dynamic positions.

The following calculations demonstrate the above principle as one method to improve the performance of the front wheels of the 4WD tractor. The optimum field test obtained in this study is chosen to illustrate the situation where the tractor operates with a trailed implement (disk harrow). The vertical reaction on the front wheels is calculated for both of static and dynamic conditions using the actual values of forces and dimensions as necessary.

i) Static condition

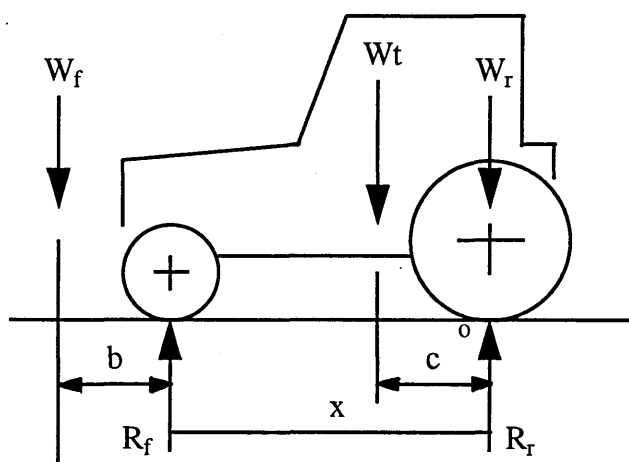


Fig. 7.5. Forces on the tractor in static position.

The general moment equation about the point O is :

$$\Sigma M_R = 0$$

$$[W_t \times c] + [W_f \times (b + x)] = R_f \times x \quad (7.5)$$

Using the following values :

$$\begin{aligned} b &= 1 \text{ m} & W_t &= 39.60 \text{ kN} \\ c &= 0.92 \text{ m} & W_f &= 6.2 \text{ kN} \\ x &= 2.37 \text{ m} \end{aligned}$$

The nominal front reaction $R_f = 24.2 \text{ kN}$

ii) Dynamic condition

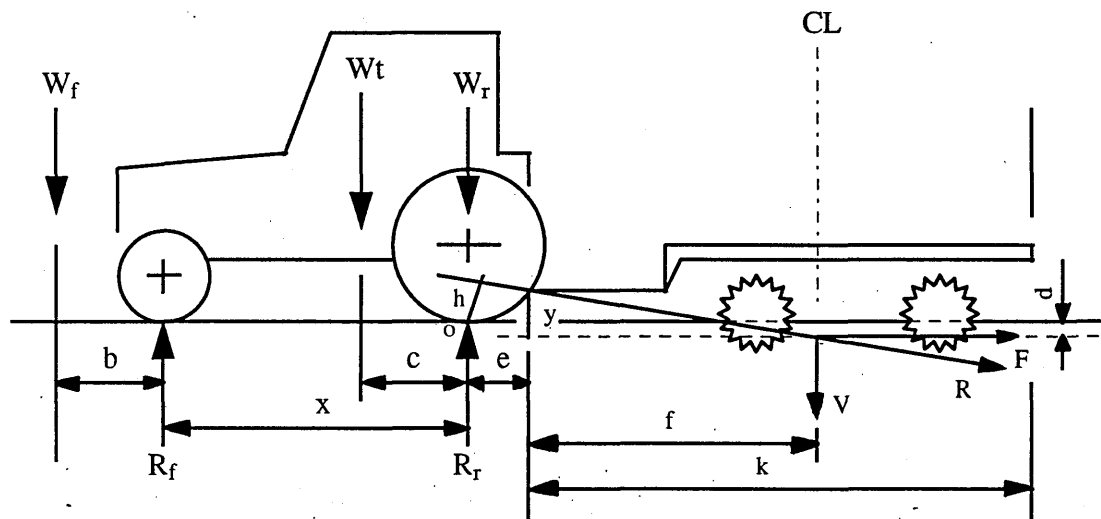


Fig. 7.6. Forces on the tractor and implement in dynamic position.

The general moment equation about the point O is :

$$\Sigma M_R = 0$$

$$[W_t \times c] + [W_f \times (b + x)] - [F \times h] = R_f \times x \quad (7.6)$$

Considering the following values :

$$\begin{aligned} e &= 0.6 \text{ m} & y &= 0.36 \text{ m} \\ f &= 3.8 \text{ m} & h &= 0.41 \text{ m} \\ k &= 6.6 \text{ m} & d &= 0.11 \text{ m} \\ F &= 17.24 \text{ kN} \end{aligned}$$

The dynamic front reaction $R_f = 21.2 \text{ kN}$

This means there is a reduction of 3 kN (12%) in the required vertical load on the front wheels which would reduce their traction. To compensate this amount of weight removed, there are two choices. The first one is to add equivalent weight manually on the front axle, however the penalty is the front axle will be over loaded when the tractor in the static or transport position. The second solution is to move the front ballast weight ahead of the tractor to a reasonable distance.

Equation (7.6) can be reworked to determine the possible distance (b) the front ballast weight should be moved from the front of the tractor using the actual value of $R_f = 24.2$ kN. Thus;

$$b = 2.15 \text{ m}$$

This amount of distance is quite a reasonable value compared to the other situations in which the tractor operates with some front attachment equipment such as front attachment mould board plough and front loader. These types of equipment work efficiently in front of the tractor having a length which may equal the tractor wheelbase dimension.

The second choice seems to be a realistic solution and the concept of having a movable front weight system would be an effective way to control the variation in tractor weight distribution.

To evaluate the situation one step more, the extra pull gained from applying the proposed system can be calculated as follows :

$$\text{Pull} = \text{COT} \times \text{Vertical wheel load}$$

When the coefficient of traction (COT) is assumed to be 0.4 then the additional pull gained is :

$$\text{Pull} = 0.4 \times 3 = 1.2 \text{ kN}$$

From the data obtained for the optimum field test (Table A6.2) the tractor drawbar pull is 17.24 kN. Thus, the total new drawbar pull is 18.44 kN resulting in an increase of 7% compared to the improvement of about 5% obtained from a similar technique used by Zang and Chancellor (1988). Referring to section 7.2.1, the optimum size of a mould board plough was determined as 7 furrows to be matched with the optimum operating combinations of tractor weight and speed. Consequently, when the tractor pull is improved to be 18.44 kN the implement size will increase to be 8 furrows. Assuming that the mould board plough has an average width of cut of 0.35m then the work rate (ha/h) will increase by about 13% at a given tractor speed. This improvement will reduce the operating cost by some amount.

It should be noted that the advantage of the suggested movable weight system would be greater when the tractor operates with fully mounted tillage implements involving large draught forces and steep angle of draught. In such situations a serious weight transfer from the front wheels is expected. However, in this situation the front ballast weight may need to be moved further to the front of the tractor.

The previous analysis leads to the question: is this improvement in front wheel performance worth the introduction of the proposed technique by the tractor manufacturer and at what price, taking in account that the condition is traction-limited only. There are several complex factors to be considered in order to answer such a question but they are outside the present study.

7.3.2 An example of ballast weight calculation for a particular 4WD tractor

From the present study on the ballast requirements it is possible to calculate the total tractor weight (bare tractor plus ballast required) that would be recommended for a particular engine power. For example, a MF 399 tractor used for primary cultivation would be expected to travel at 6.5 km/h (a typical field speed for heavy cultivation). This tractor is fitted with a 76.5 kW engine power and has a bare weight of 3870 kg (tractor catalogue).

I. Maximum tyre load capacity

To calculate the ballast requirement for such tractor in job taking the account of tyre loading capacity both in transport and work modes the following procedure is shown.

From the tractor tyre catalogue (Goodyear) the maximum load capacity of the tyre is presented in Table (7.1) showing the maximum permissible weight i.e. tyres limiting factor not axles.

Table 7.1. Tyre load data

	Maximum tyre load capacity			
Tyre size	In work (at 10 kph)		In transport (at 40 kph)	
	Per wheel	Per axle	Per wheel	Per axle
Front 11 R 28	1700 (kg) 16.7 (kN)	3400 (kg) 33.4 (kN)	1250 (kg) 12.3 (kN)	2500 (kg) 24.6 (kN)
Rear 13.6 R 38	2460 (kg) 24.1 (kN)	4920 (kg) 48.2 (kN)	1800 (kg) 17.7 (kN)	3600 (kg) 35.4 (kN)
Total	8320 (kg) 81.8 (kN)		6100 (kg) 59.8 (kN)	

Table 7.2. Bare weight of MF 399 tractor

Axle	Weight
Front	1710 kg (16.8 kN)
Rear	2300 kg (22.6 kN)
Total	3870 kg (38 kN)

II. Tractor and implement in transport mode

The next step is to check the front and rear tyre loads in transport mode where the implement is just clear off the ground. A 4 furrow full mounted reversible plough (Dowdeswell, series 100 plough) is chosen as a typical example which has 1215 kg weight.

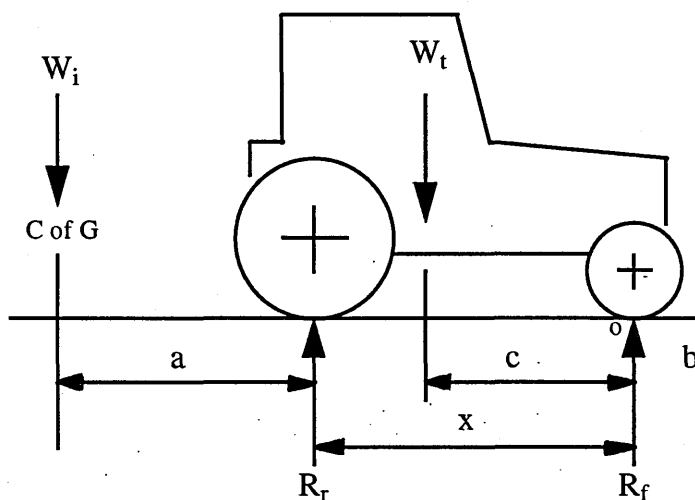


Fig. 7.7. Tractor with mounted plough clear of the ground (transport mode)

$$\Sigma M_f = 0$$

$$[W_i (a + x)] + [W_t \times c] = R_r \times x \quad (7.7)$$

where:

Tractor bare weight = 38 kN

Implement weight = 11.9 kN

$a = 2.36$ m

$c = 1.64$ m

$x = 2.64$ m

$$[11.9 \times 5] + [38 \times 1.64] = R_r \times 2.64$$

$$R_T = 46.2 \text{ kN}$$

$$\text{Load per wheel} = 23.1 \text{ kN}$$

$$\Sigma F_V = 0$$

$$R_T + R_f = W_i + W_t$$

$$46.2 + R_f = 11.9 + 38$$

$$R_f = 3.7 \text{ kN}$$

It can be seen that the amount of weight remained on the front axle in transport mode is 22% of the bare front axle weight (i.e. 3.7/16.8). This value is within the required amount to avoid the steering problem when the implement is lifted. However, the rear tyres here are over loaded at 1.6 bar tyre pressure where the tyre can carry up to 17.7 kN (Table 7.1) but the required load in transportation is 23.1 kN. In this case if large distances are involved in the farming operations then larger tyres should be fitted (e.g. 16.9 R 38). If this done, the tangential speed of the front and rear tyres must be checked to ensure that the lead is between 1.2 and 5.2 %.

III. The required ballast weight for the optimum traction performance

From the current work of this project the optimum required ballast for the tractor under consideration can be determined by using the recommended ballast equation, assuming the tractor works on a frictional soil condition, as follows :

$$\frac{W}{P^*} = \frac{1.3}{V}$$

Assuming the transmission efficiency is 0.85 then,

$$\text{Total tractor weight (W)} = 47 \text{ kN}$$

$$\text{Bare tractor weight} = 38 \text{ kN}$$

$$\text{Ballast weight required} = 9 \text{ kN}$$

$$\Rightarrow 917 \text{ kg}$$

This ballast weight can be distributed on the front and rear wheels based on the ratio of the tyre load capacity from the tyre data in Table (7.1) i.e. 40% on front and 60% on rear. Table (7.3) summarises the recommended ballast weight on the tractor wheels in both cases of field work and transpiration. Two types of ballast weights are considered. The common standard cast iron units of the weight of 27 kg and 45 kg for the front end and the weight of 47 kg for the rear wheel. The other type is water filling in tyre according to the manufacturer recommendation.

Table 7.3. The recommended ballast on tractor wheels

	Ballast weight on Front	
	Cast iron	Water ballast in tyre
Total	367 kg (3.6 kN)	367 kg (3.6 kN)
Arrangement	8 unit weights of 45 kg on front end weight	<ul style="list-style-type: none">• 103 kg (1 kN) water in each tyre• plus 163 kg (1.6 kN) cast iron on front end (6 unit weights of 27 kg)
	Ballast weight on Rear	
Total	550 kg (5.4 kN) i.e. 275 kg per wheel	550 kg (5.4 kN)
Arrangement	6 unit weights of 47 kg on each wheel	<ul style="list-style-type: none">• 209 kg (2 kN) water in each tyre• plus 71 kg (0.7 kN) cast iron on each wheel (2 unit weights of 47 kg)

IV. Recommendation summary

The step here is to compare the total weight on the front and rear wheels (including ballast) with the maximum permissible tyre capacity. Table (7.4) presents the situation considering both cases when the tractor in work and in transport mode.

Table 7.4. Assessment of recommended ballast

	Weight (kN)	
Condition	Front	Rear
Bare weight on axle	16.8	22.6
Ballast weight	3.6	5.4
Total	20.4	28
Load on one tyre	10.2	14
Maximum tyre load capacity at 10 kph	16.7	24.1
Maximum tyre load capacity at 40 kph	12.3	17.7

The above data show that when the tractor operating at optimum performance in a field condition (i.e.10 kph) the tyre load capacity is satisfactory for both the front and rear wheels because it is much less than the maximum loading value. However, in transport mode the rear tyre is over loaded due to the additional weight from the mounted implement lifted, the load capacity of the rear tyres is less than required load at 40 kph. Therefore, farmer should fit a larger rear tyre as explained in section II to overcome this problem.

A complete argument for better and more accurate compromise between the two conditions under consideration required several factors and limitations to be taken into the account which could be evaluated in future work.

As far as the ballast weight is concerned the manufacturer could consider supplying the new tractors already fitted with the weights to suit 'average' conditions so that the tractor would perform satisfactory without the farmer having to carry out any additions or changes.

8. CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

- 1) A simple prediction approach was developed to optimize the tractor performance working in a particular soil and in this case a frictional semi-dry sandy loam. The investigation demonstrated that the ballast recommendation could be modified to give a better prediction than using the generally accepted value for all soil types.

The optimum ballast recommendation for a medium size 4WD tractor operating on a frictional soil (sandy loam) with optimum slip value of 10 % is determined as:

$$\frac{W}{P^*} = \frac{1.3}{V}$$

This value is approximately 70 % of the value of all soil types theory which is :

$$\frac{W}{P^*} = \frac{1.9}{V}$$

when operating under similar conditions of 10 % wheel slip and 0.4 coefficient of traction. The recommended equation for relating maximum coefficient of traction and mobility number for the frictional soil (sandy loam) now becomes :

$$(Ct)_{\max} = 0.62 - 0.82 / M \quad \text{for rear wheel}$$

$$(Ct)_{\max} = 0.42 - 0.52 / M \quad \text{for front wheel}$$

The soil type under consideration has a higher angle of internal shearing resistance, ϕ than would be expected for an "average" soil which will have a significant proportion of clay and likely to be at a higher moisture content. The high frictional soil therefore needs less weight for the required pull.

A good agreement was shown between the study results and the work of both of Dwyer et al. (1974) and Gee-Clough et al. (1978) in terms of the mobility number and coefficient of traction relationships extracted from their data related to the tyre tractive performance operating on a sandy loam soil. The methodology developed in this study could be used to provide a modified ballasting theory for other soil conditions in other situations.

The classical theory of traction mechanics (Janosi and Hanamoto, 1961 and Reece, 1967) used to calculate tyre thrust was shown to predict the study results at 95% confidence level showing that the present results and methodology can be used with confidence.

- 2) The three methods used for soil compaction measurement showed that both tractor weight and wheel slip caused soil compaction, however, the former has more effect. The infiltration rate method is the most sensitive in detecting compaction damage to the soil. From which it can be determined that when the tractor is working at its optimum setting given by the ballast equation the resulting soil compaction is at an acceptable value. The average mobility number should be approximately 6.5 for both the front and rear tractor wheels for this soil type. It is an advantage from the compaction point of view to run the tractor at the optimum slip of 10 % because at slip values above 15 % the compaction effect is greater and may be approaching values that will depress crop yield significantly.
- 3) The application of the improved theory for tractor ballasting was demonstrated by using Desbiolles selection procedure for implement draught to show how to match the optimum tractor performance to implement draught. This procedure can be readily used by mechanization planners and farmers.
- 4) The instrumentation developed for this project was shown to work effectively under field conditions. The tractor wheel torque/weight transducer system can be fitted to a wide range of tractors with little modification to the wheel discs. The datalogger used was effective at low to medium tractor speeds. Mounting the datalogger to the tractor wheel to be rotated with the wheel eliminated the need for a slip ring device and the problems associated with it.

8.2 Recommendations

- 1) The method used for optimizing the tractor performance on a frictional soil requires extensive field experiments in order to evaluate a full statistical analysis for more accurate prediction.
- 2) The optimum working conditions and ballast recommendations obtained in the present study are applied to U.K. conditions. Therefore, there is a great need to conduct the field experiments under the condition of the place of interest i.e. Saudi Arabia, to produce real guide-lines and recommendations for machinery utilization in this region.
- 3) A higher capacity type of data collection system should be used to improve the quality of the data. The sampling capacity requires to be increased up to three times when working at high speeds i.e. above 6 kph nominal speed to avoid the undesirable errors in force measurement.
- 4) Variation in soil compaction measurement data could be minimized by conducting a large number of field measurements. Further studies should be carried out to find a method to overcome the problem of changes in the initial soil condition due to the environmental factors.
- 5) A system such as the movable front weight technique could be introduced to improve the front wheel tractive ability of the 4WD tractor. Perhaps a few prototypes could be evaluated in a farm situation.

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APPENDICES

APPENDIX 3: Modification to the existing ballast recommendation approaches

1) The original relationships of the five approaches as stated in section 3.2.1.

Table A3.1. Tractor weight/power & speed relationship for the five ballast recommendation approaches (Different conditions).

Tractor speed (V)		Dynamic tractor weight / Axle power (W/P*) (kN/kW)				
(kph)	(m/s)	Reece	Dwyer	Zoz	Gee-Clough	Bloome
3.28	0.91	0.93	1.96	1.62	1.36	1.54
4.00	1.11	0.77	1.61	1.33	1.13	1.26
4.72	1.31	0.65	1.36	1.13	0.96	1.06
5.60	1.56	0.55	1.15	0.95	0.81	0.90
6.56	1.82	0.47	0.98	0.81	0.69	0.77
7.92	2.20	0.39	0.81	0.67	0.57	0.64

2) Adjusting the original formula for each worker at similar conditions of 10% or 20 % slip, coefficient of traction of 0.4 and tractor power as axle power.

I) Reece (1968)

The original formula is :

$$\frac{W}{E} = \frac{\epsilon (1-i)550}{X \mu K' v^{1.47}} \quad (2.38)$$

He proposed some appropriate values for each term in the equation when working with 4WD tractor. Thus, when these values used as follows :

- W = total tractor weight (lb)
- E = engine power (hp)
- i = slip = 20 (%)
- ϵ = transmission efficiency = 0.83 (%)
- X = slip function = 0.8
- K' = weight utilisation factor = 1.13
- μ = coefficient of traction = 0.865
- v = field speed (mph)

His ballast recommendation for 4WD tractor becomes as :

$$\frac{W}{P} = \frac{318}{v}$$

which can be written in metric units as :

$$\frac{W}{E} = \frac{0.85}{V} \quad (2.39)$$

where :

W = total tractor weight (kN)
P = engine power (kW)
V = forward speed (m/s)

a. Adjusting Eq. (2.39) to be at 20% slip and 0.4 COT by changing the value of μ in Eq. (2.38) from 0.865 to 0.4 to become as :

$$\frac{W}{P} = \frac{1.83}{V}$$

and to change the engine power P to axle power P^* , a transmission efficiency of 0.83 is assumed (Reece 1968) i.e. $P^* = 0.83 P$. Then,

$$\frac{W}{P^*} = \frac{2.2}{V} \quad (A3.1)$$

b. Adjusting Eq. (2.39) to be at 10% slip and 0.4 COT by changing the value of μ and i in Eq. (2.38) from 0.865 to 0.4 and from 0.2 to 0.1 respectively to become as:

$$\frac{W}{P} = \frac{2.06}{V}$$

Again using axle power rather than engine power this equation takes the form of :

$$\frac{W}{P^*} = \frac{2.48}{V} \quad (A3.2)$$

II) Gee-Clough et al. (1982)

He proposed the following formula :

$$\frac{W V_0}{P^*} = \frac{1}{0.78 - 0.7 [\exp(-7.74 i)]} \quad (A3.3)$$

where :

W = dynamic weight on the derive wheels (kN)
 P^* = axle power (kW)
 V_0 = no-load forward speed (m/s)

He suggested that if slip is held at 20% then the minimum value of the ballast number to ensure the tires can deliver the available tractor power is 1.26 as:

$$\frac{W V_0}{P^*} = \frac{1}{0.631}$$

but $V = V_0 (1 - i)$

then, $\frac{W}{P^*} = \frac{1.26}{V}$ (2.43)

To determine the coefficient of traction, Gee-Clough et al. (1982) explained the following :

$$\eta P^* = W C_t V = W C_t V_0 (1 - i)$$

$$P^* = \frac{W C_t V_0 (1 - i)}{\eta}$$

$$\frac{W V_0}{P^*} = \frac{\eta}{C_t (1 - i)} \quad (A3.4)$$

or $\frac{W V_0}{P^*} = \frac{R_n}{(1 - i)} \quad (A3.5)$

where η is the tractive efficiency, C_t is the coefficient of traction and R_n is the ballast recommendation number.

From Eqs. (A3.3 and A3.4) and assuming $\eta = .70$ and $i = 0.2$:

$$\frac{\eta}{C_t (1 - i)} = \frac{1}{0.78 - 0.7 [\exp(-7.74 i)]}$$

$$\frac{0.7}{C_t (1 - 0.2)} = \frac{1}{0.631}$$

$$C_t = 0.55$$

- a. To adjust Eq. (2.43) at 20% slip and 0.4 COT, the value of $C_t = 0.4$ is used in Eq. (A3.4) and again $V = V_0 (1 - i)$:

$$\frac{W V_0}{P^*} = \frac{\eta}{C_t (1 - i)}$$

$$\frac{W V_0}{P^*} = \frac{0.7}{0.4 (1 - 0.2)} = 2.18$$

or $\frac{W}{P^*} = \frac{2.18 (1 - 0.2)}{V}$

then,
$$\frac{W}{P^*} = \frac{1.75}{V} \quad (A3.6)$$

b. To adjust Eq. (2.43) at 10% slip and 0.4 COT, the values of $C_t = 0.4$ and $i = 0.1$ are used in Eq. (A3.4) in similar way as in last step then,

$$\frac{W}{P^*} = \frac{1.96}{V} \quad (A3.7)$$

III) Dwyer et al. (1978)

He gave the following equation to calculate optimum ratio for the power required at the driving wheels to the weight carried by them, related to the speed as :

$$\frac{W}{P^*} = \frac{1.75}{V} \quad (2.41)$$

However, Gee Clough et al. (1982) cited a slightly different equation for Dwyer (1978) as :

$$\frac{W}{P^*} = \frac{1.79}{V} \quad (2.42)$$

He suggested working at a slip value of 10% and coefficient of traction of 0.4. Equation (2.42) was considered as a latest version equation of Dwyer work in this aspect and therefore, it was used in the present study.

