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Present State of Research on Development of a High Clearance Vehicle for Paddy Fields

[1]M.S. Abubakar, [1]D. Ahmad, [1]J. Othman, and [2]S. Sulaiman

[1]Department of Biological and Agricultural Engineering, Universiti Putra Malaysia
[2]Department of Mechanical and Manufacturing Engineering, Universiti Putra Malaysia

Abstract: The concepts of developing a high clearance vehicle for