To correct Eq. (2.42) at 20% slip and 0.4 COT, a similar adjusting procedure is followed using Eq. (A3.5) as follows :

$$\frac{W V_0}{P^*} = \frac{R_n}{(1-i)}$$

$$\frac{W V_0}{P^*} = \frac{1.79}{(1-0.1)} = 1.99$$

or
$$\frac{W}{P^*} = \frac{1.99 (1-0.2)}{V}$$

then,
$$\frac{W}{P^*} = \frac{1.59}{V} \quad (A3.8)$$

IV) Brixius and Zoz (1976)

They produced a ballasting recommendation for 4WD tractors which is of the form :

$$W/P^* = 1.48/V \quad (2.40)$$

assuming that the 13% slip and 0.5 coefficient of traction are the typical values.

a. Adjusting Eq. (2.40) to be at 20% slip and 0.4 COT using Eq. (A3.5) :

$$\frac{W V_0}{P^*} = \frac{R_n}{(1-i)}$$

$$\frac{W V_0}{P^*} = \frac{1.48}{(1-0.13)} = 1.7$$

or

$$\frac{W}{P^*} = \frac{1.7 (1-i)}{V}$$

$$\frac{W}{P^*} = \frac{1.7 (1-0.2)}{V} = \frac{1.36}{V}$$

$$\frac{W}{P^*} = \frac{1.36}{V} \times \frac{0.5}{0.4}$$

$$\frac{W}{P^*} = \frac{1.7}{V} \quad (A3.9)$$

b. Adjusting Eq. (2.40) to be at 10% slip and 0.4 COT using Eq. (A3.5) with a similar calculation in a) then,

$$\frac{W}{P^*} = \frac{1.91}{V} \quad (A3.10)$$

V) Bloome et al. (1983)

He suggested the following equation assuming a coefficient of traction of 0.5 at 20% wheel slip is reasonable :

$$\frac{W}{P^*} = \frac{1.4}{V} \quad (2.46)$$

a. To adjust Eq. (2.46) at 20% slip and 0.4 COT :

$$\frac{W}{P^*} = \frac{1.4}{V} \times \frac{0.5}{0.4}$$

$$\frac{W}{P^*} = \frac{1.75}{V} \quad (A3.11)$$

b. To adjust Eq. (2.46) at 10% slip and 0.4 COT using Eqs. (A3.5 and A3.11) :

$$\frac{W V_0}{P^*} = \frac{1.75}{(1-i)}$$

$$\frac{W V_0}{P^*} = \frac{1.75}{(1-0.2)} = 2.18$$

$$\frac{W V_0}{P^*} = \frac{2.18}{(1-i)}$$

or

$$\frac{W}{P^*} = \frac{2.18 (1-i)}{V}$$

$$\frac{W}{P^*} = \frac{2.18 (1-0.1)}{V}$$

$$\frac{W}{P^*} = \frac{1.96}{V} \quad (A3.12)$$

Table A3.2. Tractor weight/power & speed relationship for the five ballast recommendation approaches at 10% Slip & 0.4 COT

Tractor speed (V)		Dynamic tractor weight / Axle power (W/P*) (kN/kW)				
(kph)	(m/s)	Reece	Dwyer	Zoz	Gee-Clough	Bloome
3.28	0.91	2.73	1.96	2.10	2.15	2.15
4.00	1.11	2.23	1.61	1.72	1.76	1.76
4.72	1.31	1.89	1.37	1.46	1.49	1.49
5.60	1.56	1.59	1.15	1.23	1.26	1.26
6.56	1.82	1.36	0.98	1.05	1.07	1.07
7.92	2.20	1.12	0.81	0.87	0.89	0.89

Table A3.3. Tractor weight/power & speed relationship for the five ballast recommendation approaches at 20% Slip & 0.4 COT.

Tractor speed (V)		Dynamic tractor weight / Axle power (W/P*) (kN/kW)				
(kph)	(m/s)	Reece	Dwyer	Zoz	Gee-Clough	Bloome
3.28	0.91	2.42	1.74	1.88	1.92	1.92
4.00	1.11	1.98	1.43	1.54	1.57	1.57
4.72	1.31	1.68	1.21	1.30	1.33	1.33
5.60	1.56	1.41	1.02	1.10	1.12	1.12
6.56	1.82	1.21	0.87	0.94	0.96	0.96
7.92	2.20	1.00	0.72	0.78	0.79	0.79

APPENDIX 4: Materials and methods data

A4.1 Specification of wheel transducer design system

The wheel transducer and other parts were designed to be standard for both the front and the rear wheel of the MF 3065 tractor used in the study for the advantage of ease manufacture, calibration and handling. Also, the modified transducer discs are of equivalent dimensions to the original wheel disc so that all the normal wheel width adjustments can be made as required. The rear wheel is taken the critical case of loading because it is subjected to heavier loads and higher torques than the front wheel. Two types of force which may be exerted on the transducer were considered in the design calculations, namely tension forces and lateral forces.

(1) Tension force situation

When the tractor is at work there are both traction and vertical forces applied on the wheel. The maximum exerted force through the three transducers of each wheel when they are in tension is considered to be the combination of i) the load from the engine torque, via the gear box, applied to the wheel plus ii) the load from the vertical ballast weight. However, the following assumptions were made to specify the design force as:

- The tractor engine is operating at maximum rated speed rev/min.
- The rear axle is loaded to 90% of its maximum limits.
- For the 4WD, almost 2/3 of the engine torque is transferred to the rear axle.
- The worse case of loading when the wheel in such position only two transducers carrying the load and at the lowest tractor speed which may chosen.

$$\text{Engine power} = \frac{2\pi N}{60} T \quad (\text{kW})$$

where:

$$\begin{aligned} N &= \text{engine speed (2200 rev/min)} \\ T &= \text{engine torque (N.m.)} \end{aligned}$$

$$62.5 \times 10^3 = \frac{2\pi \times 2200 \times T}{60}$$

$$T = 271 \text{ N.m}$$

Assuming the rear wheel fitted with 13.6R38 tyre is taken as a critical case of loading and the lowest forward speed of tractor working in field is 4 kph, where:

Rolling circumference = 4.658 m (from tyre catalogue)
 i.e. Radius, R = 0.74 m
 Link radius, r = 0.29 m (from engineering drawing)

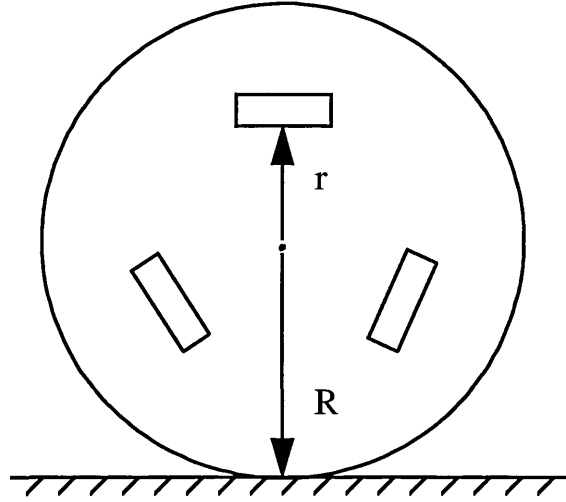


Fig. A4.1. Tractor rear wheel

Then,

$$\begin{aligned}\text{No. of rev/min of rear wheel} &= \frac{\text{Forward speed}}{2\pi R} \quad (\text{kph}) \\ &= \frac{4000}{60 \times 4.658} \\ &= 14.3 \text{ rev/min}\end{aligned}$$

$$\begin{aligned}\text{Gear ratio} &= \frac{\text{Engine revs.}}{\text{Rear wheel revs.}} \\ &= \frac{2200}{14.3} = 154\end{aligned}$$

$$\begin{aligned}\text{Rear axle torque} &= \text{Engine torque} \times \text{Gear ratio} \times 2/3 \\ &= 271 \times 154 \times 2/3 \\ &\Rightarrow 27.82 \text{ kN.m}\end{aligned}$$

i) Load from engine torque

$$\text{Torque on one rear wheel} = \frac{27.82}{2} = 13.91 \text{ kN.m}$$

$$\text{Wheel thrust} = \frac{\text{Wheel torque}}{R}$$

$$= \frac{13.91}{0.74} = 18.8 \text{ kN}$$

$$\text{Wheel thrust} \times R = \text{Transducer force} \times r \times 3$$

$$\text{Transducer force} = \frac{18.8 \times 0.74}{0.29 \times 3} = 16 \text{ kN}$$

ii) Load from vertical weight (static and ballast)

It is assumed that the tractor rear axle is loaded up to 90% of its maximum limit (from MF tractor catalogue), then :

$$\text{Allowed vertical load on the rear axle} = 90\% \times 37.77 = 34 \text{ kN}$$

$$\text{i.e. vertical load per wheel} = 17 \text{ kN}$$

Using Eq (2.46) to calculate the force applied on each transducer by the vertical weight as :

$$\Sigma F_v = F_1 \cdot \sin \theta + F_2 \cdot \sin (\theta + 120^\circ) + F_3 \cdot \sin (\theta + 240^\circ)$$

When the wheel position in critical case, $\theta = 0$ and $F_2 = F_3$ in Fig A4.2.

$$\begin{aligned} \Sigma F_v &= 0 + F_2 \cdot (\sin 120^\circ) - F_3 \cdot (\sin 240^\circ) \\ 17 &= F_2 (\sin 120^\circ - \sin 240^\circ) \\ F_2 &= 9.8 \text{ kN} \end{aligned}$$

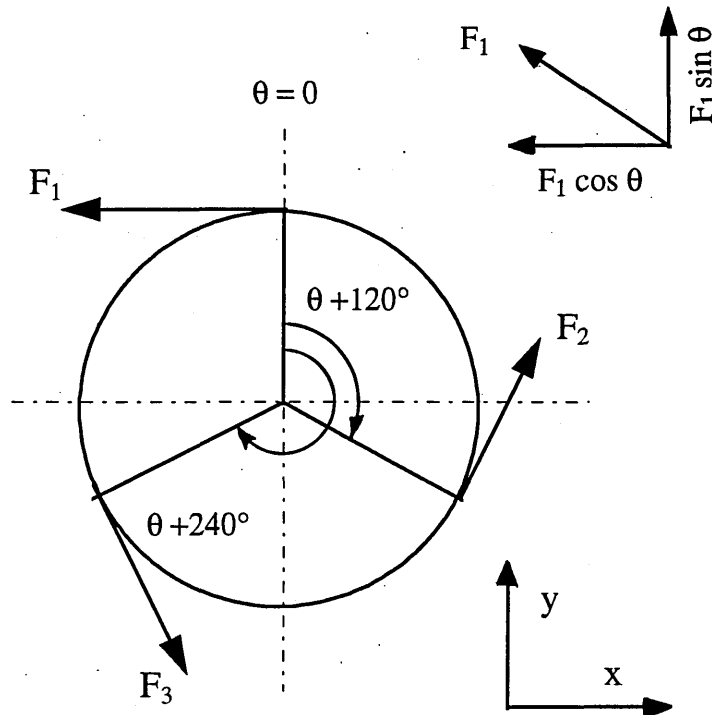


Fig. A4.2. Force diagram on a rear wheel

Therefore, the maximum tension force per transducer $F_t = 16 + 9.8 = 25.8 \text{ kN}$

Assuming safety factor of 3 which is a commonly used value in dynamically loaded agricultural design applications. So, the design tension force is as follows:

$$\begin{aligned}\text{Maximum force} &= 25.8 \text{ kN} \\ \text{Safety factor} &= 3 \\ \text{Design force} &= 25.8 \times 3 = 77.4 \text{ kN}\end{aligned}$$

(2) Link size

The actual dimensions of the link (transducer) were decided from the engineering drawing for the complete equipment assembly to be located in the optimum position between the modified wheel discs. However, there are two thicknesses should be considered t_1 and t_2 as shown in Fig. A4.3.

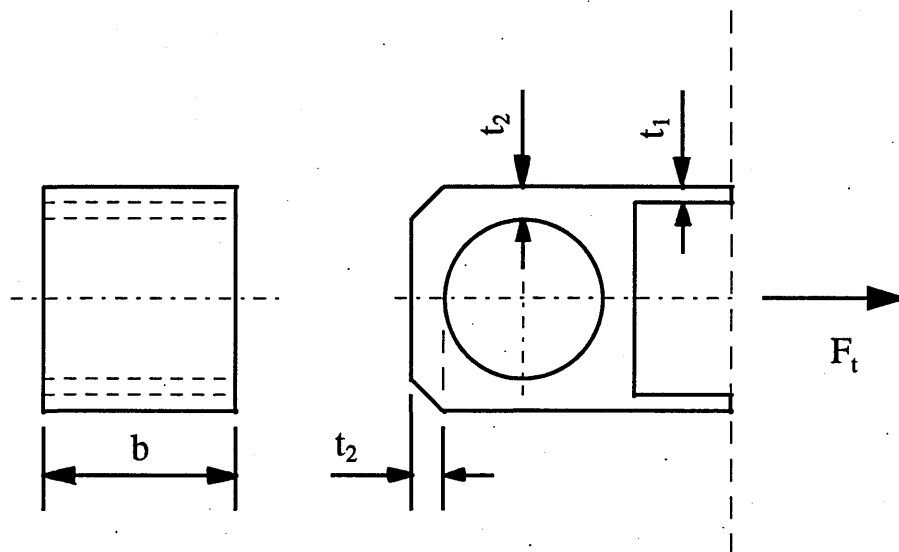


Fig. A4.3. The tension forces on the link

For HE Alloy Aluminium, the proof stress $\sigma = 270 \text{ MN/m}^2$ (manufacturer specification)

$$\begin{aligned}\text{Maximum allowable tension stress } \sigma_{\max} &= 0.85 \times 270 \\ &\Rightarrow 230 \text{ MN/m}^2\end{aligned}$$

$$\begin{aligned}\text{Maximum allowable shear stress } \tau_{\max} &= 230/2 \\ &= 115 \text{ MN/m}^2\end{aligned}$$

To find thickness t_1 , area under tension A is :

$$\begin{aligned}A &= 2 t_1 \times b \\ b &= 54 \text{ mm} \quad (\text{from engineering drawing})\end{aligned}$$

$$\delta = F/A$$

$$0.85 \times 270 \times 10^6 = \frac{77.4 \times 10^3}{2t_1 \times 0.054}$$

$$t_1 = 0.0031 \text{ m} \Rightarrow 3.1 \text{ mm}$$

To determine thickness t_2 , area under shear A' is :

$$A' = 2 t_2 \times b$$

$$\tau = F/A'$$

$$115 \times 10^6 = \frac{77.4 \times 10^3}{2t_2 \times 0.054}$$

$$t_2 = 0.0062 \text{ m} \Rightarrow 6.2 \text{ mm}$$

However, t_1 was decided to be 4 mm to allow for any potential manufacturing errors and surface damage due to strain gauge placement preparation. Also, t_2 was suggested to be 7 mm for convenience of the design layout and to meet the interference fit stress due to the bushes.

(3) Pin diameter

The link pins were manufactured from En 24 T steel.

$$\text{Force on pin} = 77.4 \text{ kN}$$

$$\text{Bending moment arm} = 0.045 \text{ m} \quad (\text{from engineering drawing})$$

$$\delta = \frac{M}{Z}$$

where:

δ = yield strength

M = bending moment

Z = section modulus $\left(\frac{\pi d^3}{32} \right)$

$$600 \times 10^6 = \frac{77.4 \times 10^3 \times 0.045}{\frac{\pi \times d^3}{32}}$$

$$d = 0.039 \text{ m}$$

$$\Rightarrow 40 \text{ mm}$$

(4) Lateral force situation

The wheel transducers may be subjected to a lateral force in a certain circumstances such as in one or both of the following situations :

- i) When the tractor travelling along the direction of a contour line on a slope (Fig. A4.4).

In this case it was assumed that the maximum field surface slope $\beta = 10^\circ$ for practical workability.

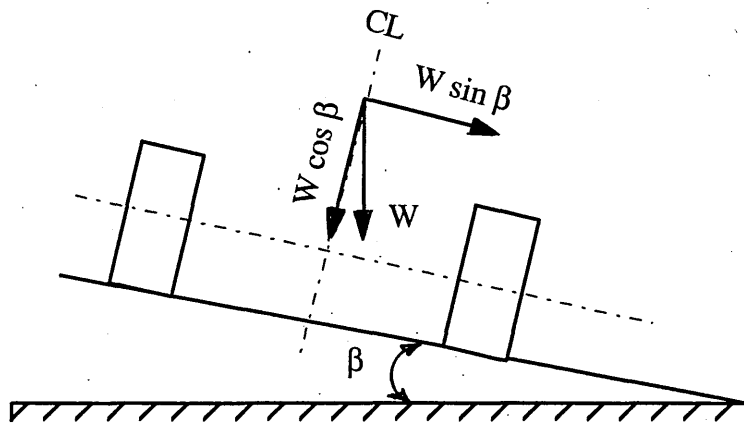


Fig. A4.4

- ii) When working with one of the tractor wheel in furrow i.e. with mould plough (Fig. A4.5).

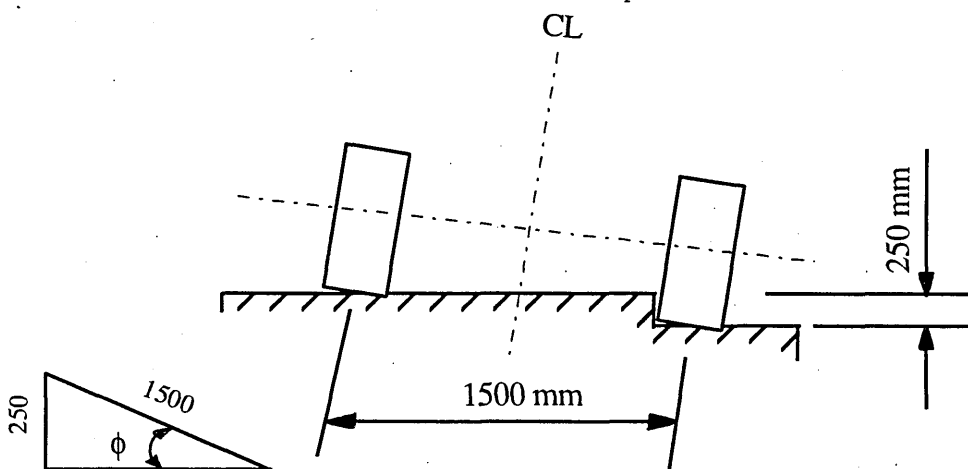


Fig. A4.5

In such an extreme case, the tractor rear wheel width spacing was assumed fitted to the narrowest choice of 1500 mm and ploughing depth of 250 mm. It is also assumed that the lateral force will be carried by both the rear wheels having equal share (i.e. 6 transducers).

$$\sin \phi = 250/1500$$

$$\phi \Rightarrow 9.6^\circ$$

$$\text{Maximum side slope of } \alpha = \beta + \phi$$

$$\alpha = 19.6^\circ$$

$$\text{Maximum vertical load} = 34 \text{ kN}$$

$$\text{Total lateral force, } F_L = W \sin \alpha$$

$$= 34 \times \sin 19.6$$

$$\Rightarrow 11.41 \text{ kN}$$

$$\text{Lateral force per transducer} = 1.9 \text{ kN}$$

So, the design lateral force per transducer with safety factor of 2 is :

$$\text{Design lateral force} = \frac{11.41 \times 2}{6} = 3.8 \text{ kN}$$

Link strength can be checked as follows :

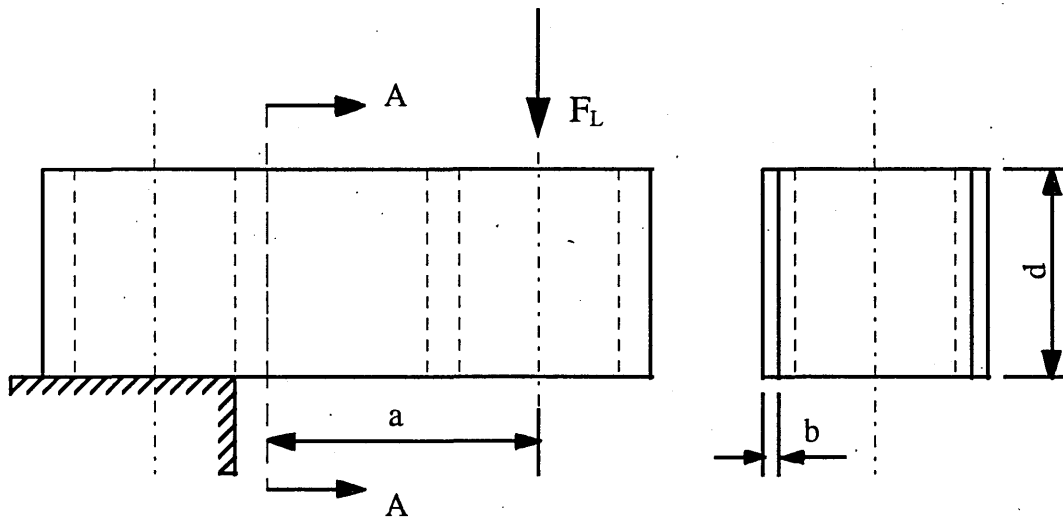


Fig. A4.6. The effect of lateral force on the link.

Using the following formula :

$$\frac{\sigma}{y} = \frac{M}{I}$$

Where :

σ = yield stress

M = applied moment about A-A section ($F_L \cdot a$)

I = moment of inertia $\left(\frac{b d^3}{12} \right)$

a = 70 mm

b = 4 mm

d = 54 mm ($y = 1/2 d$)

$$\sigma = \frac{M y}{I} = \frac{3.8 \times 10^3 \times 0.07 \times 0.027}{\frac{2 \times 0.004 \times 0.054^3}{12}} = 68.4 \text{ MN/m}^2$$

Then,

$$\begin{aligned} \text{actual } \sigma \text{ due to lateral force} &= 68.4/2 \\ &= 34.2 \text{ MN/m}^2 \end{aligned}$$

$$\begin{aligned} \text{actual } \sigma \text{ due to tension force} &= 230/3 \\ &= 76.7 \text{ MN/m}^2 \end{aligned}$$

$$\begin{aligned} \text{total actual stress} &= 34.2 + 76.7 \\ &= 110.9 \text{ MN/m}^2 \end{aligned}$$

$$\text{maximum allowable stress } \sigma_{\max} = 230 \text{ MN/m}^2$$

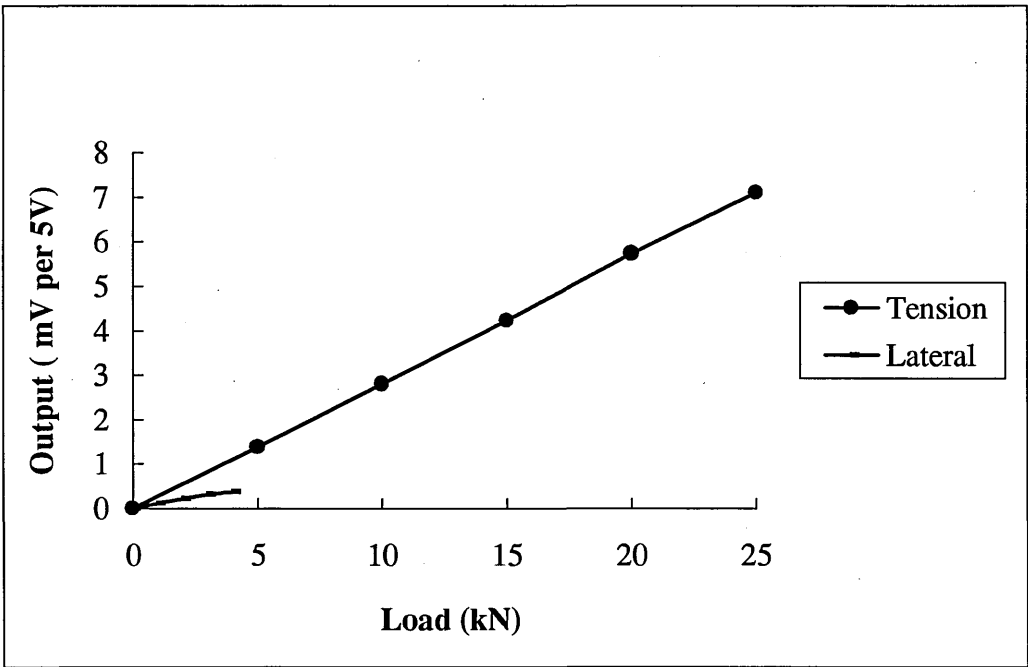
$$\begin{aligned} \text{safety factor} &= 230/110.9 \\ &= 2.1 \end{aligned}$$

This is for the worse situation with maximum load due to tension and lateral load. A lower factor of safety could be tolerated in this case because the tractor would be driven much slower on such a steep side slop due to stability consideration leading to lower shock loads.

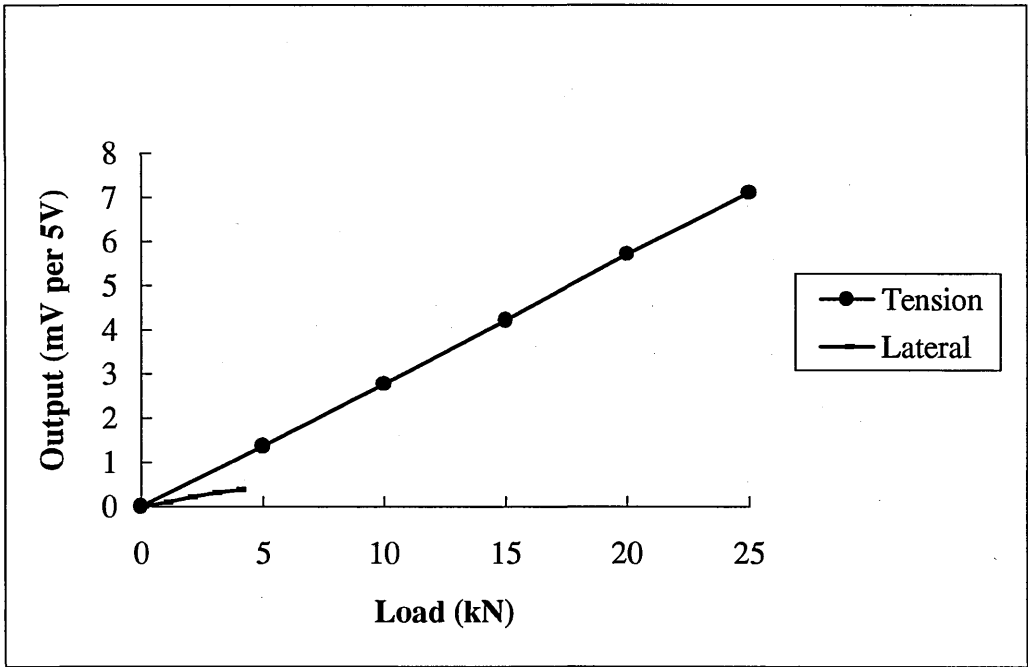
(5) The modified wheel discs

All the modified discs for the front and the rear wheels were designed to be similar the original wheel discs in terms of the material type and thickness. They were manufactured from plough-ground mild steel plate having a thickness of 10 mm so their strength was not calculated in this case.

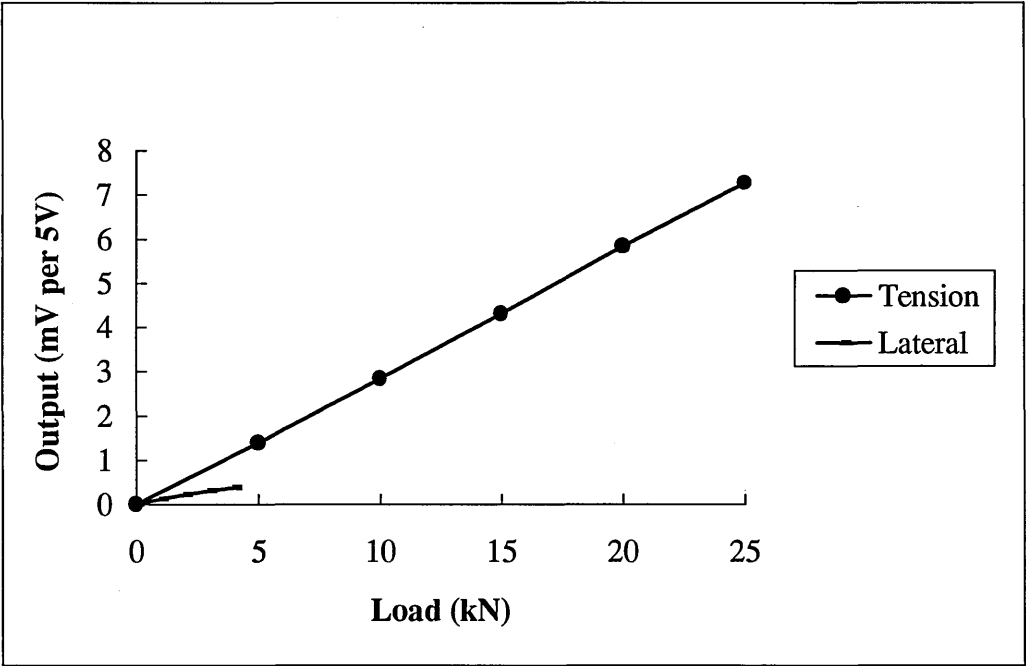
A4.2 Calibration characteristics of wheel transducers by using Digital Volt Meter (DVM)



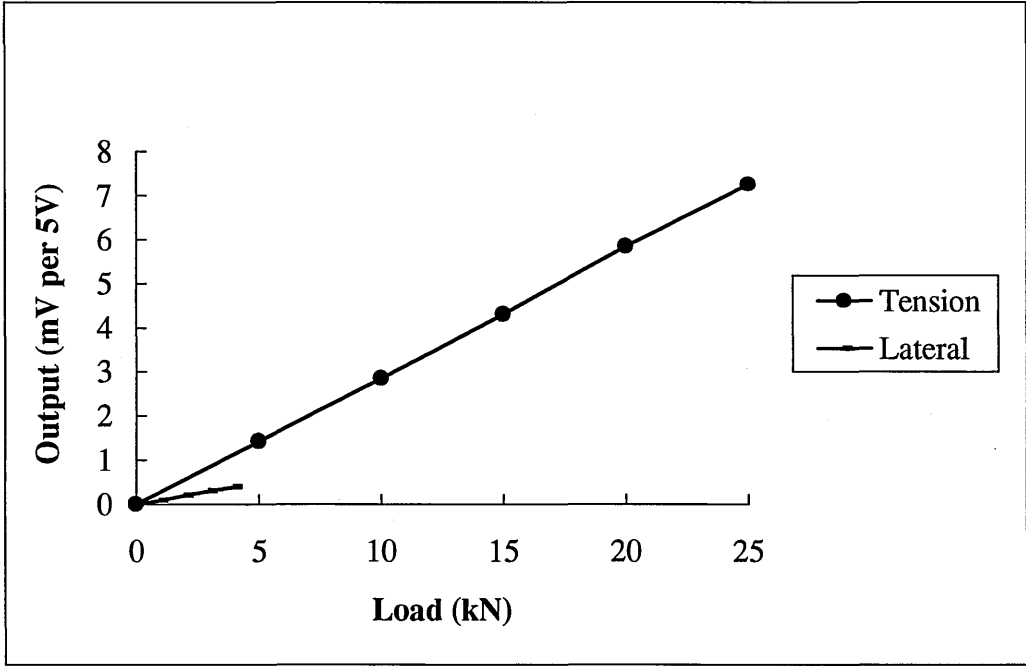
A4.7. Calibration of transducer No. (2)



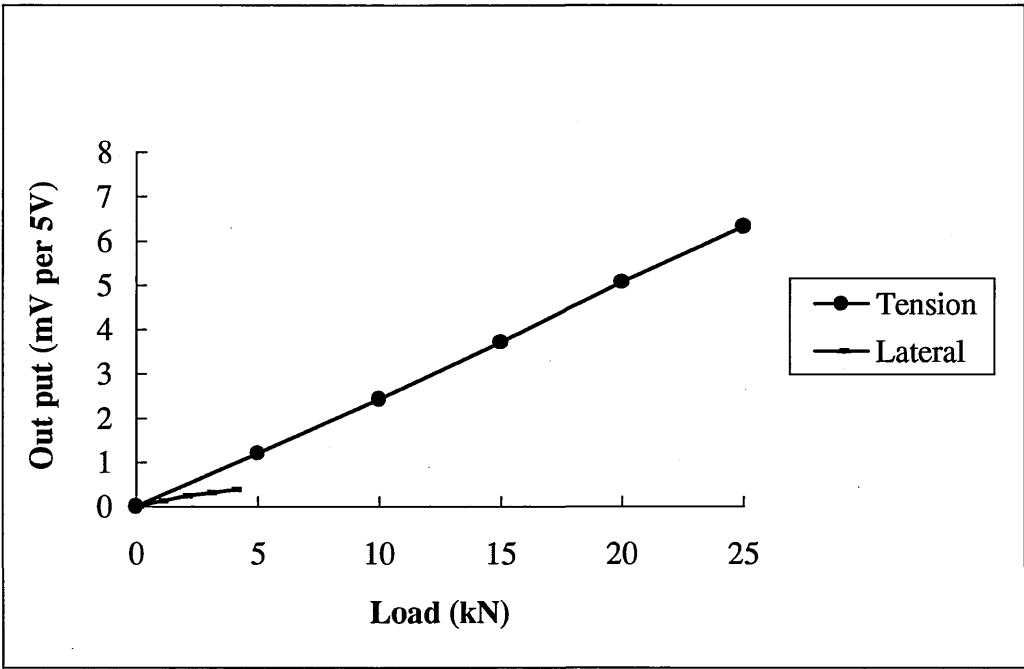
A4.8. Calibration of transducer No. (3)



A4.9. Calibration of transducer No. (4)



A4.10. Calibration of transducer No. (5)



A4.11. Calibration of transducer No. (6)

A4.3 Calibration data of wheel transducers by using Digital Volt Meter (DVM)

Table A4.1. Calibration of transducer No.(1) (Tension load)

	Output mV per 5V (Loading up)					Output mV per 5V (Loading down)				
Load (kN)	Rep.1	Rep.2	Rep.3	Rep.4	Ave.	Rep.1	Rep.2	Rep.3	Rep.4	Ave.
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5	1.368	1.367	1.366	1.366	1.367	1.345	1.343	1.343	1.345	1.344
10	2.771	2.770	2.771	2.771	2.771	2.755	2.754	2.755	2.748	2.753
15	4.192	4.194	4.196	4.186	4.192	4.179	4.180	4.180	4.173	4.178
20	5.747	5.738	5.732	5.691	5.727	5.680	5.689	5.680	5.668	5.679
25	7.098	7.116	7.110	7.090	7.101	7.098	7.116	7.100	7.090	7.101

Table A4.2. Calibration of transducer No.(1) (Lateral load)

	Output mV per 5V (Loading up)					Output mV per 5V (Loading down)				
Load (kN)	Rep.1	Rep.2	Rep.3	Rep.4	Ave.	Rep.1	Rep.2	Rep.3	Rep.4	Ave.
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	0.098	0.104	0.100	0.100	0.101	0.081	0.133	0.133	0.130	0.119
2	0.177	0.215	0.217	0.215	0.206	0.185	0.258	0.260	0.258	0.240
3	0.253	0.298	0.304	0.314	0.292	0.250	0.341	0.339	0.340	0.318
4	0.315	0.370	0.378	0.382	0.361	0.315	0.370	0.378	0.382	0.361

Table A4.3. Calibration of transducer No.(2) (Tension load)

	Output mV per 5V (Loading up)					Output mV per 5V (Loading down)				
Load (kN)	Rep.1	Rep.2	Rep.3	Rep.4	Ave.	Rep.1	Rep.2	Rep.3	Rep.4	Ave.
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5	1.391	1.391	1.375	1.384	1.385	1.374	1.366	1.356	1.365	1.365
10	2.801	2.801	2.793	2.789	2.796	2.791	2.788	2.778	2.779	2.784
15	4.221	4.220	4.216	4.216	4.218	4.211	4.215	4.208	4.210	4.211
20	5.743	5.731	5.725	5.730	5.732	5.695	5.697	5.706	5.700	5.700
25	7.095	7.111	7.096	7.095	7.099	7.095	7.111	7.096	7.095	7.099

Table A4.4. Calibration of transducer No.(2) (Lateral load)

	Output mV per 5V (Loading up)					Output mV per 5V (Loading down)				
Load (kN)	Rep.1	Rep.2	Rep.3	Rep.4	Ave.	Rep.1	Rep.2	Rep.3	Rep.4	Ave.
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	0.106	0.107	0.107	0.118	0.110	0.115	0.117	0.118	0.118	0.117
2	0.209	0.211	0.212	0.235	0.217	0.235	0.236	0.235	0.235	0.235
3	0.316	0.291	0.310	0.330	0.312	0.333	0.331	0.328	0.330	0.331
4	0.370	0.371	0.375	0.376	0.373	0.370	0.371	0.375	0.376	0.373

Table A4.5. Calibration of transducer No.(3) (Tension load)

	Output mV per 5V (Loading up)					Output mV per 5V (Loading down)				
Load (kN)	Rep.1	Rep.2	Rep.3	Rep.4	Ave.	Rep.1	Rep.2	Rep.3	Rep.4	Ave.
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5	1.366	1.361	1.362	1.355	1.361	1.345	1.353	1.346	1.345	1.347
10	2.773	2.763	2.775	2.765	2.769	2.758	2.760	2.764	2.762	2.761
15	4.206	4.210	4.215	4.202	4.208	4.195	4.196	4.202	4.199	4.198
20	5.712	5.704	5.712	5.713	5.710	5.678	5.682	5.694	5.690	5.686
25	7.106	7.105	7.101	7.096	7.102	7.106	7.105	7.101	7.096	7.102

Table A4.6. Calibration of transducer No.(3) (Lateral load)

	Output mV per 5V (Loading up)					Output mV per 5V (Loading down)				
Load (kN)	Rep.1	Rep.2	Rep.3	Rep.4	Ave.	Rep.1	Rep.2	Rep.3	Rep.4	Ave.
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	0.087	0.087	0.090	0.091	0.089	0.097	0.105	0.102	0.107	0.103
2	0.206	0.202	0.204	0.207	0.205	0.246	0.246	0.250	0.244	0.247
3	0.300	0.301	0.301	0.302	0.301	0.342	0.347	0.348	0.345	0.346
4	0.391	0.386	0.372	0.389	0.385	0.391	0.386	0.372	0.389	0.385

Table A4.7. Calibration of transducer No.(4) (Tension load)

	Output mV per 5V (Loading up)					Output mV per 5V (Loading down)				
Load (kN)	Rep.1	Rep.2	Rep.3	Rep.4	Ave.	Rep.1	Rep.2	Rep.3	Rep.4	Ave.
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5	1.391	1.389	1.392	1.384	1.389	1.383	1.382	1.378	1.374	1.379
10	2.836	2.839	2.832	2.830	2.834	2.833	2.834	2.828	2.821	2.829
15	4.303	4.309	4.299	4.292	4.301	4.301	4.307	4.291	4.288	4.297
20	5.823	5.832	5.848	5.823	5.832	5.814	5.823	5.810	5.817	5.816
25	7.258	7.266	7.255	7.250	7.257	7.258	7.266	7.255	7.250	7.257

Table A4.8. Calibration of transducer No.(4) (Lateral load)

	Output mV per 5V (Loading up)					Output mV per 5V (Loading down)				
Load (kN)	Rep.1	Rep.2	Rep.3	Rep.4	Ave.	Rep.1	Rep.2	Rep.3	Rep.4	Ave.
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	0.111	0.110	0.111	0.112	0.111	0.113	0.124	0.118	0.133	0.122
2	0.209	0.212	0.216	0.219	0.214	0.239	0.237	0.239	0.234	0.237
3	0.304	0.301	0.303	0.315	0.306	0.335	0.344	0.335	0.322	0.334
4	0.372	0.370	0.373	0.383	0.375	0.372	0.370	0.373	0.383	0.375

Table A4.9. Calibration of transducer No.(5) (Tension load)

	Output mV per 5V (Loading up)					Output mV per 5V (Loading down)				
Load (kN)	Rep.1	Rep.2	Rep.3	Rep.4	Ave.	Rep.1	Rep.2	Rep.3	Rep.4	Ave.
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5	1.420	1.438	1.421	1.419	1.425	1.360	1.438	1.361	1.356	1.391
10	2.850	2.852	2.843	2.842	2.846	2.810	2.852	2.800	2.802	2.816
15	4.305	4.310	4.304	4.295	4.304	4.270	4.284	4.270	4.268	4.273
20	5.845	5.847	5.842	5.841	5.844	5.826	5.826	5.805	5.814	5.818
25	7.257	7.246	7.240	7.235	7.245	7.257	7.246	7.240	7.235	7.245

Table A4.10. Calibration of transducer No.(5) (Lateral load)

	Output mV per 5V (Loading up)					Output mV per 5V (Loading down)				
Load (kN)	Rep.1	Rep.2	Rep.3	Rep.4	Ave.	Rep.1	Rep.2	Rep.3	Rep.4	Ave.
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	0.075	0.081	0.082	0.085	0.081	0.087	0.088	0.085	0.084	0.085
2	0.195	0.196	0.198	0.197	0.197	0.216	0.215	0.220	0.213	0.216
3	0.307	0.309	0.303	0.308	0.306	0.320	0.321	0.320	0.313	0.319
4	0.393	0.400	0.391	0.393	0.394	0.393	0.400	0.391	0.393	0.394

Table A4.11. Calibration of transducer No.(6) (Tension load)

	Output mV per 5V (Loading up)					Output mV per 5V (Loading down)				
Load (kN)	Rep.1	Rep.2	Rep.3	Rep.4	Ave.	Rep.1	Rep.2	Rep.3	Rep.4	Ave.
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5	1.194	1.192	1.191	1.193	1.193	1.162	1.157	1.158	1.154	1.158
10	2.431	2.425	2.419	2.421	2.424	2.382	2.394	2.392	2.394	2.391
15	3.710	3.708	3.702	3.706	3.707	3.676	3.672	3.689	3.694	3.683
20	5.088	5.064	5.065	5.072	5.072	5.030	5.044	5.047	5.055	5.044
25	6.327	6.337	6.320	6.336	6.330	6.327	6.337	6.320	6.336	6.330

Table A4.12. Calibration of transducer No.(6) (Lateral load)

	Output mV per 5V (Loading up)					Output mV per 5V (Loading down)				
Load (kN)	Rep.1	Rep.2	Rep.3	Rep.4	Ave.	Rep.1	Rep.2	Rep.3	Rep.4	Ave.
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	0.118	0.142	0.116	0.112	0.122	0.096	0.120	0.091	0.096	0.101
2	0.224	0.238	0.223	0.217	0.226	0.196	0.229	0.205	0.202	0.208
3	0.301	0.325	0.302	0.295	0.306	0.285	0.320	0.286	0.278	0.292
4	0.361	0.393	0.396	0.355	0.376	0.361	0.393	0.396	0.355	0.376

A4.4 Datalogger Program

Two individual programs were developed for the datalogger. One for the front wheel and the other for the rear wheel. The multiplier and offset values derived from the calibration tests were used in the program.

I. Rear Wheel Program

Program: Rear Wheel Transducers (1-2, 3-4, 5-6) [ProgRe]
Flag Usage: 1
Input Channel Usage: 1:Tr(1-2), 2:Tr (3-4), 3:Tr(5-6), 7:RCS
Excitation Channel Usage: 1:Tr(1-2), 2:Tr (3-4), 3:Tr(5-6)
Continuos Analog Output Usage: None
Control Port Usage: None
Pulse Input Channel Usage: 1: H. Switch, 2:100pulse, 3:25pulse, 4:5th Wh.
Output Array Definitions: ----

*			Table 1 Programs
	01:	1 0.075	Sec. Execution Interval
01:		P3	Pulse
	01:	1	Rep
	02:	1	Pulse Input Chan
	03:	2	Switch Closure
	04:	1	Loc [:Switch]
	05:	1	Mult
	06:	0	Offset
02:		P89	If X<=>F
	01:	1	X Loc switch
	02:	2	<>
	03:	0	F
	04:	1	Call Subroutine 1
03:		P91	If Flag
	01:	21	1 is reset
	02:	00	Go to end of Program Table
04:		P6	Full Bridge
	01:	1	Rep
	02:	12	15 mV fast Range
	03:	1	IN Chan
	04:	1	Excite all reps w/EXchan 1
	05:	2000	mV Excitation
	06:	2	Loc [:Tr(1-2)]

07:	18.1	Mult
08:	- 3.32	Offset
05:	P6	Full Bridge
01:	1	Rep
02:	12	15 mV fast Range
03:	2	IN Chan
04:	2	Excite all reps w/EXchan 1
05:	2000	mV Excitation
06:	3	Loc [:Tr(3-4)]
07:	18	Mult
08:	6.74	Offset
06:	P6	Full Bridge
01:	1	Rep
02:	12	15 mV fast Range
03:	3	IN Chan
04:	3	Excite all reps w/EXchan 1
05:	2000	mV Excitation
06:	4	Loc [:Tr(5-6)]
07:	18	Mult
08:	- 4.06	Offset
07:	P3	Pulse
01:	1	Rep
02:	2	Pulse Input Chan
03:	2	Switch Closure
04:	5	Loc [: Re: 100P]
05:	1	Mult
06:	0	Offset
08:	P3	Pulse
01:	1	Rep
02:	3	Pulse Input Chan
03:	2	Switch Closure
04:	6	Loc [: Re: 25P,Syn.]
05:	1	Mult
06:	0	Offset
09:	P3	Pulse
01:	1	Rep
02:	4	Pulse Input Chan
03:	2	Switch Closure
04:	7	Loc [: Re:5th Wh.]
05:	1	Mult
06:	0	Offset
10:	P3	Volt (SE)

01:	1	Rep
02:	15	5000 mV fast Range
03:	7	IN Chan
04:	8	Loc [: Re: Radio Cont.]
05:	1	Mult
06:	0	Offset
11:	P86	Do
01:	10	Set flag 0 (output)
12:	P70	Sample
01:	7	Reps
02:	2	Loc Tr(1-2)
13:	P	End Table 1
*	2	Table 2 Programs
01:	0	Sec. Execution Interval
01:	P	End Table 2
*	3	Table 3 Subroutines
01:	P85	Beginning of Subroutine
01:	1	Subroutine Number
02:	P91	If Flag
01:	11	1 is set
02:	30	Then Do
03:	P86	Do
01:	21	Reset flag 1
04:	P94	Else
05:	P86	Do
01:	11	Set flag 1
06:	P95	End
07:	P95	End
08:	P	End Table 3
*	4	Mode 4 Output Options

	01:	00	(Tape OFF) (Printer OFF)
	02:	00	Printer 300 Baud
*		A	Mode 10 Memory Allocation
	01:	28	Input Locations
	02:	64	Intermediate Locations
*		C	Mode 12 Security
	01:	00	Security Option
	02:	0000	Security Code

Input Location Assignments (with comments):

Key:

T = Table Number
E = Entry Number
L = Location Number

T:	E:	L:
1:	1:	1: Loc [:Switch]
1:	4:	2: Loc [:Tr(1-2)]
1:	5:	3: Loc [:Tr(3-4)]
1:	6:	4: Loc [:Tr(5-6)]
1:	7:	5: Loc [:Re: 100P]
1:	8:	6: Loc [:Re: 25P,Syn.]
1:	9:	7: Loc [:Re: 5th Wh.]
1:	10:	8: Loc [:Re: Radio Cont.]

Input Location Labels:

1: Switch	2: Tr(1-2)	3: Tr(3-4)	4: Tr(5-6)
5: Re: 100P	6: Re: 25P,Syn.	7: Re: 5th Wh.	8: Re: Radio Cont.

II. Front Wheel Program

Program: Front Wheel Transducers (7-8, 9-10, 11-12) [ProgFr]
Flag Usage: 1
Input Channel Usage: 1:Tr(7-8), 2:Tr (9-10), 3:Tr(11-12), 7:RCS
Excitation Channel Usage: : 1:Tr(7-8), 2:Tr (9-10), 3:Tr(11-12)
Continuos Analog Output Usage: None
Control Port Usage: None
Pulse Input Channel Usage: 1: H. Switch, 2:100pulse, 3:25pulse, 4:5th Wh.
Output Array Definitions: ----

*	1	Table 1 Programs
01:	0.075	Sec. Execution Interval
01:	P3	Pulse
01:	1	Rep
02:	1	Pulse Input Chan
03:	2	Switch Closure
04:	1	Loc [:Switch]
05:	1	Mult
06:	0	Offset
02:	P89	If X<=>F
01:	1	X Loc switch
02:	2	<>
03:	0	F
04:	1	Call Subroutine 1
03:	P91	If Flag
01:	21	1 is reset
02:	00	Go to end of Program Table
04:	P6	Full Bridge
01:	1	Rep
02:	12	15 mV fast Range
03:	1	IN Chan
04:	1	Excite all reps w/EXchan 1
05:	2000	mV Excitation
06:	2	Loc [:Tr(7-8)]
07:	17.3	Mult
08:	4.02	Offset
05:	P6	Full Bridge
01:	1	Rep
02:	12	15 mV fast Range
03:	2	IN Chan
04:	2	Excite all reps w/EXchan 1

05:	2000	mV Excitation
06:	3	Loc [:Tr(9-10)]
07:	17.5	Mult
08:	- 4.10	Offset
06:	P6	Full Bridge
01:	1	Rep
02:	12	15 mV fast Range
03:	3	IN Chan
04:	3	Excite all reps w/EXchan 1
05:	2000	mV Excitation
06:	4	Loc [:Tr(11-12)]
07:	20.2	Mult
08:	- 6.4	Offset
07:	P3	Pulse
01:	1	Rep
02:	2	Pulse Input Chan
03:	2	Switch Closure
04:	5	Loc [: Fr: 100P]
05:	1	Mult
06:	0	Offset
08:	P3	Pulse
01:	1	Rep
02:	3	Pulse Input Chan
03:	2	Switch Closure
04:	6	Loc [: Fr: 25P,Syn.]
05:	1	Mult
06:	0	Offset
09:	P3	Pulse
01:	1	Rep
02:	4	Pulse Input Chan
03:	2	Switch Closure
04:	7	Loc [: Fr: 5th Wh.]
05:	1	Mult
06:	0	Offset
10:	P3	Volt (SE)
01:	1	Rep
02:	15	5000 mV fast Range
03:	7	IN Chan
04:	8	Loc [: Fr: Radio Cont.]
05:	1	Mult
06:	0	Offset
11:	P86	Do

01:	10	Set flag 0 (output)
12:	P70	Sample
01:	7	Reps
02:	2	Loc Tr(7-8)
13:	P	End Table 1
*	2	Table 2 Programs
01:	0	Sec. Execution Interval
01:	P	End Table 2
*	3	Table 3 Subroutines
01:	P85	Beginning of Subroutine
01:	1	Subroutine Number
02:	P91	If Flag
01:	11	1 is set
02:	30	Then Do
03:	P86	Do
01:	21	Reset flag 1
04:	P94	Else
05:	P86	Do
01:	11	Set flag 1
06:	P95	End
07:	P95	End
08:	P	End Table 3
*	4	Mode 4 Output Options
01:	00	(Tape OFF) (Printer OFF)
02:	00	Printer 300 Baud
*	A	Mode 10 Memory Allocation
01:	28	Input Locations
02:	64	Intermediate Locations

*	C	Mode 12 Security
01:	00	Security Option
02:	0000	Security Code

Input Location Assignments (with comments):

Key:

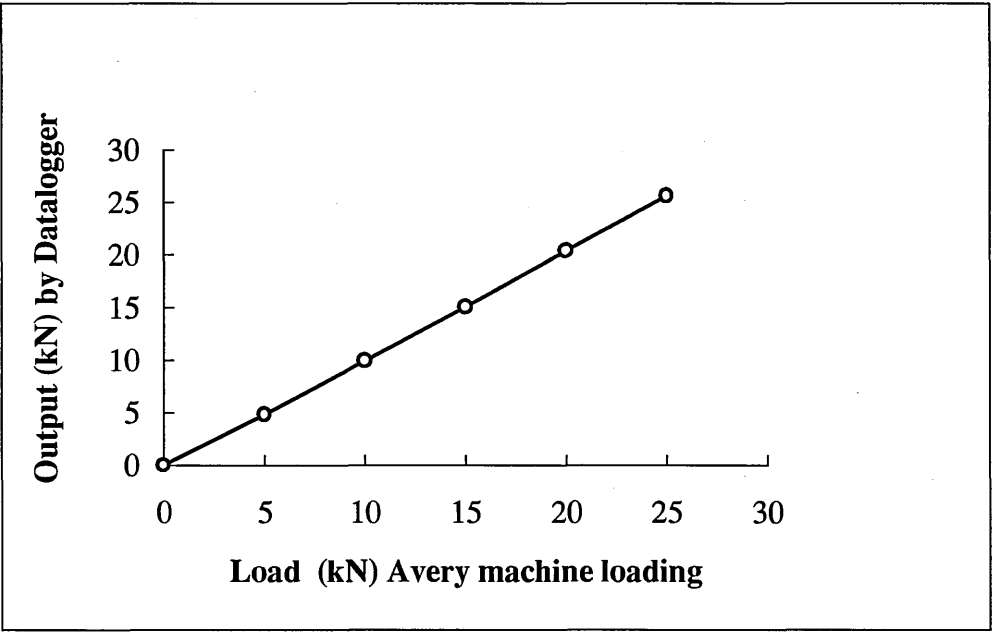
T = Table Number
E = Entry Number
L = Location Number

T:	E:	L:
1:	1:	1: Loc [:Switch]
1:	4:	2: Loc [:Tr(7-8)]
1:	5:	3: Loc [:Tr(9-10)]
1:	6:	4: Loc [:Tr(11-12)]
1:	7:	5: Loc [:Fr: 100P]
1:	8:	6: Loc [:Fr: 25P,Syn.]
1:	9:	7: Loc [:Fr: 5th Wh.]
1:	10:	8: Loc [:Fr: Radio Cont.]

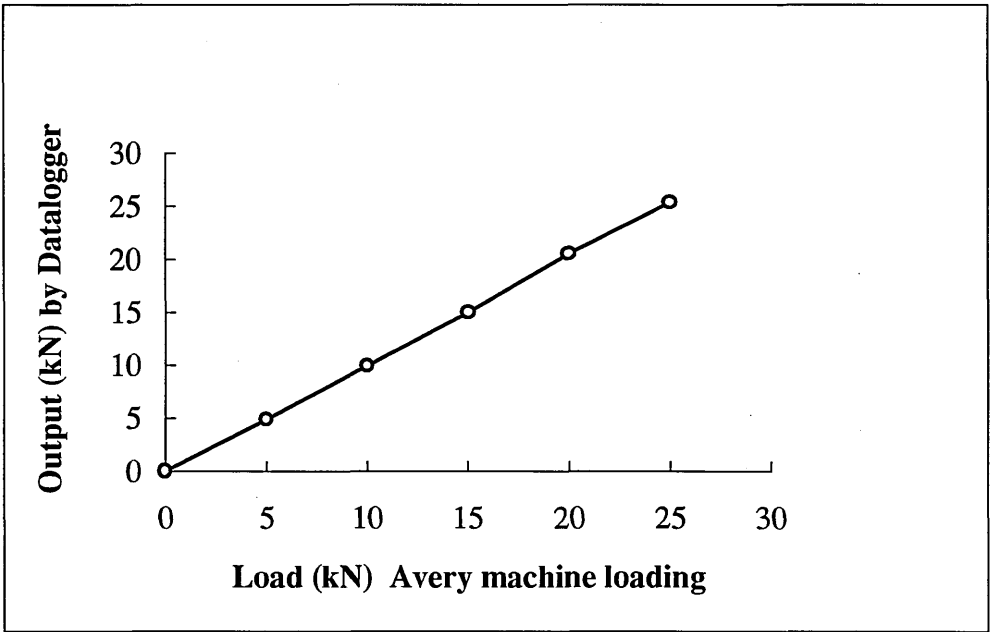
Input Location Labels:

1: Switch	2: Tr(7-8)	3: Tr(9-10)	4: Tr(11-12)
5: Fr: 100P	6: Fr: 25P,Syn.	7: Fr: 5th Wh.	8: Fr: Radio Cont.

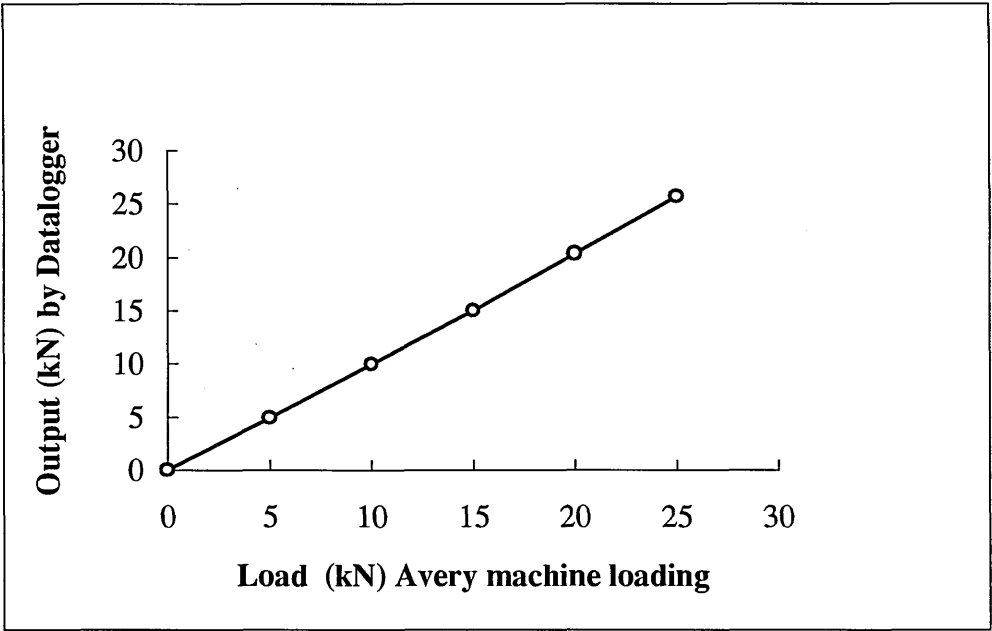
A4.5 Calibration characteristics of wheel transducers by using Data logger,
(Tension load)



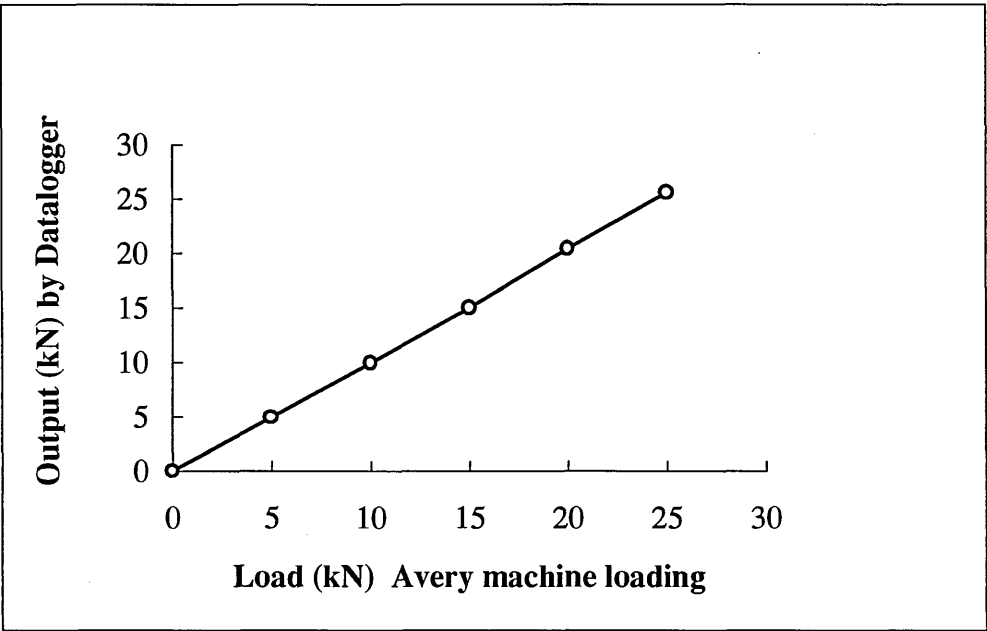
A4.12. Calibration of transducer No. (2)



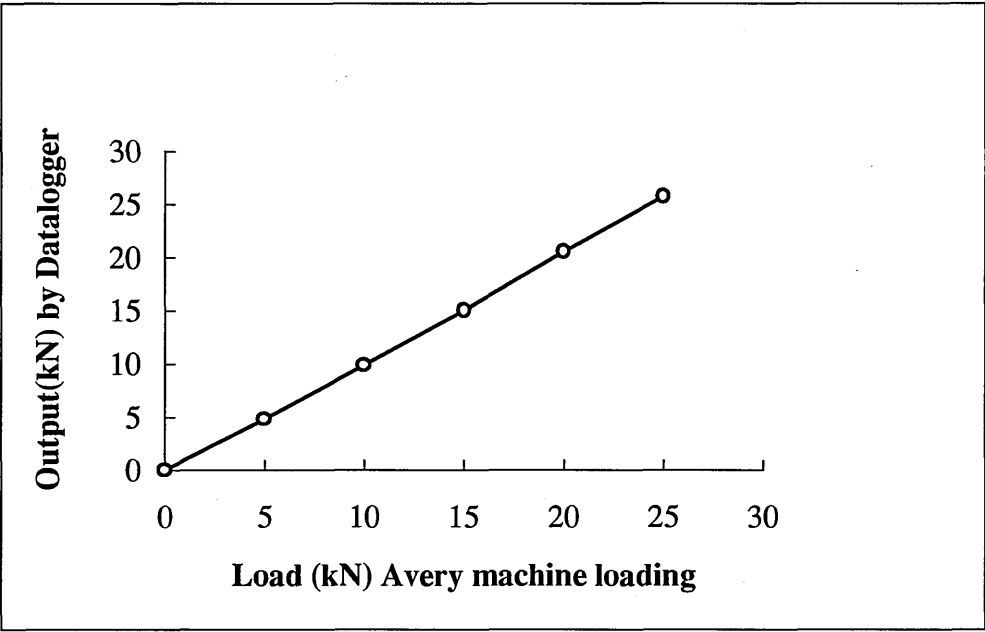
A4.13. Calibration of transducer No. (3)



A4.14. Calibration of transducer No. (4)



A4.15. Calibration of transducer No. (5)



A4.16. Calibration of transducer No. (6)

A4.6 Calibration data of wheel transducers by using the Data logger
(Tension load)

Table A4.13. Calibration of transducer No.(1)

	Output kN (Loading up)				Output kN (Loading down)			
Load (kN)	Rep.1	Rep.2	Rep.3	Ave.	Rep.1	Rep.2	Rep.3	Ave.
0	0.00	0.00	0.00	0.00	0.000	0.00	0.00	0.00
5	4.85	4.84	4.86	4.85	4.84	4.84	4.85	4.84
10	9.91	9.94	9.91	9.92	9.91	9.92	9.93	9.92
15	15.05	15.00	15.00	15.02	15.00	15.00	15.00	15.00
20	20.42	20.43	20.70	20.52	20.40	20.40	20.40	20.40
25	25.41	25.52	25.80	25.58	25.41	25.52	25.80	25.58

Table A4.14. Calibration of transducer No.(2)

	Output kN (Loading up)				Output kN (Loading down)			
Load (kN)	Rep.1	Rep.2	Rep.3	Ave.	Rep.1	Rep.2	Rep.3	Ave.
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	4.82	4.86	4.90	4.84	4.74	4.74	4.73	4.74
10	9.91	9.89	9.91	9.90	9.84	9.81	9.81	9.82
15	15.00	15.04	15.00	15.00	15.00	15.00	14.91	14.97
20	20.42	20.36	20.32	20.37	20.12	20.23	20.10	20.15
25	25.57	25.43	25.40	25.47	25.57	25.40	25.40	25.47

Table A4.15. Calibration of transducer No.(3)

	Output kN (Loading up)				Output kN (Loading down)			
Load (kN)	Rep.1	Rep.2	Rep.3	Ave.	Rep.1	Rep.2	Rep.3	Ave.
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	4.90	4.91	4.89	4.90	4.86	4.86	4.86	4.86
10	9.95	9.96	9.94	9.95	9.92	9.94	9.93	9.93
15	15.00	15.00	14.92	14.97	15.00	15.00	15.00	15.00
20	20.51	20.48	20.57	20.52	20.32	20.21	20.40	20.31
25	25.52	25.35	25.24	25.37	25.52	25.35	25.24	25.37

Table A4.16. Calibration of transducer No.(4)

	Output kN (Loading up)				Output kN (Loading down)			
Load (kN)	Rep.1	Rep.2	Rep.3	Ave.	Rep.1	Rep.2	Rep.3	Ave.
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	4.94	4.92	4.90	4.92	4.97	4.97	4.96	4.97
10	9.96	9.95	9.95	9.95	10.00	10.00	10.00	10.00
15	15.00	15.06	15.00	15.02	15.10	15.10	15.00	15.00
20	20.33	20.37	20.28	20.33	20.15	20.18	20.10	20.14
25	25.54	25.66	25.77	25.66	25.54	25.66	25.77	25.66

Table A4.17. Calibration of transducer No.(5)

	Output kN (Loading up)				Output kN (Loading down)			
Load (kN)	Rep.1	Rep.2	Rep.3	Ave.	Rep.1	Rep.2	Rep.3	Ave.
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	4.90	4.92	4.93	4.92	5.08	5.09	5.08	5.08
10	9.94	9.95	9.95	9.95	10.10	10.10	10.00	10.07
15	15.00	15.00	15.00	15.00	15.10	15.10	15.10	15.10
20	20.44	20.40	20.37	20.40	20.31	20.14	20.16	20.20
25	25.67	25.43	25.70	25.60	25.67	25.43	25.70	25.60

Table A4.18. Calibration of transducer No.(6)

	Output kN (Loading up)				Output kN (Loading down)			
Load (kN)	Rep.1	Rep.2	Rep.3	Ave.	Rep.1	Rep.2	Rep.3	Ave.
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	4.83	4.83	4.83	4.83	4.81	4.72	4.74	4.76
10	9.88	9.89	9.86	9.88	9.93	9.89	9.92	9.91
15	15.05	14.92	14.95	14.97	15.10	14.92	15.10	15.04
20	20.52	20.50	20.58	20.53	20.25	20.32	20.40	20.32
25	25.78	25.62	25.70	25.70	25.78	25.62	25.70	25.70

A4.7 A worked example for the calibration of the equipped tractor on yard

A sample of calculations carried out for the results in Table (4.4 and 4.5) is given below. The proportion of the weight of the driver and fuel on the rear and front axles was taken into account in the calculations of the vertical force on the wheel.

i) The tractor without ballast

The tractor static weight determined based on the weigh bridge measurement, including both of the weights of the driver and fuel, is shown in Table (A.19).

Table A.19. The tractor static weight based on Weigh Bridge measurement

Side	Weight (kN)	
	per axle	per wheel
Front	15.20	7.60
Rear	25.40	12.70
Total	40.60	20.30

The following example given below is for the front wheel when the tractor nominal speed is 1kph. The measurement was taken between two known points of 20 m ground distance.

The summation of vertical forces ΣF_v measured by the system = 6.68 kN

The weight of the unsensed part = 0.95 kN

The total vertical weight = 7.63 kN

$$\begin{aligned} \% \text{ error} &= \frac{\text{Vertical weight by weigh bridge} - \text{Vertical weight by system}}{\text{Vertical weight by weigh bridge}} \times 100 \\ &= \frac{7.6 - 7.63}{7.6} \times 100 = - 0.4 \% \end{aligned}$$

The percentage error in the travel distance measured by the fifth wheel can be determined as :

$$\% \text{ error} = \frac{\text{Real ground distance} - \text{Measured distance by 5th wheel}}{\text{Real ground distance}} \times 100$$

However, the measured distances by the front and rear wheels are 19.96m and 20.02m respectively. So the % error in the front fifth wheel measurement is :

$$\% \text{ error} = \frac{20 - 19.96}{20} \times 100 = 0.2 \%$$

Similar calculation to find the % error for the rear fifth wheel = - 0.10 %. Thus, the average % error is 0.05 %.

ii) The tractor with ballast

For the purpose of testing the accuracy of the measurement system, the equipped tractor was ballasted on the front and on the rear as shown in the following example.

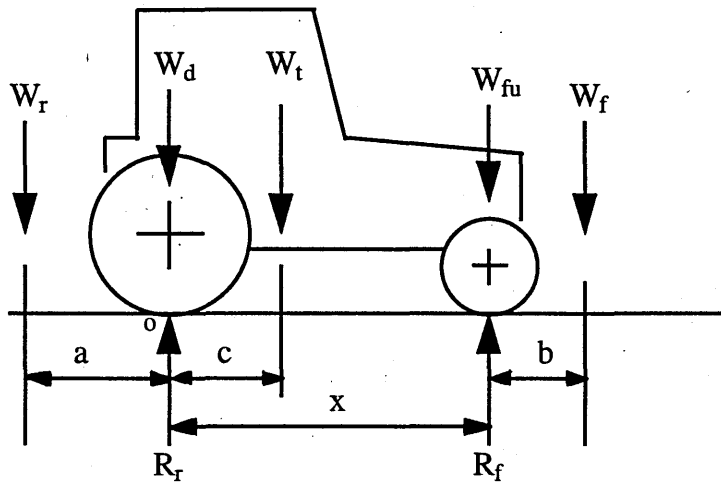


Fig. A4.7. The tested tractor with ballast weights.

Where :

W_r = rear wheel ballast	= 191 kg	$\Rightarrow$ 1.87 kN
W_t = tractor weight	= 4037 kg	$\Rightarrow$ 39.60 kN
W_f = front wheel ballast	= 135 kg	$\Rightarrow$ 1.32 kN
W_d = driver weight	= 80 kg	$\Rightarrow$ 0.78 kN
W_{fu} = fuel weight	= 21 kg	$\Rightarrow$ 0.20 kN
a	= 1.10 m	
b	= 0.70 m	
c	= 0.92 m	
x	= 2.37 m	

The moment about the point O is :

$$\Sigma M_R = 0$$

$$[-W_r \times a] + [W_t \times c] + [W_{fu} \times x] + [W_f \times (b + x)] = R_f \times x$$

$$- [1.87 \times 1.1] + [39.60 \times 0.92] + [0.2 \times 2.37] + [1.32 \times (0.70 + 2.37)] = R_f \times 2.37$$

$$R_f = 16.40 \text{ kN}$$

$$\text{Vertical load per front wheel} = \frac{16.4}{2} = 8.20 \text{ kN}$$

$$\Sigma F_v = 0$$

$$\begin{aligned} R_r + R_f &= W_r + W_d + W_t + W_{fu} + W_f \\ R_r + 16.40 &= 1.87 + 0.78 + 39.60 + 0.20 + 1.32 \\ R_r &= 27.40 \text{ kN} \end{aligned}$$

$$\text{Vertical load per rear wheel} = \frac{26.40}{2} = 13.70 \text{ kN}$$

A worked example is given below for the rear wheel when the tractor nominal speed is 1 kph.

Summation of vertical forces ΣF_v measured by the system = 12.54 kN

Weight of the unsensed part = 1.5 kN

Total vertical weight = 14.04 kN

$$\begin{aligned} \% \text{ error} &= \frac{\text{Vertical weight by weigh bridge} - \text{Vertical weight by system}}{\text{Vertical weight by weigh bridge}} \times 100 \\ &= \frac{13.70 - 14.04}{13.70} \times 100 = -2.50 \% \end{aligned}$$

APPENDIX 5: Pilot test data and experimental plan

Table A5.1. The pilot study results

Tractor speed	Variable Measured	Front wheel				Rear wheel			
		Rep. 1	Rep. 2	mean	C.V. (%)	Rep. 1	Rep. 2	mean	C.V. (%)
Low	ΣF_V (kN)	5.16	5.39	5.28	3.08	11.80	12.35	12.08	3.22
	ΣF_H (kN)	1.64	1.45	1.55	8.70	3.80	3.22	3.51	11.68
	TD_f (m)	14.16	14.14	14.15	0.10	14.19	14.19	14.19	00.00
Med.	ΣF_V (kN)	5.05	5.38	5.22	4.47	12.19	12.11	12.15	0.47
	ΣF_H (kN)	1.44	1.56	1.50	5.65	3.81	3.61	3.71	3.81
	TD_f (m)	14.76	14.50	14.63	1.26	14.76	14.45	14.61	1.50
High	ΣF_V (kN)	4.82	4.98	4.90	2.30	13.25	12.86	13.06	2.11
	ΣF_H (kN)	0.96	0.98	0.97	1.45	4.10	3.70	3.90	7.25
	TD_f (m)	14.19	13.84	14.02	1.76	14.14	13.94	14.04	1.00

Where :

ΣF_V = Summation of vertical wheel forces

ΣF_H = Summation of horizontal wheel forces

Td_f = Travel distance measured by the fifth wheel

C.V. = Coefficient of Variance

Calculation of the tractor ballast weight

The maximum ballast weight used to ballast the tractor was decided based on the maximum tyre load capacity and tractor axle limit considered in wheel transducer design, in addition to the physical limitation. The proportion of the weight of the driver and fuel on the rear and front axles was taken into account.

Table A5.2. Tractor Ballast weight

Condition	Total weight of tractor (kN)		
	No Ballast	Med. Ballast	Max. Ballast
Front axle	16	19.23	21.68
Rear axle	25.48	31.11	35.78
Total	41.48	50.44	57.46

B1 P2 S2	B2 P1 S3	B3 P3 S1	B1 P3 S2	B2 P3 S3	B1 P2 S1	B3 P2 S2	B2 P2 S1	B1 P2 S3	B3 P3 S2	B2 P3 S1	B1 P1 S3	B3 P2 S1	B2 P1 S1	B3 P1 S2	B2 P2 S2	B1 P2 S2	B3 P3 S3	B2 P2 S2	B1 P2 S1	B3 P3 S3	B2 P3 S1	B1 P2 S1	B3 P1 S1	B2 P2 S2	B1 P1 S1	B3 P2 S1	B2 P3 S2	B1 P3 S3
B1 P2 S1	B2 P1 S2	B3 P3 S2	B1 P3 S1	B2 P3 S3	B1 P2 S3	B3 P2 S2	B2 P2 S2	B1 P2 S1	B3 P3 S1	B2 P3 S2	B1 P1 S2	B3 P2 S2	B2 P1 S3	B3 P1 S1	B2 P2 S1	B1 P2 S3	B3 P3 S3	B2 P2 S1	B1 P2 S3	B3 P3 S1	B2 P3 S2	B1 P2 S2	B3 P1 S2	B2 P2 S3	B1 P1 S3	B3 P2 S2	B2 P3 S3	B1 P3 S1
B1 P2 S3	B2 P1 S1	B3 P3 S3	B1 P3 S3	B2 P3 S1	B1 P2 S2	B3 P2 S3	B2 P2 S3	B1 P2 S2	B3 P3 S2	B2 P3 S3	B1 P1 S1	B3 P2 S3	B2 P1 S2	B3 P1 S3	B2 P2 S3	B1 P2 S2	B3 P3 S1	B2 P2 S3	B1 P2 S2	B3 P3 S2	B2 P3 S1	B1 P2 S3	B3 P1 S3	B2 P2 S1	B1 P1 S2	B3 P2 S3	B2 P3 S1	B1 P3 S2

Replication 1

Replication 2

Replication 3

Fig. A5.2. A layout of a factorai al expermint design

Where :

- B = Ballast weight
- P = Implement pull
- S = Tractor speed

APPENDIX 6: Experimental result data and analysis

A6.1 Laboratory results

Soil cohesion c and angle of internal friction ϕ were measured by using the triaxial test method at a similar average value of both of soil bulk density and moisture content when the field tests were carried out.

Soil dry bases moisture content MC : 15%

Soil dry bulk density : 1.54 g/cm³

Table A6.1. Results of soil shear strength properties

Soil property	Rep. 1	Rep. 2	Rep. 3	Rep. 4	Average
c (kN/m ²)	7.5	8.6	10	10.2	9.1
ϕ (deg.)	25	22	23	26	24

A6.2 Field results

Table A6.2. Traction Performance Field Results

Tractor nominal Speed	Ballast setting	Pull setting	Total tractor weight (kN)	Total drawbar pull (kN)	Average actual speed V_a (m/s)	Tractor drawbar power (kW)	Wheel slip (%)
4	No	Low	39.82	9.48	1.07	10.14	10.60
		Med.	37.82	11.38	1.02	11.61	14.50
		High	36.26	18.24	0.57	10.40	51.50
6	No	Low	40.46	7.70	1.25	9.63	11.35
		Med.	38.60	9.22	1.43	13.19	13.50
		High	37.10	14.74	1.12	16.51	30.50
9	No	Low	41.06	9.20	1.93	17.76	19.25
		Med.	40.76	8.58	1.96	16.82	19.00
		High	---	---	---	---	---
4	Med.	Low	50.70	8.40	1.10	9.24	7.50
		Med.	48.66	12.14	1.05	12.75	10.25
		High	47.68	18.48	0.97	17.93	18.60
6	Med.	Low	50.16	8.00	1.47	11.76	9.65
		Med.	48.44	10.96	1.44	15.78	12.00
		High	47.72	17.60	1.11	19.54	22.00
9	Med.	Low	50.80	5.40	2.20	11.88	10.50
		Med.	50.06	7.26	1.80	13.10	11.80
		High	49.46	13.80	0.92	12.70	16.85
4	Max.	Low	58.60	8.46	1.10	9.31	6.05
		Med.	56.92	12.84	1.10	14.12	7.60
		High	55.96	18.56	1.04	19.30	10.95
6	Max.	Low	57.86	10.06	1.51	15.19	7.00
		Med.	56.20	17.24	1.50	25.86	10.00
		High	56.64	22.78	1.00	22.78	19.90
9	Max.	Low	58.78	5.16	2.10	10.84	9.25
		Med.	58.92	8.22	1.87	15.37	11.75
		High	---	---	---	---	---

(---) in the table means the tractor proved not capable of working at this combination of speed, weight and pull setting

Rolling resistance measurement :

The rolling resistance of the tractor was measured by driving the equipped tractor without implement on different places in the field and the average value was taken. The tractor with medium ballast condition was chosen and the rolling resistance for the other two conditions (i.e. with no ballast and maximum ballast) was calculated proportionally to the tractor weight. The rolling resistance of each of the tractor front and rear wheels was estimated proportionally to the wheel diameter. Table (A6.3) summarised these results.

Table A6.3. Rolling resistance of the tractor wheels

Condition	Rolling resistance (kN)		
	Front wheel	Rear wheel	Total tractor
No ballast	0.29	0.41	1.4
Medium ballast	0.33	0.47	1.6
Maximum ballast	0.36	0.54	1.8

A6.3 Predicting the new ballast number for the frictional loose soil

From the field experiments, the dynamic tractor weight W , and the actual tractor speed V were determined for each individual test. The theoretical axle power P^* was estimated from the tractor catalogue assuming that (axle power = engine power $\times$ transmission efficiency). Then, the ballast number developed from the study was calculated from the following expression as explained in section 3.2.3 :

$$\frac{W}{P^*} = \frac{R_n}{V}$$

The test conditions which gave the highest tractor performance were chosen (Table A6.2), where :

$W = 56.2 \text{ kN}$ (Total vertical load on the tractor wheels [$(\Sigma F_{v_f} + \Sigma F_{v_r}) \cdot 2$])
 $V = 1.5 \text{ m/s}$ (Average actual wheel speed of both rear and front wheels)
 $P^* = 52 \text{ kW}$ (Tractor axle power = (Engine power $\times$ 0.83))

Then,

$$\frac{W}{P^*} = \frac{1.62}{V} \tag{6.1}$$

at wheel slip of 10% and 0.31 coefficient of traction. To adjusting the new ballast recommendation at 10% slip and 0.4 COT a similar procedure was followed as used in Appendix 3 part (2) :

$$\begin{aligned} \frac{W}{P^*} &= \frac{1.62}{V} \times \frac{0.31}{0.4} \\ \frac{W}{P^*} &= \frac{1.26}{V} \\ \frac{W}{P^*} &\Rightarrow \frac{1.3}{V} \end{aligned} \tag{6.2}$$

A6.4 Comparison between the study and ballast recommendation approaches

Table A6.4. Recommended tractor weight/axle power Vs speed at 10% slip and 0.4 COT. by Theory and Study (Similar conditions)

Tractor speed (V)		Dynamic tractor weight / Axle power (W/P*) (kN/kW)				
(kph)	(m/s)	Dwyer	Zoz	Gee-Clough	Bloome	Study
3.28	0.91	1.96	2.10	2.15	2.15	1.43
4.00	1.11	1.61	1.72	1.76	1.76	1.17
4.72	1.31	1.37	1.46	1.49	1.49	0.99
5.60	1.56	1.15	1.23	1.26	1.26	0.83
6.56	1.82	0.98	1.05	1.07	1.07	0.71
7.92	2.20	0.81	0.87	0.89	0.89	0.59

Fig. A6.5. Tractor weight/axle power Vs speed at 10% slip and 0.4 COT.
Comparison between Theory high & low limits with those of Study
at 95% confidence

Tractor speed (kph)	Dynamic tractor weight / Axle power (W/P*) (kN/kW)			
	Low limit of Study	High limit of Study	Average low limit of Theory	Average high limit of Theory
3.28	1.227	1.481	1.689	2.023
4.00	1.091	1.268	1.502	1.735
4.72	0.966	1.092	1.330	1.499
5.60	0.821	0.921	1.130	1.262
6.56	0.675	0.779	0.931	1.069
7.92	0.503	0.626	0.695	0.857

Fig. 6.6. Tractor weight/axle power Vs. speed at 10% slip and 0.4 COT.
Comparison between the work of Gee-Clough and Study at 95% confidence

Tractor speed (kph)	Dynamic tractor weight / Axle power (W/P*) (kN/kW)			
	Low limit of Study	High limit of Study	Average low limit of Gee- Clough & study	Average high limit of Gee- Clough & study
3.28	1.227	1.481	1.539	1.851
4.00	1.091	1.268	1.370	1.586
4.72	0.966	1.092	1.212	1.366
5.60	0.821	0.921	1.031	1.154
6.56	0.675	0.779	0.848	0.976
7.92	0.503	0.626	0.633	0.784

A6.5 Data of $(C_t)_{\max}$ and M from the study work

Table A6.7. Relationship between maximum coefficient of traction $(C_t)_{\max}$ and mobility number M from the study work

	Front wheel		Rear wheel	
Field test No.	$(C_t)_{\max}$	M	$(C_t)_{\max}$	M
1	0.38	11.8	0.46	8.6
2	0.36	12.9	0.48	8.5
3	0.37	15.0	0.56	8.7
4	0.29	11.5	0.37	8.4
5	0.33	12.1	0.39	8.5
6	0.30	14.0	0.50	8.8
10	0.31	8.7	0.45	7.2
11	0.37	8.9	0.50	7.3
12	0.44	9.5	0.54	6.8
13	0.24	9.0	0.35	7.2
14	0.26	9.1	0.43	7.3
15	0.36	9.9	0.49	6.6
19	0.42	6.8	0.38	6.1
20	0.45	7.0	0.54	5.7
21	0.50	6.4	0.61	4.9
22	0.28	7.1	0.53	6.0
23	0.39	6.9	0.68	5.9
24	0.40	6.4	0.56	4.8

A6.6 Data extracted from Dwyer et al. (1974)

Table A6.8. Data extracted from the original work by Dwyer et al. (1974)

Tyre size	13.6/12-38	
Section width, b (mm)	347	
Undelected diameter, d (mm)	1555	
Soil type	Sandy loam soil	
Soil conditions (Fields)	Stubble field	Ploughed field
Cone index (kN/m ²)	690	250

Table A6.9. Results of the maximum coefficient of traction $(C_t)_{max}$ and mobility number (M) determined from original work by Dwyer et al. (1974)

Operating conditions		Stubble field		Ploughed field	
Load on the tyre W (kg)	Deflection section hight (δ / h)	M	$(C_t)_{max}$	M	$(C_t)_{max}$
1530	19.2	8.8	0.59	3.5	0.43
2000	16.6	6.3	0.54	2.5	0.33
1395	18.8	9.5	0.60	3.9	0.46
1395	16.3	8.9	0.59	3.6	0.44
1395	13.4	8.0	0.58	3.2	0.41
1990	18.9	6.7	0.55	2.7	0.36

A6.7 An example of Mathcad calculations

An example of calculations by Mathcad to evaluate the value of deformation modulus K using Eq. (3.4) is given below. The field test condition chosen is :
Tractor with **no ballast, 6 kph nominal speed and low pull setting.**

Rear wheel		Front wheel
$D_1 := 1.556$	wheel diameter.(m)	$D_2 := 1.188$
$B_1 := .35$	width of wheel (m)	$B_2 := .29$
$W_1 := 13.80$	load on wheel (kN)	$W_2 := 6.43$
$i_1 := .10$	whell slip (%)	$i_2 := .127$
$L_1 := .472$	length of tyre contact area (m)	$L_2 := .429$
$A_1 := L_1 \cdot B_1$	tyre contact area (rectangular path, m ²)	$A_2 := L_2 \cdot B_2$
$c := 9.1$	cohesion for the soil (kN/m ²)	
$\phi := 24\text{-deg}$	angle of shearing resistance (deg)	
$K := .035, .036 \dots .048$	deformation modulus (m)	

$$H(K) := \left[(A_1 \cdot c + W_1 \cdot \tan(\phi)) \cdot \left[1 + \frac{K}{i_1 \cdot L_1} \cdot \left(e^{-i_1 \frac{L_1}{K}} - 1 \right) \right] \right] \cdot 2 + \left[(A_2 \cdot c + W_2 \cdot \tan(\phi)) \cdot \left[1 + \frac{K}{i_2 \cdot L_2} \cdot \left(e^{-i_2 \frac{L_2}{K}} - 1 \right) \right] \right] \cdot 2$$

K	H(K)
0.035	10.837
0.036	10.646
0.037	10.462
0.038	10.283
0.039	10.11
0.04	9.942
0.041	9.78
0.042	9.623
0.043	9.47
0.044	9.322
0.045	9.178
0.046	9.039
0.047	8.904
0.048	8.772

This value is taken because it is the nearest one to the measured (ie. 9.10 kN)

A6.8 Regression Analysis to compare the measured and calculated thrust forces

A regression statistics has been done to compare the measured and calculated thrust force values. The following data was used to examine the difference between the two at 95% confidence level using t-test.

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.865514282
R Square	0.749114972
Adjusted R Square	0.733434657
Standard Error	2.413989268
Observations	18

Analysis of Variance					
	df	Sum of Squares	Mean Square	F	Significance F
Regression	1	278.3968931	278.3968931	47.77423201	3.49825E-06
Residual	16	93.23750695	5.827344184		
Total	17				
	Coefficient	Standard Error	Lower 95%	Upper 95%	
Intercept	0.965049131	2.070711783	- 3.424662761	5.354761022	
X Variable 1	1.079483661	0.156177769	0.748401654	1.410565667	

A6.9 Soil compaction measurement data

The measurements of soil density, penetration resistance and water infiltration rate were taken on the same day after each tractor field test has been conducted. Soil moisture content range (dry bases) was between 13.5 and 18.5 % during the period of field experiments. This range includes the measurements at the depth of 5 and 20 cm.

(1) Soil dry density

Soil sample done with a 150 cm³ density ring volume following the standard oven drying method procedure.

Table A6.10. Soil density for tests of No ballast at different implement pulls

	Soil dry density (g /cm ³)					
	Low Pull		Medium Pull		High Pull	
Depth (cm)	Undist. location	Wheeled location	Undist. location	Wheeled location	Undist. location	Wheeled location
5	1.55	1.57	1.60	1.67	1.58	1.63
20	1.56	1.52	1.67	1.65	1.61	1.62
40	1.62	1.64	1.65	1.67	1.66	1.77

Table A6.11. Soil density for tests of Medium ballast at different implement pulls

	Soil dry density (g /cm ³)					
	Low Pull		Medium Pull		High Pull	
Depth (cm)	Undist. location	Wheeled location	Undist. location	Wheeled location	Undist. location	Wheeled location
5	1.56	1.64	1.49	1.61	1.47	1.58
20	1.55	1.65	1.54	1.65	1.48	1.59
40	1.56	1.58	1.65	1.73	1.63	1.75

Table A6.12. Soil density for tests of Maximum ballast at different implement pulls

	Soil dry density (g /cm ³)					
	Low Pull		Medium Pull		High Pull	
Depth (cm)	Undist. location	Wheeled location	Undist. location	Wheeled location	Undist. location	Wheeled location
5	1.46	1.56	1.42	1.57	1.46	1.58
20	1.44	1.49	1.51	1.62	1.42	1.56
40	1.54	1.65	1.53	1.65	1.56	1.68

(2) Penetration resistance

The readings were carried out using a standard cone penetrometer fitted with a 12.83 cone size. The multiplier factor into kPa unit : 76.2

Table A6.13. Penetration resistance for tests of No ballast at different implement pulls

	Cone Penetration Resistance (MPa)					
	Low Pull		Medium Pull		High Pull	
Depth (cm)	Undist. location	Wheeled location	Undist. location	Wheeled location	Undist. location	Wheeled location
0.00	0.000	0.000	0.000	0.000	0.000	0.000
3.30	0.163	0.210	0.267	0.163	0.171	0.152
6.60	0.435	0.638	0.508	0.544	0.486	0.219
9.90	0.751	1.000	0.673	0.958	0.791	0.267
13.20	1.034	1.219	0.927	1.208	1.000	0.381
16.50	1.110	1.362	0.953	1.197	0.972	1.010
19.80	1.089	1.229	0.927	1.328	0.972	1.295
23.10	1.099	1.286	0.991	1.404	1.010	1.334
26.40	1.132	1.391	1.130	1.361	1.172	1.619
29.70	1.110	1.429	1.054	1.285	1.114	1.724
33.00	1.099	1.467	1.092	1.339	1.086	1.581
36.30	1.056	1.591	1.067	1.568	1.153	1.553
39.60	1.263	1.753	1.207	1.807	1.286	1.667
42.90	1.698	1.943	1.435	2.036	1.429	1.991
46.20	2.003	2.191	1.778	2.373	1.581	2.343
49.00	2.199	2.372	2.489	2.700	2.162	2.886

Table A6.14. Penetration resistance for tests of Medium ballast at different implement pulls

	Cone Penetration Resistance (MPa)					
	Low Pull		Medium Pull		High Pull	
Depth (cm)	Undist. location	Wheeled location	Undist. location	Wheeled location	Undist. location	Wheeled location
0.00	0.000	0.000	0.000	0.000	0.000	0.000
3.30	0.200	0.267	0.191	0.131	0.181	0.114
6.60	0.543	0.800	0.524	0.642	0.543	0.276
9.90	0.695	1.086	0.733	1.143	0.648	0.791
13.20	1.048	1.191	0.981	1.241	0.943	1.143
16.50	1.048	1.286	1.038	1.241	0.962	1.400
19.80	1.048	1.257	1.038	1.328	1.076	1.534
23.10	1.067	1.229	1.076	1.339	1.086	1.505
26.40	1.010	1.257	1.057	1.470	1.124	1.591
29.70	0.972	1.343	1.019	1.480	1.191	1.629
33.00	1.076	1.476	1.067	1.578	1.229	1.734
36.30	1.191	1.562	1.334	1.644	1.467	1.772
39.60	1.257	1.629	1.419	1.676	1.648	2.419
42.90	1.419	1.667	1.448	1.949	1.772	2.991
46.20	1.467	2.124	1.657	2.569	2.038	3.400
49.00	1.619	2.515	1.953	3.179	2.076	3.553

Table A6.15. Penetration resistance for tests of Maximum ballast at different implement pulls

	Cone Penetration Resistance (MPa)					
	Low Pull		Medium Pull		High Pull	
Depth (cm)	Undist. location	Wheeled location	Undist. location	Wheeled location	Undist. location	Wheeled location
0.00	0.000	0.000	0.000	0.000	0.000	0.000
3.30	0.171	0.124	0.210	0.229	0.152	0.207
6.60	0.448	0.752	0.429	0.619	0.392	0.414
9.90	0.743	1.124	0.752	0.886	0.631	0.610
13.20	1.000	1.314	0.857	1.124	0.762	0.860
16.50	0.991	1.362	0.924	1.343	0.751	1.078
19.80	1.038	1.381	1.038	1.476	0.849	1.165
23.10	1.019	1.438	1.057	1.448	0.871	1.252
26.40	1.038	1.448	1.029	1.457	0.969	1.361
29.70	1.133	1.391	1.076	1.514	0.991	1.480
33.00	1.200	1.553	1.067	1.572	1.034	1.502
36.30	1.238	1.524	1.048	1.514	1.089	1.763
39.60	1.257	1.629	1.048	1.591	1.176	1.938
42.90	1.343	1.829	1.114	1.743	1.404	2.134
46.20	1.534	2.257	1.191	2.048	1.437	2.340
49.00	1.800	2.657	1.238	2.057	1.513	2.428

Table A6.16. Infiltration rate for tests of No ballast at different implement pulls

	Infiltration Rate (cm/min)					
	Low Pull		Medium Pull		High Pull	
Time (min)	Undist. location	Wheeled location	Undist. location	Wheeled location	Undist. location	Wheeled location
5	1.80	0.20	1.88	0.19	2.00	0.18
10	1.30	0.17	1.44	0.18	1.45	0.18
15	1.10	0.15	1.26	0.15	1.22	0.166
20	1.05	0.15	1.12	0.14	1.13	0.16
25	1.00	0.145	1.10	0.137	1.00	0.15
30	1.00	0.145	1.00	0.13	0.96	0.14
35	1.00	0.14	0.93	0.13	0.94	0.13
40	0.98	0.14	0.90	0.13	0.94	0.127
45	0.95	0.14	0.90	0.13	0.92	0.12
50	0.95	0.13	0.86	0.126	0.92	0.12
55	0.93	0.13	0.86	0.12	0.92	0.11
60	0.93	0.13	0.86	0.12	0.92	0.105
65	0.93	0.13	0.86	0.12	0.92	0.10
70	0.93	0.12	0.86	0.114	0.92	0.10
Average infiltration rate at the last 20 minutes	0.93	0.128	0.86	0.118	0.92	0.104

Table A6.17. Infiltration rate for tests of Medium ballast at different implement pulls

	Infiltration Rate (cm/min)					
	Low Pull		Medium Pull		High Pull	
Time (min)	Undist. location	Wheeled location	Undist. location	Wheeled location	Undist. location	Wheeled location
5	2.64	0.30	3.30	0.30	3.20	0.24
10	2.00	0.28	2.50	0.26	2.24	0.22
15	1.70	0.27	2.20	0.25	1.86	0.21
20	1.50	0.26	2.01	0.24	1.60	0.205
25	1.30	0.24	1.90	0.24	1.45	0.20
30	1.20	0.23	1.75	0.24	1.36	0.19
35	1.10	0.21	1.65	0.22	1.27	0.19
40	1.00	0.20	1.55	0.22	1.20	0.18
45	0.99	0.19	1.47	0.20	1.13	0.18
50	0.95	0.18	1.36	0.20	1.10	0.17
55	0.90	0.17	1.28	0.20	1.06	0.17
60	0.88	0.17	1.21	0.19	1.00	0.16
65	0.83	0.16	1.16	0.18	0.97	0.16
70	0.80	0.16	1.10	0.18	0.96	0.16
Average infiltration rate at the last 20 minutes	0.85	0.165	1.18	0.188	1.00	0.16

Table A6.18. Infiltration rate for tests of Maximum ballast at different implement pull

	Infiltration Rate (cm/min)					
	Low Pull		Medium Pull		High Pull	
Time (min)	Undist. location	Wheeled location	Undist. location	Wheeled location	Undist. location	Wheeled location
5	1.30	0.34	1.56	0.24	0.80	0.02
10	0.95	0.32	1.20	0.22	0.56	0.02
15	0.85	0.3	1.04	0.2	0.50	0.02
20	0.80	0.27	0.98	0.19	0.48	0.02
25	0.75	0.26	0.94	0.185	0.45	0.02
30	0.73	0.25	0.91	0.18	0.43	0.02
35	0.71	0.23	0.85	0.177	0.42	0.02
40	0.68	0.22	0.80	0.17	0.40	0.02
45	0.65	0.217	0.78	0.166	0.39	0.02
50	0.61	0.21	0.77	0.16	0.38	0.02
55	0.58	0.20	0.73	0.16	0.35	0.02
60	0.565	0.19	0.70	0.16	0.35	0.02
65	0.56	0.19	0.67	0.155	0.33	0.019
70	0.55	0.19	0.65	0.15	0.31	0.019
Average infiltration rate at the last 20 minutes	0.57	0.193	0.69	0.159	0.335	0.0195

Table A6.19. Pull-Slip relationship at 6 Nominal tractor speed used in Compaction assessments

Ballast weight setting	Pull setting	Wheel slip (%)
No	Low	11.35
	Medium	13.50
	High	30.50
Medium	Low	9.65
	Medium	12.00
	High	22.00
Maximum	Low	7.00
	Medium	10.00
	High	19.90

APPENDIX 7: Reference data

Table A7.1. Change in infiltration rate ratio with slip at the average of all ballast values

Tractor wheel slip (%)	Infiltration rate Ratio
9.33	0.224
11.83	0.176
24.13	0.111

Note:

The value of the infiltration rate ratio at the three types of tractor ballast weights are combined altogether taking their average. Also, the values of wheel slip at the three types of tractor ballast weights are combined using their average.

Table A7.2. Change in infiltration rate with slip at Maximum ballast condition

Tractor wheel slip (%)	Infiltration rate Ratio
7	0.34
10	0.23
19.9	0.06

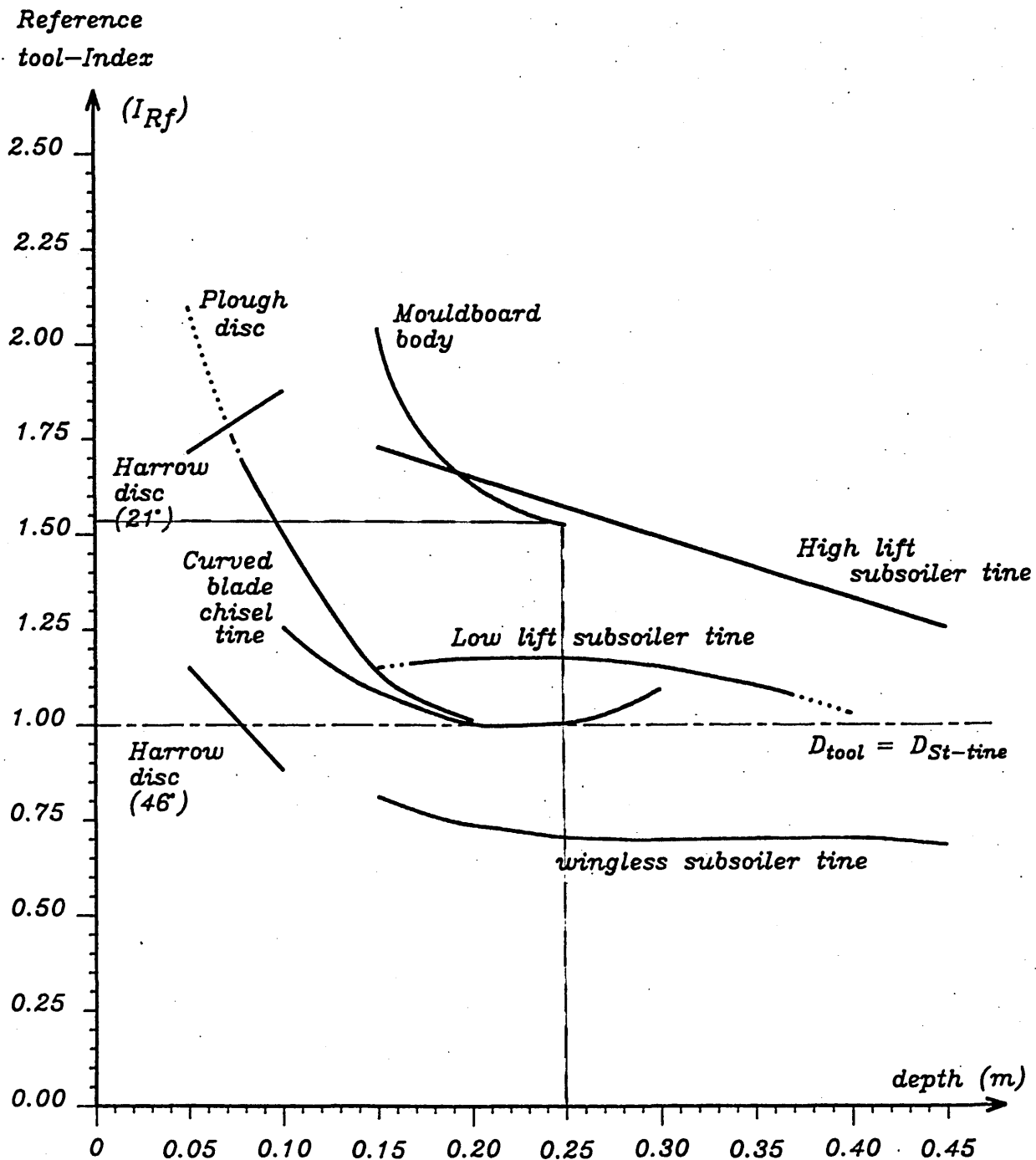


Fig. A7.1. Reference tool-Index curves (from Desbiolles, 1994)

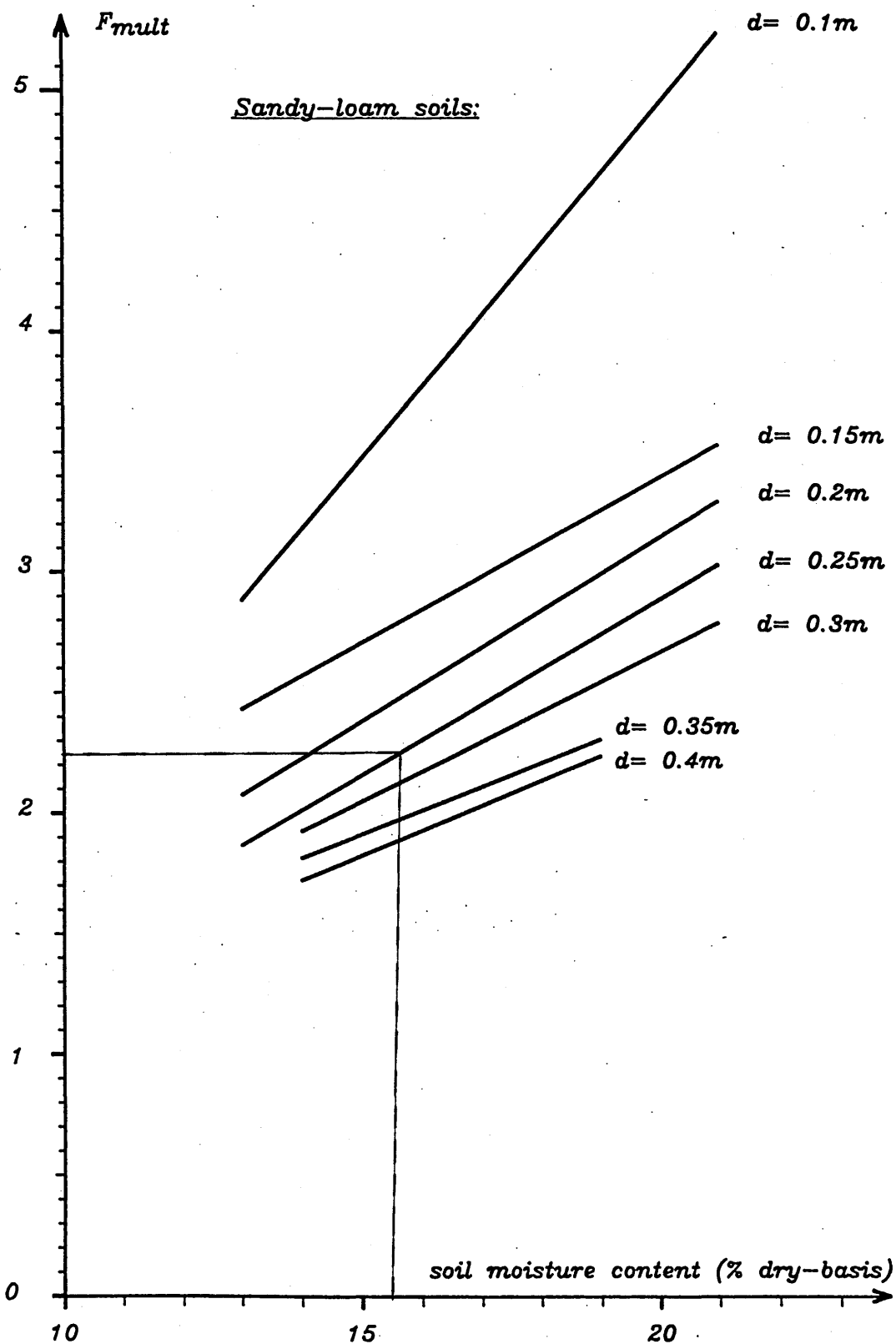


Fig. A7.2. Regression lines for F_{mult} in sandy-loam soils
(from Desbiolles, 1994)

APPENDIX 8: ENGINEERING DRAWING

- 1. List of parts**
- 2. Engineering drawing sheets**

PART NO.	NAME OF PART	MATERIAL	SIZE	NO. OFF ONE ASS.	NO. OFF TOTAL ASS.	NOTE
4	M48 NUT			6	12	
5	LINK PIN	EN 24 T	225 × 60Ø	6	12	
6	BUSH	NYLATRON	28 × 60Ø	12	24	
7	M27 NUT			6	12	
8	WASHER	BRIGHT M/S	3 × 60Ø	6	12	
9	LINK	AL HE 30	160×60×54	3	6	
12.1	JIG BASE	MILD STEEL	10×65×20	1	1	
12.2	JIG BASE	MILD STEEL	240×10×100	1	1	
13	GAUGE GUIDE BLOCK	AL	120×25×28	1	1	
14	CLAMP	MILD STEEL	110×15×20	1	1	
15	PIN	SILVER STEEL	40× 8Ø	5	5	
16	GAUGE COVER PLATE	AL	46×60×8	2	12	
17	M8 THREADED ROD		110 LONG	1	1	
18	M8 WING NUT			1	1	
19	M3 C' SUNK SCREW		65 LONG	1	6	
20	M3 NYLOC NUT			1	6	

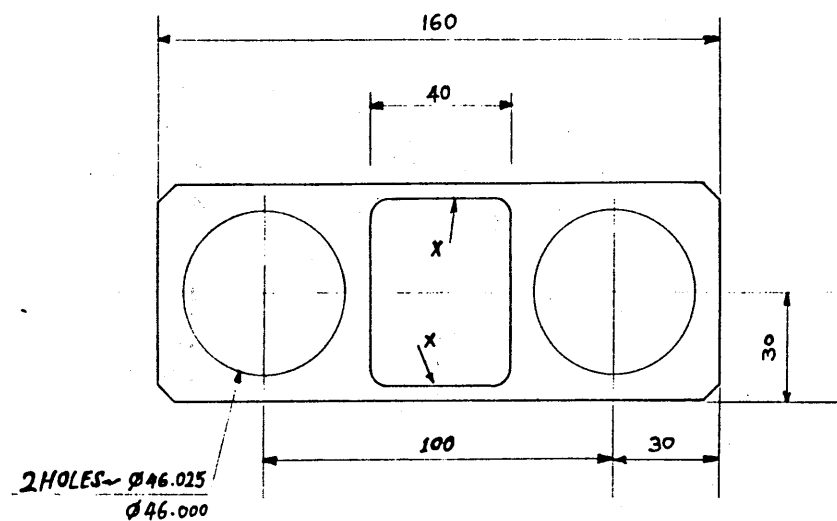
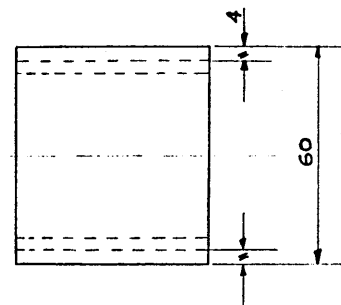
PROJECT NAME :			TRACTOR WHEEL TORQUE\WEIGHT TRANSDUCER SYSTEM		
DRAWN	APPD	CHKD	DEPT. OF AGRI. & ENVI. ENGINEERING		
AL-HASHEM	J. KILJOUR	J. KILJOUR	SILSOE COLLEGE		
DATE	DATE	DATE	CRANFIELD UNIVERSITY		
			SHEET 1 OF 5		

PART NO.	NAME OF PART	MATERIAL	SIZE	NO. OFF ONE ASS.	NO. OFF TOTAL ASS.	NOTE
21.1	INNER PLATE REAR	PLOUGH GROUND M/S	720ø x10	1	1	SEE DRGS.
21.2	REINFORCING PLATE	MILD STEEL	90x90x8	3	6	
22.1	OUTER PLATE REAR	PLOUGH GROUND M/S	851ø x10	1	1	SEE DRGS.
24.1	INNER PLATE FRONT	PLOUGH GROUND M/S	646ø x10	1	1	SEE DRGS.
24.2	REINFORCING PLATE	MILD STEEL	90x80x8	3	6	
24.3	INNER PLATE FRONT	MILD STEEL	55 x10 THICK	1	1	
24.4	INNER PLATE FRONT	PLOUGH GROUND M/S	646ø x10	1	1	
24.5	INNER PLATE FRONT	PLOUGH GROUND M/S	626ø x10	1	1	RING MAKE FROM (1338.3) ROLLED UP FLAT STRIP M/S
25.1	OUTER PLATE FRONT	PLOUGH GROUND M/S	646ø x10	1	1	
27	WASHER	BRIGHT M/S	3x70ø	6	12	
DRAWN <i>H.A.</i> AL-HASHEM 2.8.94 DATE			APPD <i>JK</i> J. KILJOUR 2.8.94 DATE	CHKD <i>JK</i> J. KILJOUR 2.8.94 DATE	PROJECT NAME : TRACTOR WHEEL TORQUE\WEIGHT TRANSDUCER SYSTEM	

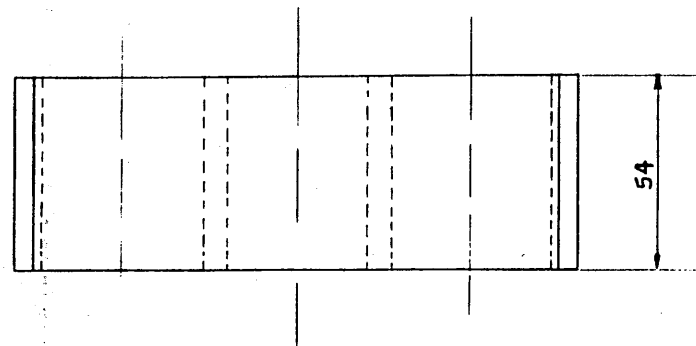
PART NO.	NAME OF PART	MATERIAL	SIZE	NO. OFF ONE ASS.	NO. OFF TOTAL ASS.	NOTE
32	FRONT WHEEL BRACKET	MILD STEEL	115x105x8	1	2	
33.1	FRONT FIXED DISC	BRIGHT M/S	415Ø x3	1	1	
33.2	FRONT FIXED DISC JOINT	MILD STEEL	50x55x5	2	2	
34.1	REAR WHEEL BRACKET	MILD STEEL	70x50x8	1	1	
34.2	REAR WHEEL BRACKET	MILD STEEL	220x160x8	1	1	
35	REAR FIXED DISC	BRIGHT M/S	400Ø x3	1	1	
37.1	BUSH	NYLATRON	37x50Ø	2	4	
37.2.1	BEARING HOUSING	MILD STEEL	70x50Ø	1	2	
37.2.2	RING	MILD STEEL	1.5x85Ø	1	2	
37.3	5TH WHEEL ARM	MILD STEEL	420x33.7Ø	1	2	
37.4	FORK	MILD STEEL	25x5 THICK	1	2	
38.1.1	5TH WHEEL AXLE	METAL PIPE	360x33.7Ø	1	2	WATER PIPE 3.25 MM WALL THICK
38.1.2	RING	MILD STEEL	5x50Ø	1	2	
DRAWN H.A. AL-HASHEM	APPD JK J. KILJOUR 17.3.95 DATE	CHKD JK J. KILJOUR 17.3.95 DATE	PROJECT NAME : TRACTOR WHEEL TORQUEWEIGHT TRANSDUCER SYSTEM			
16.3.95 DATE	DEPT. OF AGRI. & ENVI. ENGINEERING SILSOE COLLEGE CRANFIELD UNIVERSITY					SHEET 3 OF 5

PART NO.	NAME OF PART	MATERIAL	SIZE	NO. OFF ONE ASS.	NO. OFF TOTAL ASS.	NOTE
38.2	MOUNTING PLATE	MILD STEEL	217×50×6	1	2	
38.3	STEADY PLATE	MILD STEEL	200×60×6	1	2	
38.4	SUPPORT PLATE	MILD STEEL	400×50×6	1	2	
39	RING	MILD STEEL	1.5×85ø	1	2	
40	CASING	MILD STEEL	82×1.5 THICK	1	2	
41	RING	MILD STEEL	10×50ø	1	2	
42	RING	MILD STEEL	10×27.2ø	1	2	
43	BAR	MILD STEEL	80×15ø	1	2	
44	SPACER	MILD STEEL	20×160ø	1	2	
45	5TH WHEEL DISC	MILD STEEL	20×6ø	2	4	
46	SENSOR HOLDER	MILD STEEL	80×25×6	1	2	
DRAWN H.A. AL-HASHEM 16.3.95 DATE			APPD JK J. KILJOUR 17.3.95 DATE		CHKD JK J. KILJOUR 17.3.95 DATE	
DEPT. OF AGRIL. & ENVI. ENGINEERING SILSOE COLLEGE CRANFIELD UNIVERSITY			PROJECT NAME : TRACTOR WHEEL TORQUEWEIGHT TRANSDUCER SYSTEM			
SHEET 4 OF 5						

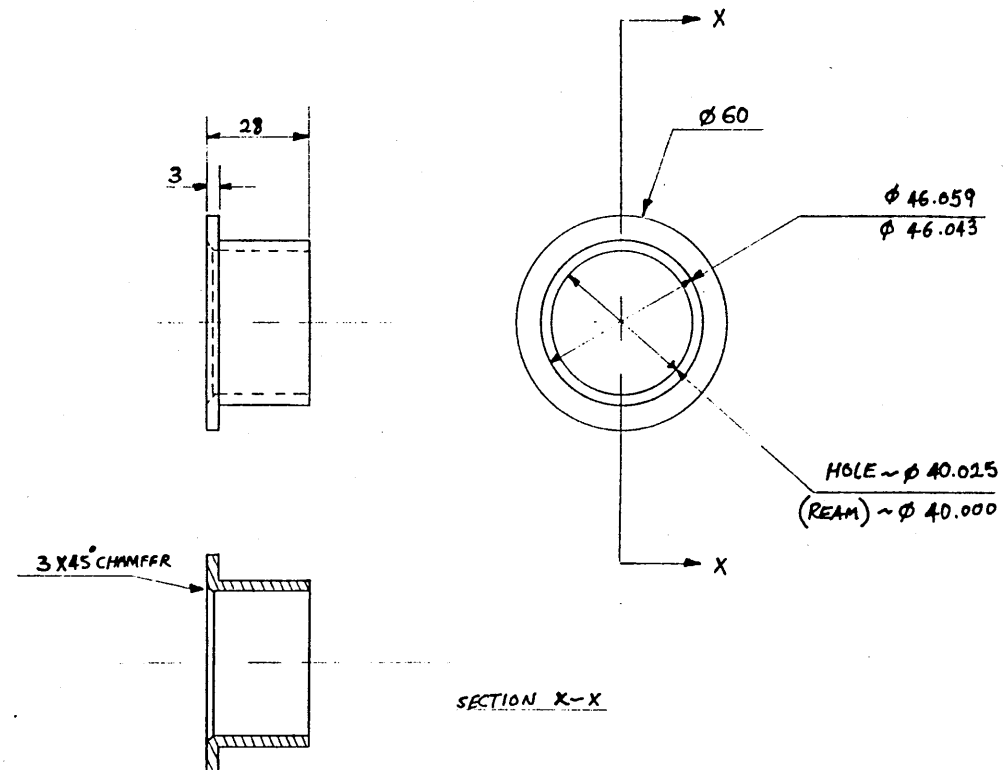
PART NO.	NAME OF PART	MATERIAL	SIZE	NO. OFF ONE ASS.	NO. OFF TOTAL ASS.	NOTE
48	ADAPTER DISC	MILD STEEL	10x448ø	1	2	
49	ROUND BAR	MILD STEEL	880x20ø	4	8	
50	SQUARE BAR	MILD STEEL	150x165x8	8	16	
51	SQUARE BAR	MILD STEEL	50x500x6	2	4	
52	FRONT HEAD FRAME	MILD STEEL	200x150x12	2	2	
			62x150x12	2	2	
			648x150x12	2	2	
			606x150x12	1	1	
53	SET SCREWS		20 LONG	8	8	
DRAWN H.A. AL-HASHEM 21.6.95 DATE	APPD J.K J. KILJOUR 21.6.95 DATE	CHKD J.K J. KILJOUR 21.6.95 DATE	PROJECT NAME : TRACTOR WHEEL TORQUE\WEIGHT TRANSDUCER SYSTEM			
DEPT. OF AGRI. & ENVI. ENGINEERING SILSOE COLLEGE CRANFIELD UNIVERSITY			SHEET 5 OF 5			



NOTE:
 • ALL CHAM. $5 \times 45^\circ$
 • ALL RAD. 5
 • X SMOOTH SURFACE FOR STRAIN GAUGES

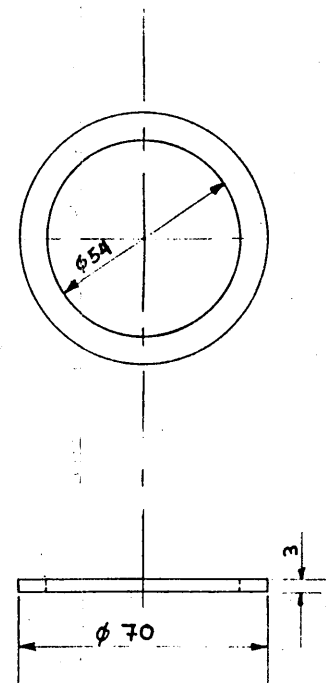


TITLE LINK	
MATL. SEE PARTS LIST	
SCALE 1:1	No. OFF 6
PART No. 9	

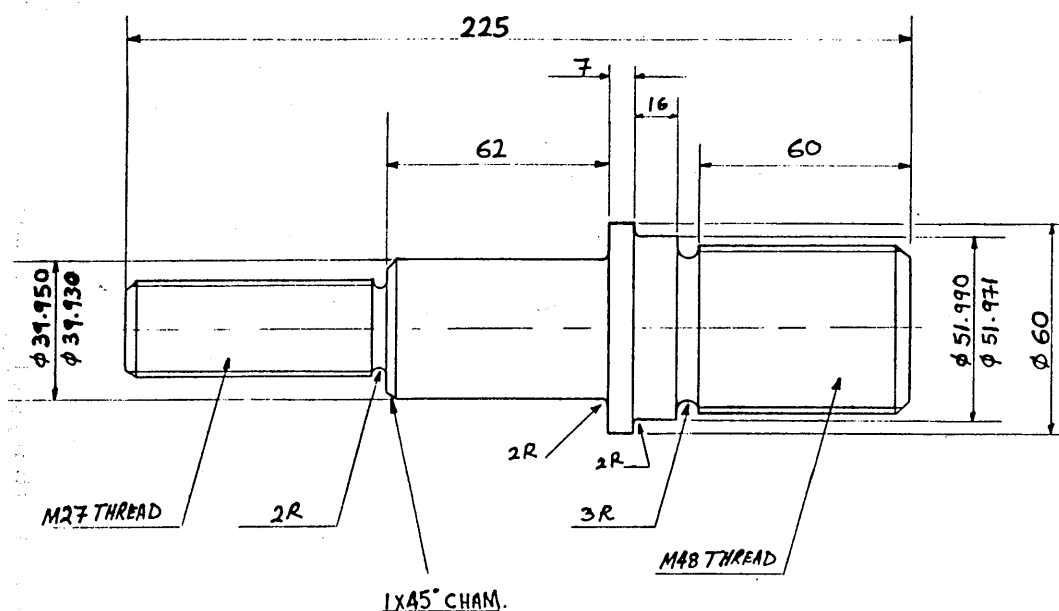


NOTE:
 MACHINE BUSHES IN LINK AFTER ASSEMBLY

TITLE BUSH	
MATL. SEE PARTS LIST	
SCALE 1:1	No. OFF 24
PART No. 6	

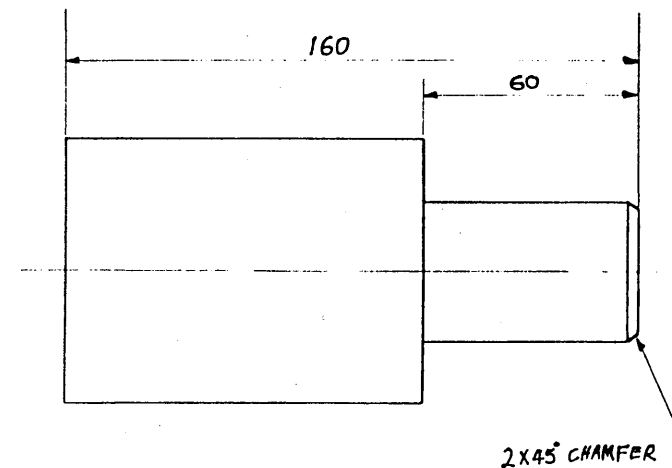
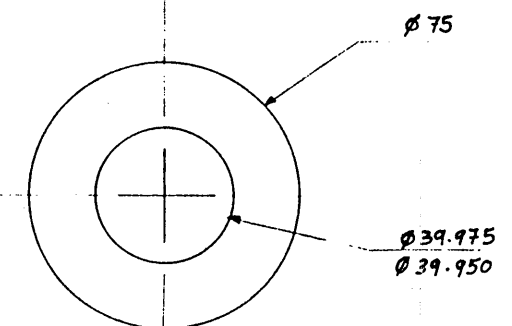


TITLE WASHER	
MATL. SEE PARTS LIST	
SCALE 1:1	No. OFF 12
PART No. 27	



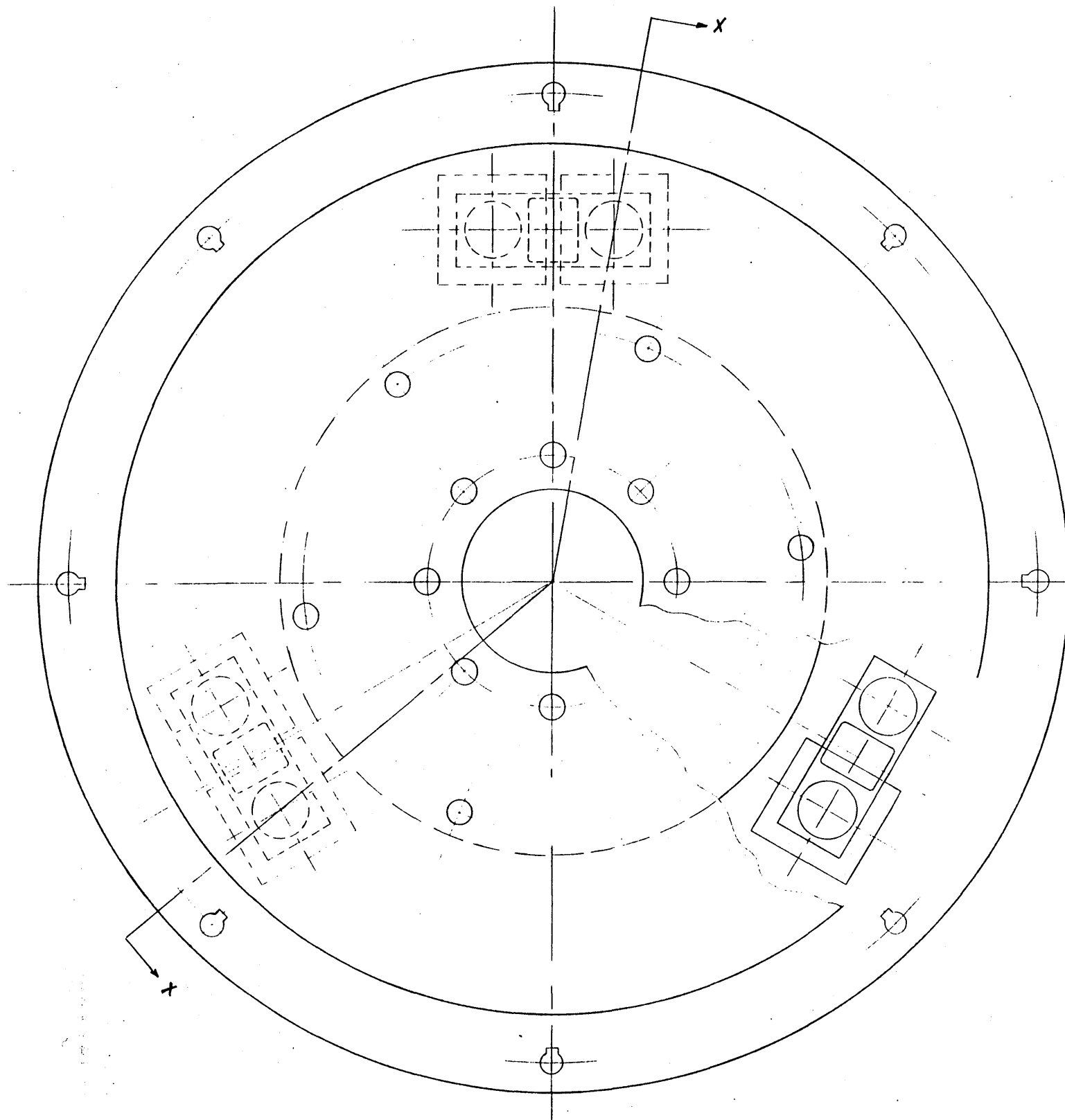
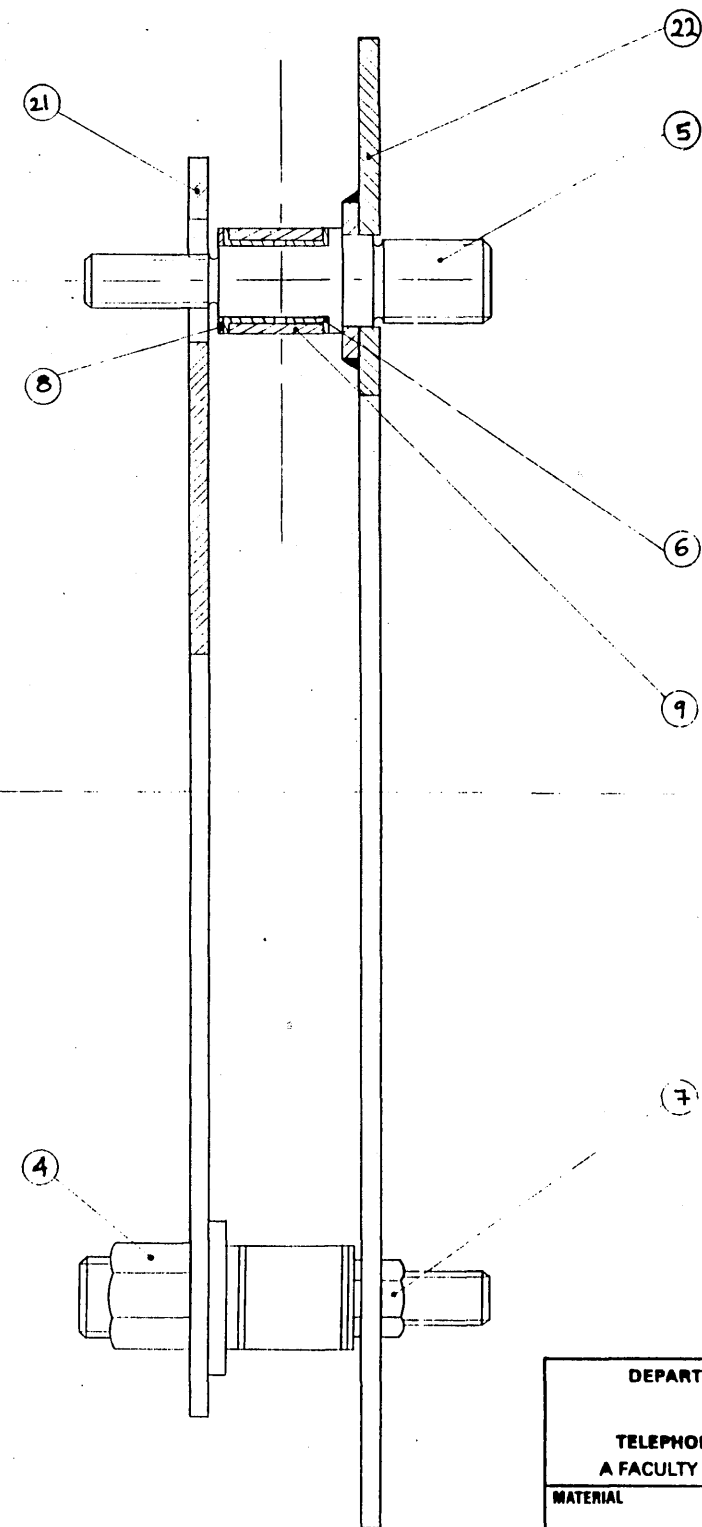
NOTE:
 ALL CHAM. $2 \times 45^\circ$ UNLESS OTHERWISE STATED.

TITLE LINK PIN	
MATL. SEE PARTS LIST	
SCALE 1:1	No. OFF 12
PART No. 5	



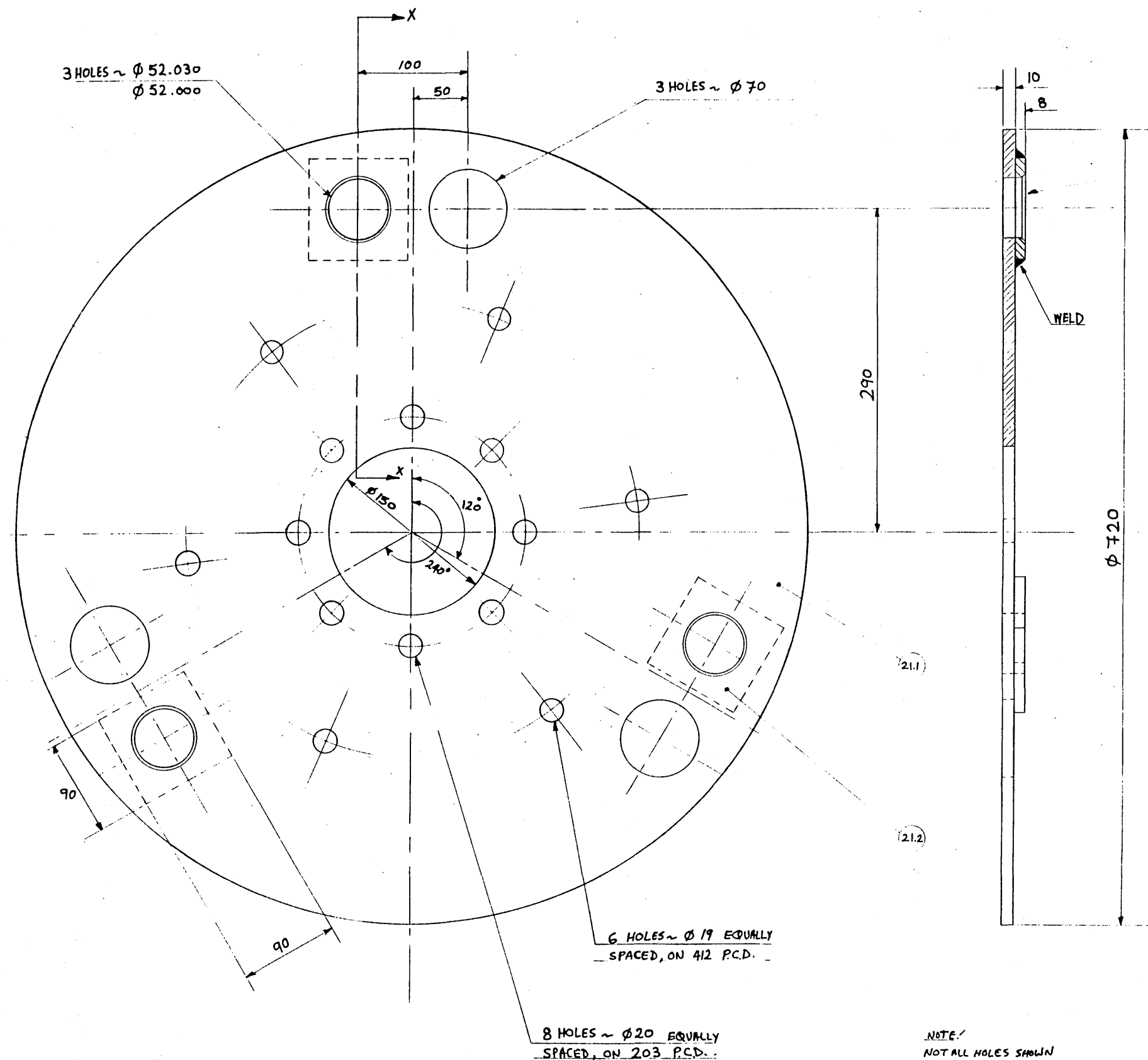
TITLE CALIBRATION BAR	
MATL. SEE PARTS LIST	
SCALE 1:1	No. OFF 1
PART No. 10	

DEPARTMENT OF ENGINEERING FOR AGRICULTURE SILSOE COLLEGE, SILSOE CAMPUS, SILSOE, BEDFORD. MK45 4DT TELEPHONE: 0525 80428 TELEX: 288871 FAX: 61627 A FACULTY OF THE CRANFIELD INSTITUTE OF TECHNOLOGY		
MATERIAL SEE PARTS LIST		
TOLERANCE		
FIRST THIRD ANGLE PROJECTION		SCALE SEE DRGS.
DRAWN BY H. ALHASHEM	CHECKED JK	APPROVED BY JK
DATE 20-4-94	DATE 28-7-94	DATE 28-7-94
PROJECT NAME WHEEL TORQUE/WIEGHT TRANSDUCER		
PART NAME LINK; LINK PIN; BUSH; CAL. BAR; WASHER		
PART NUMBER 9, 5, 6, 10, 27		
DRAWING NUMBER HA 603/1		
SHEET 2 OF 16		



SECTION X-X

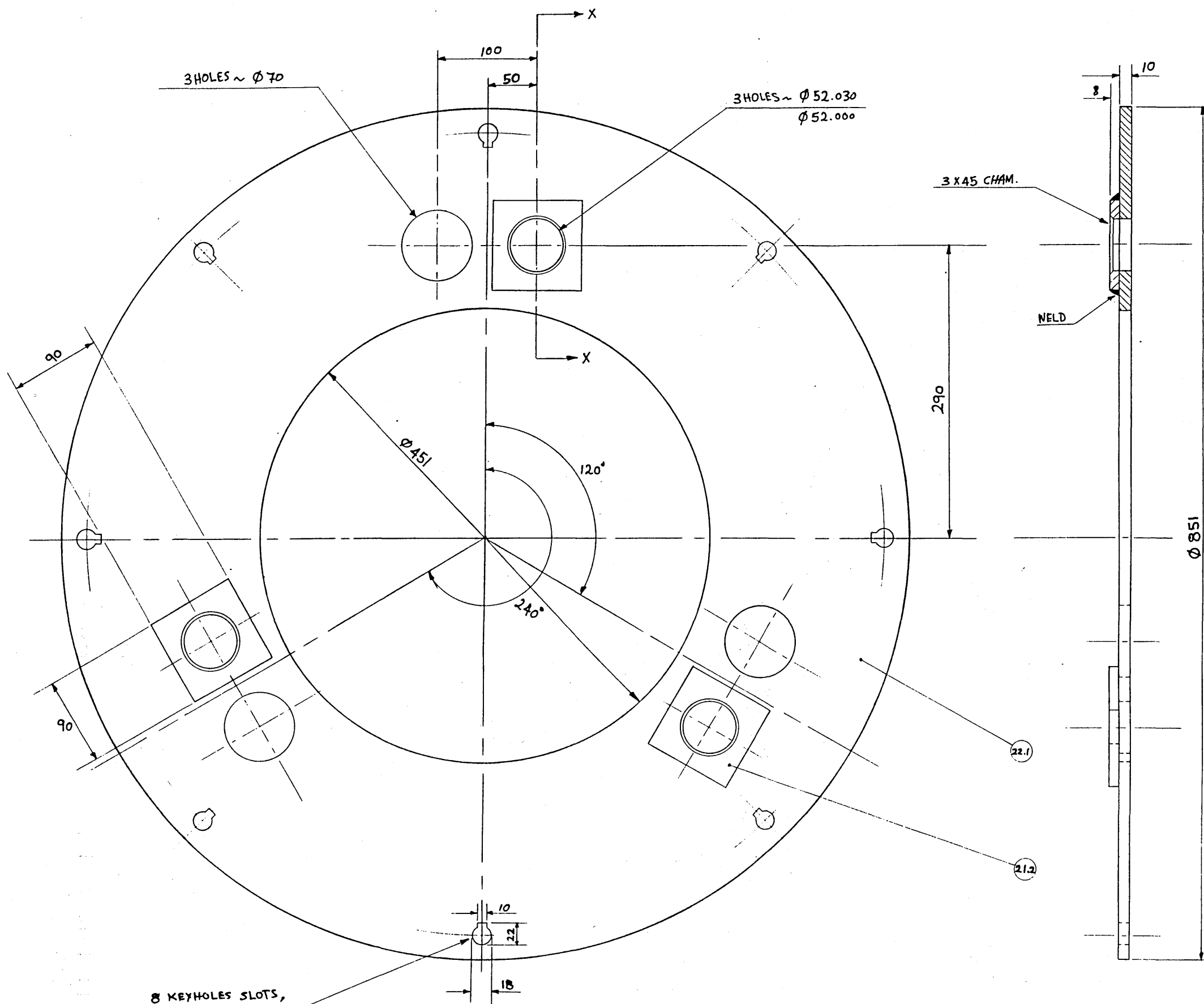
DEPARTMENT OF ENGINEERING FOR AGRICULTURE SILSOE COLLEGE, SILSOE CAMPUS, SILSOE, BEDFORD. MK45 4DT TELEPHONE: 0825 60428 TELEX: 266871 FAX: 01627 A FACULTY OF THE CRANFIELD INSTITUTE OF TECHNOLOGY			
MATERIAL		SEE PARTS LIST	
TOLERANCE			
FIRST THIRD ANGLE PROJECTION		SCALE 1:2	
DRAWN BY	CHECKED	APPROVED BY	
HASAN ALHASHEM	JK	JK	
DATE 27-7-94	DATE 28-7-94	DATE 28-7-94	
PROJECT NAME WHEEL TORQUE/WEIGHT TRANSDUCER			
PART NAME GENERAL ASSY: REAR WHEEL			No OFF
PART NUMBER 23			1
DRAWING NUMBER HA 603			SHEET 5 OF 16



NOTE:
NOT ALL HOLES SHOWN

ALL DIMS. IN MILLIMETERS

DEPARTMENT OF ENGINEERING FOR AGRICULTURE SILBOE COLLEGE, SILBOE CAMPUS, SILBOE, BEDFORD. MK46 4DT TELEPHONE: 0525 60428 TELEX: 266871 FAX: 61627 A FACULTY OF THE CRANFIELD INSTITUTE OF TECHNOLOGY			
MATERIAL		SEE PARTS LIST	
TOLERANCE			
FIRST THIRD ANGLE PROJECTION		SCALE 1:2	
DRAWN BY HASAN ALHASHEM	CHECKED JK	APPROVED BY JK	
DATE 27-7-94	DATE 28-7-94	DATE 28-7-94	
PROJECT NAME WHEEL TORQUE/WEIGHT TRANSDUCER			
PART NAME INNER PLATE: REAR WHEEL			No OFF 1
PART NUMBER 21			
DRAWING NUMBER HA 603			SHEET 6 OF 16



SECTION X-X

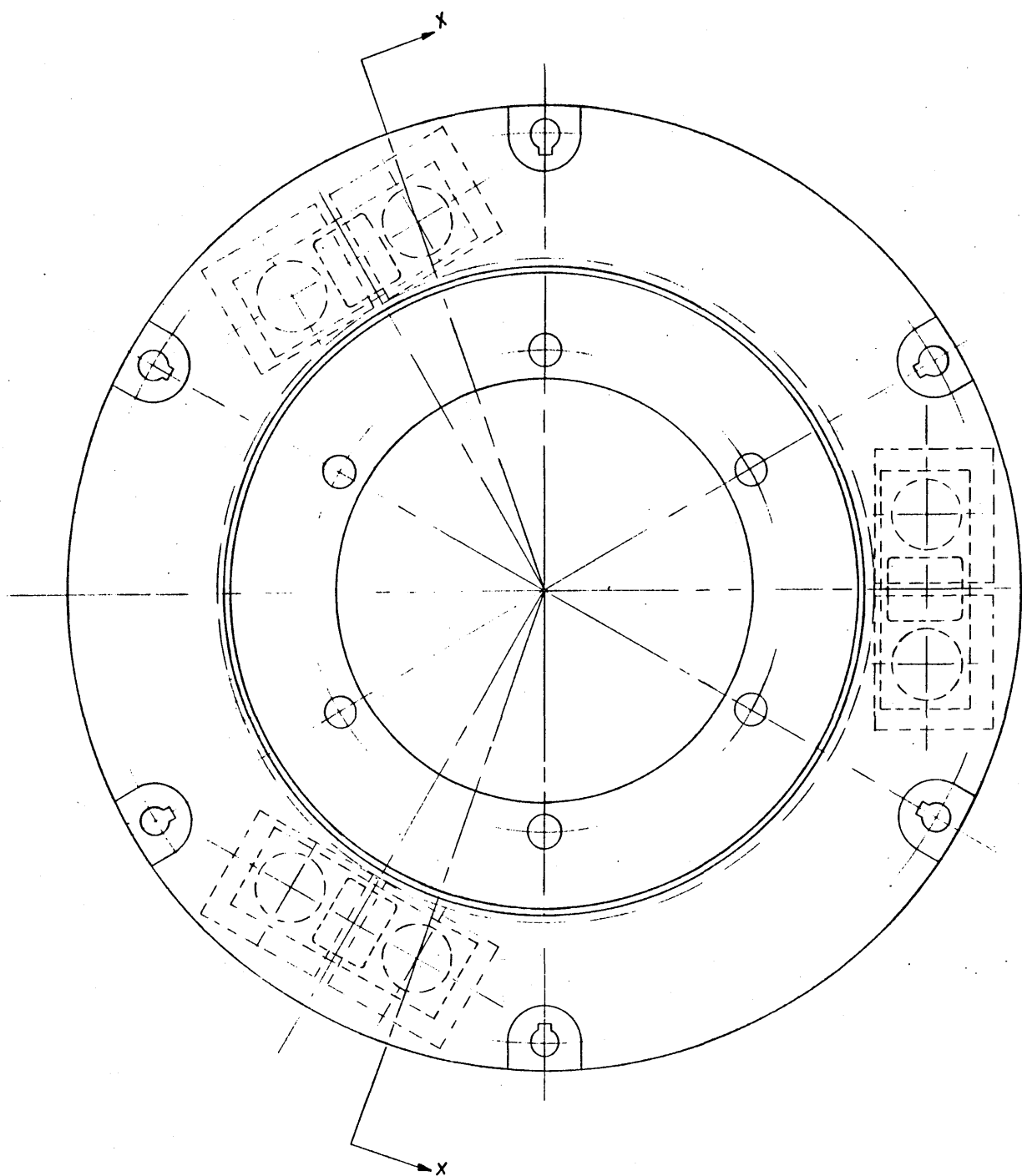
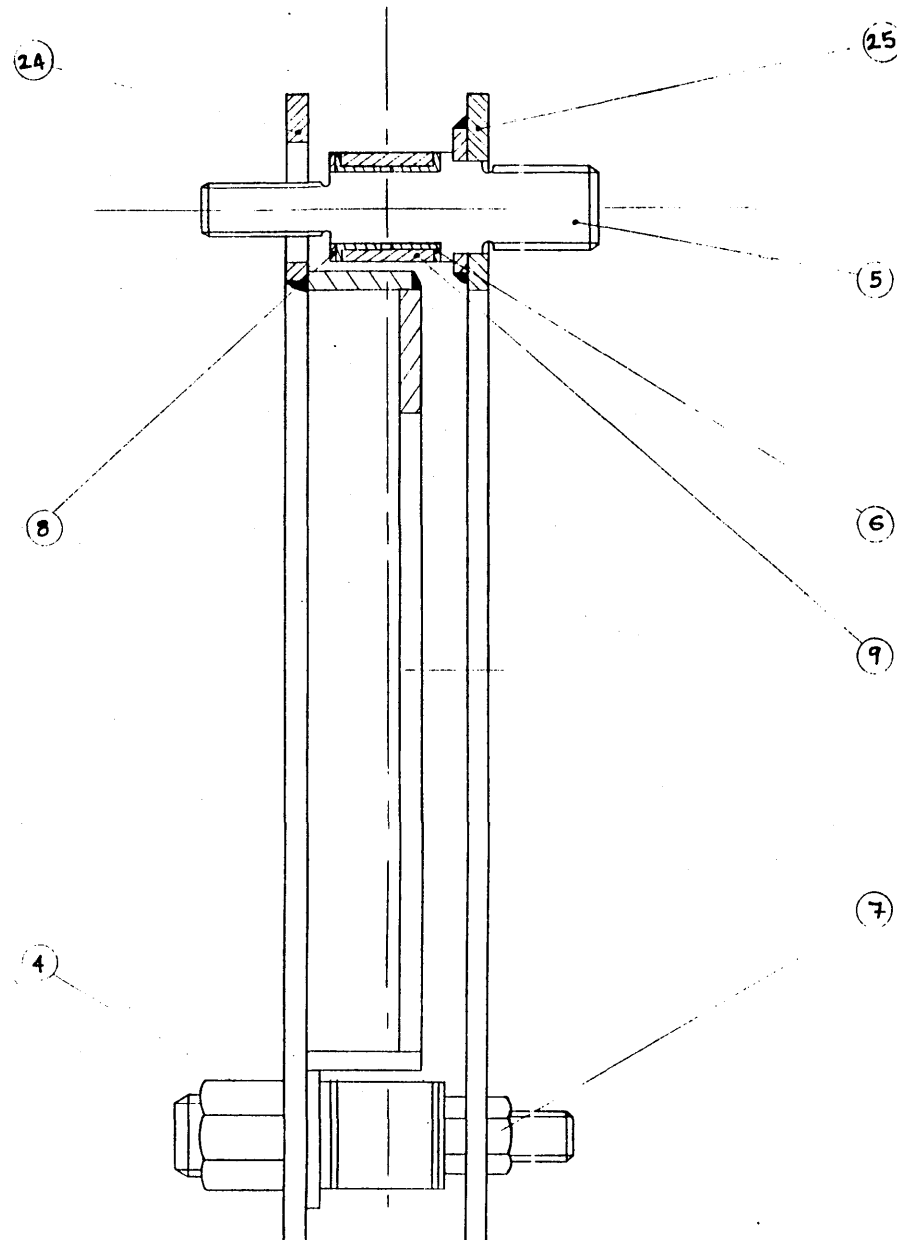
10MM THICK PLOUGH GROUND
MILD STEEL PLATE.

ALL DIMS. IN MILLIMETERS

DEPARTMENT OF ENGINEERING FOR AGRICULTURE SILBOE COLLEGE, SILBOE CAMPUS, SILBOE, BEDFORD. MK45 4DT TELEPHONE: 0525 60428 TELEX: 285871 FAX: 61627 A FACULTY OF THE CRANFIELD INSTITUTE OF TECHNOLOGY			
MATERIAL		SEE PARTS LIST	
TOLERANCE			
FIRST THIRD ANGLE PROJECTION		SCALE 1:2	
DRAWN BY HASAN ALHASHEM	CHECKED JK	APPROVED BY JR	
DATE 27-7-94	DATE 28-7-94	DATE 28-7-94	
PROJECT NAME WHEEL TORQUE/WEIGHT TRANSDUCER			
PART NAME OUTER PLATE: REAR WHEEL			No OFF
PART NUMBER 22			1
DRAWING NUMBER HA 603			SHEET 7 OF 18

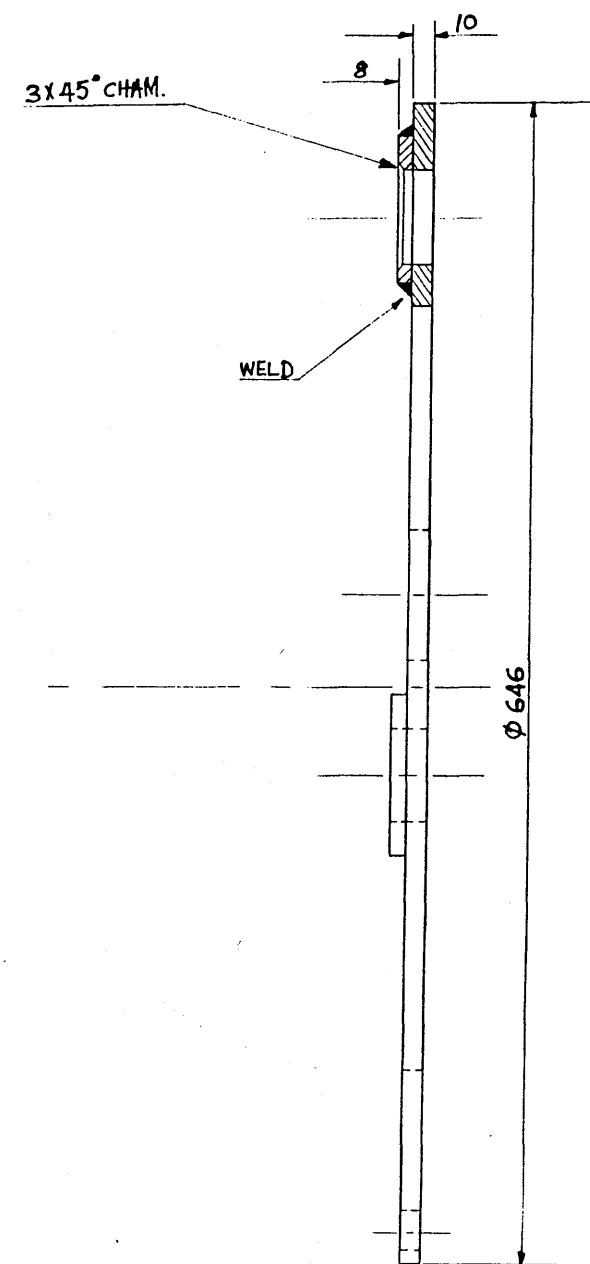
NOTE:
NOT ALL HOLES SHOWN.

8 KEYHOLES SLOTS,
EQUALLY SPACED, ON
800 P.C.D.



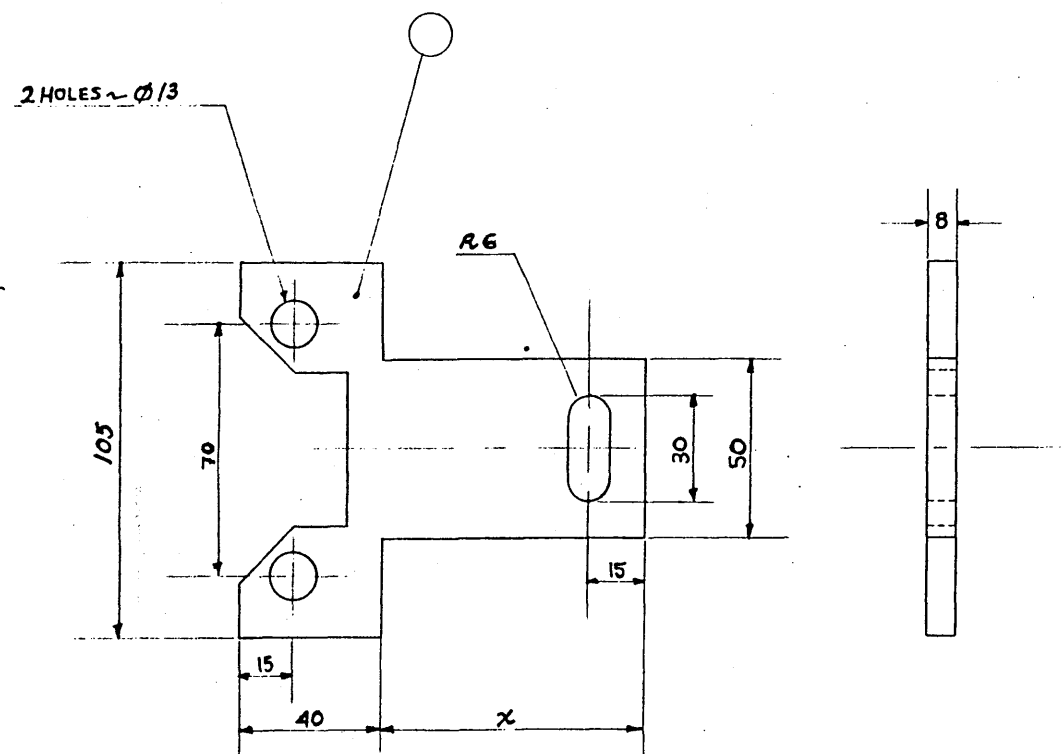
SECTION X-X

DEPARTMENT OF ENGINEERING FOR AGRICULTURE SILSOE COLLEGE, SILSOE CAMPUS, SILSOE, BEDFORD. MK45 4DT TELEPHONE: 0525 60428 TELEX: 265871 FAX: 61527 A FACULTY OF THE CRANFIELD INSTITUTE OF TECHNOLOGY			
MATERIAL		SEE PARTS LIST	
TOLERANCE			
FIRST THIRD ANGLE PROJECTION		SCALE	1:2
DRAWN BY	CHECKED	APPROVED BY	
HASAN ALHASHEN	JK	JK	
DATE 27-7-94	DATE 28-7-94	DATE 28-7-94	
PROJECT NAME WHEEL TORQUE/WEIGH TRANSDUCER			
PART NAME GENERAL ASSY: FRONT WHEEL			No OFF
PART NUMBER 26			1
DRAWING NUMBER HA 603			SHEET 8 OF 16



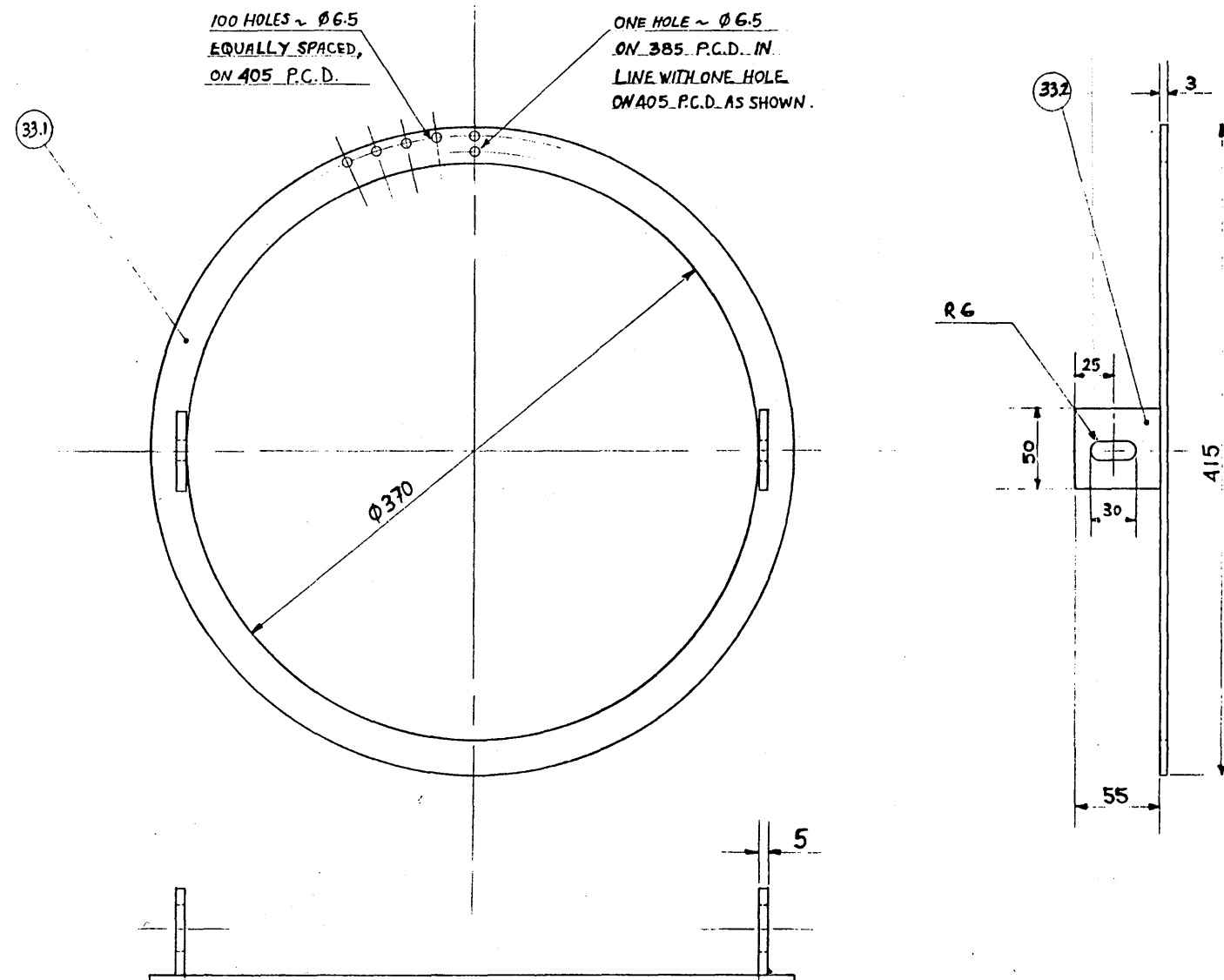
DEPARTMENT OF ENGINEERING FOR AGRICULTURE SILSOE COLLEGE, SILSOE CAMPUS, SILSOE, BEDFORD. MK45 4DT TELEPHONE: 0525 60428 TELEX: 265871 FAX: 01527 A FACULTY OF THE CRANFIELD INSTITUTE OF TECHNOLOGY			
MATERIAL		See PARTS LIST	
TOLERANCE			
FIRST THIRD ANGLE PROJECTION		SCALE	
DRAWN BY HASAN ALHASHEM DATE 27-7-94		CHECKED JK DATE 28.7.94	
		APPROVED BY JK DATE 28.7.94	
PROJECT NAME			
WHETORQUE /WEIGHT TRANSDUCER			
PART NAME		No OFF	
OUTER PLATE, FRONT WHEEL		1	
PART NUMBER			
25			
DRAWING NUMBER		SHEET 10... OF 16...	
HA 603			

NOTE/
NOT ALL HOLES SHOWN



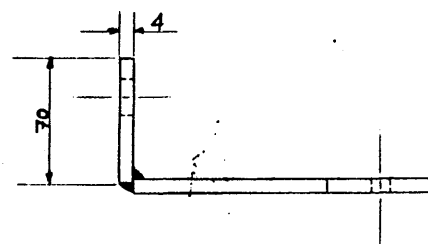
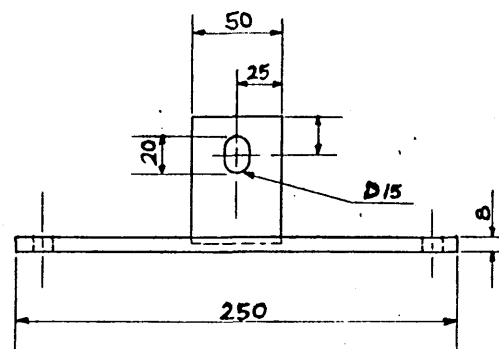
NOTE:
 X = 75 1 OFF
 X = 40 1 OFF

TITLE FRONT WHEEL BRACKET	
MATERIAL MILD STILL	
SCALE 1:1	No OFF 2
PART No 32	

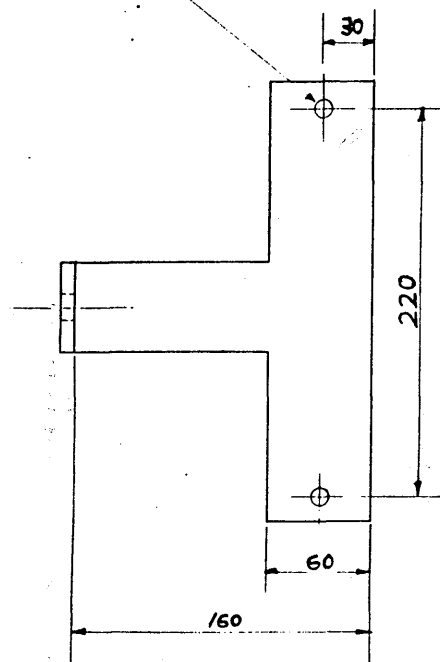


TITLE FRONT FIXED DISC	
MATERIAL BRIGHT MILD STILL	
SCALE 1:2	No OFF 1
PART No 33	

DEPARTMENT OF ENGINEERING FOR AGRICULTURE SILSOE COLLEGE, SILSOE CAMPUS, SILSOE, BEDFORD, MK45 4DT TELEPHONE: 0525 60428 TELEX: 265871 FAX: 61527 A FACULTY OF THE CRANFIELD INSTITUTE OF TECHNOLOGY			
MATERIAL		SEE PARTS LIST	
TOLERANCE			
FIRST THIRD ANGLE PROJECTION		SCALE	SEE DRGS
DRAWN BY HASAN ALHASHIM	CHECKED JK	APPROVED BY JK	
DATE 7.1.95	DATE 9.1.95	DATE 9.1.95	
PROJECT NAME WHEEL TORQUE/WEIGHT TRANSDUCER			
PART NAME FRONT WHEEL BRACKET ; FRONT FIXED DISC			No OFF
PART NUMBER 32 ; 33			
DRAWING NUMBER HA 603			SHEET 12 OF 16



2 HOLES ~ Ø10.5

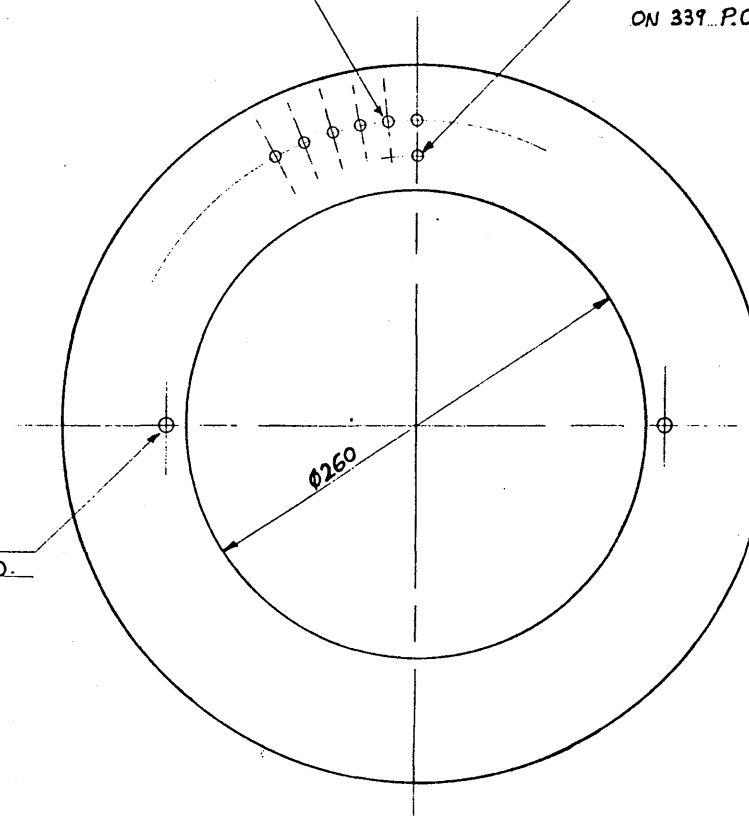


TITLE REAR WHEEL BRACKET
MATERIAL MILD STEEL
SCALE 1:2 No. OFF 1
PART No. 34

100 HOLES ~ Ø5.3
EQUALLY SPACED,
ON 339 P.C.D.

ONE HOLE ~ Ø5.3
ON 297 P.C.D. IN
LINE WITH ONE HOLE
ON 339 P.C.D.

2 HOLES ~ Ø8
ON 278 P.C.D.

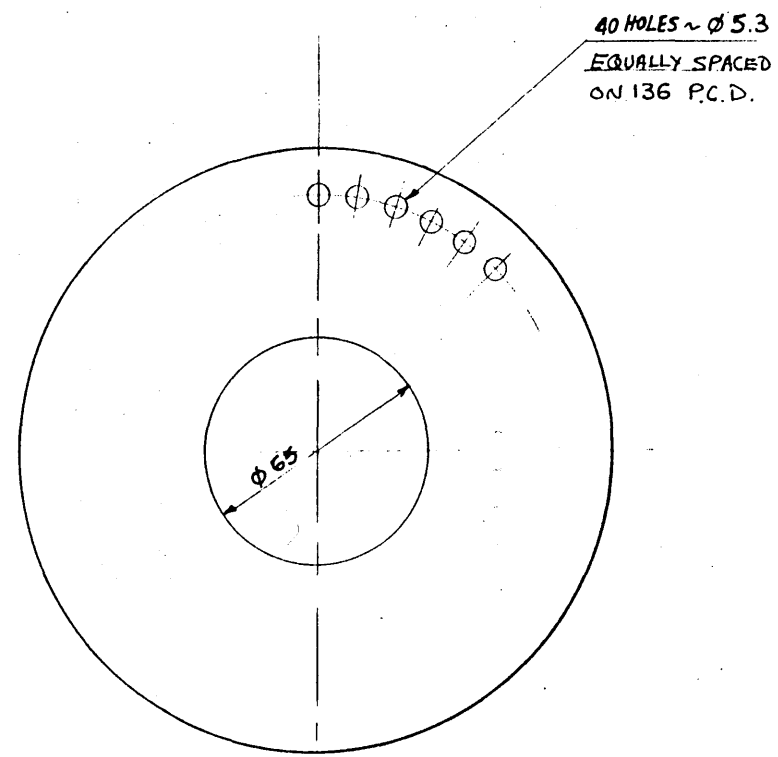
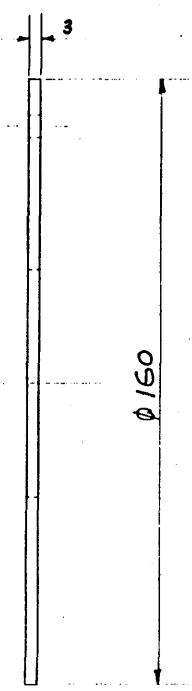


TITLE REAR FIXED DISC
MATERIAL BRIGHT MILD STEEL
SCALE 1:2 No. OFF 1
PART No. 35

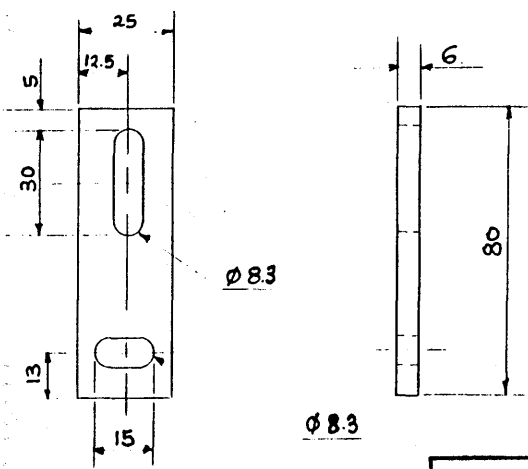
ALL DIMS. IN MILLIMETERS

DEPARTMENT OF ENGINEERING FOR AGRICULTURE SILSOE COLLEGE, SILSOE CAMPUS, SILSOE, BEDFORD. MK45 4DT TELEPHONE: 0525 60428 TELEX: 265871 FAX: 61627 A FACULTY OF THE CRANFIELD INSTITUTE OF TECHNOLOGY		
MATERIAL SEE PARTS LIST		
TOLERANCE		
FIRST THIRD ANGLE PROJECTION		SCALE SEE DRGS.
DRAWN BY HASAN ALHASHEM DATE 7.1.95	CHECKED JK DATE 9.1.95	APPROVED BY JK DATE 9.1.95
PROJECT NAME WHEEL TORQUE/WEIGHT TRANSDUCER		
PART NAME REAR WHEEL BRACKET, REAR FIXED DISC		
PART NUMBER 34, 35		
DRAWING NUMBER HA 603		SHEET 13 OF 16

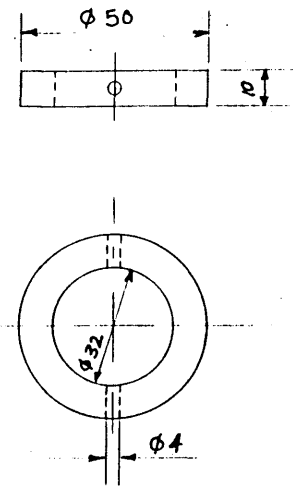
No.	MODIFICATION	APP. & DATE



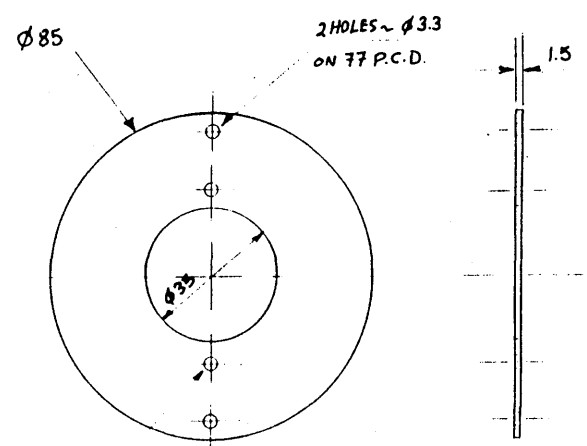
TITLE 5TH WHEEL DISC	
MATL. SEE PARTS LIST	
SCALE 1:1	No. OFF 2
PART No. 45	



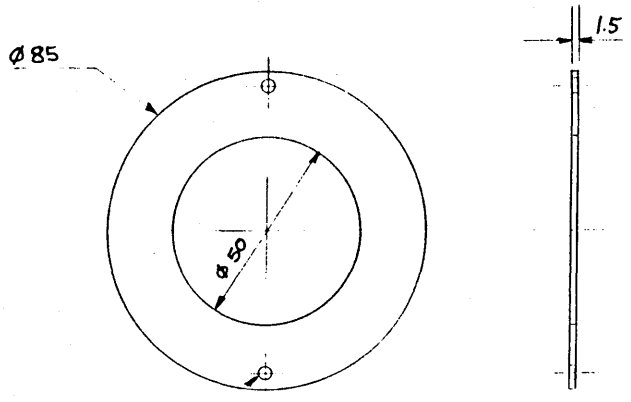
TITLE SENSOR HOLDER	
MATL. SEE PARTS LIST	
SCALE 1:1	No. OFF 2
PART No. 46	



TITLE RING	
MATL. SEE PARTS LIST	
SCALE 1:1	No. OFF 2
PART No. 41	

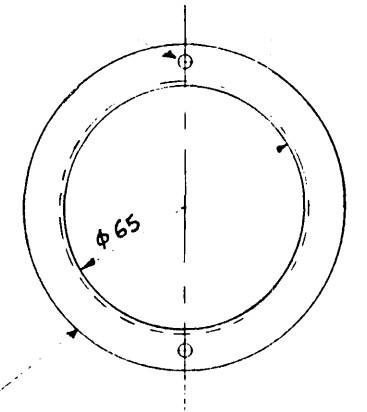
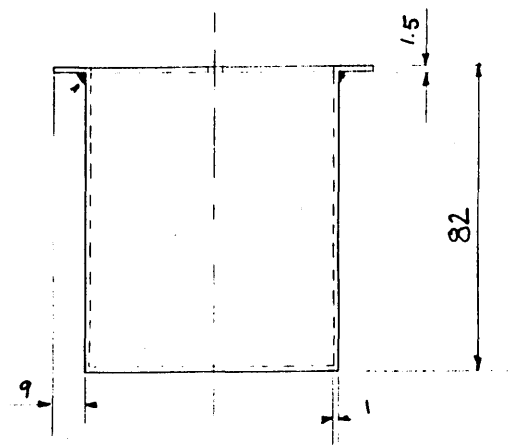


TITLE RING	
MATL. SEE PARTS LIST	
SCALE 1:1	No. OFF 2
PART No. 39	



TITLE RING	
MATL. SEE PARTS LIST	
SCALE 1:1	No. OFF 2
PART No. 37.2.2	

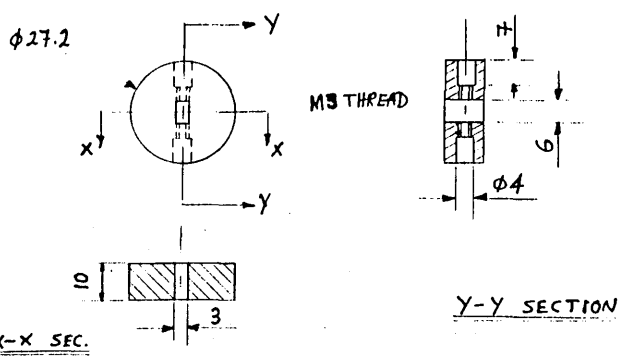
2 HOLES ~ $\phi 3.3$
ON 77 P.C.D.



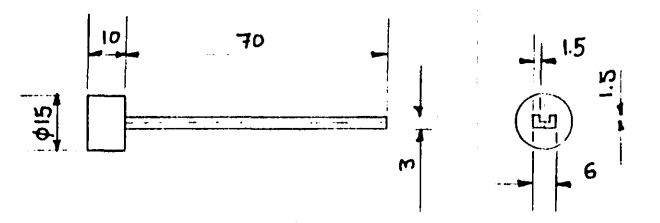
WELD

NOTE!
SEE PARTS LIST
FOR DETAILS.

TITLE CASING	
MATL. SEE PARTS LIST	
SCALE 1:1	No. OFF 2
PART No. 40	



TITLE RING	
MATL. SEE PARTS LIST	
SCALE 1:1	No. OFF 2
PART No. 42	



TITLE BAR	
MATL. SEE PARTS LIST	
SCALE 1:1	No. OFF 2
PART No. 43	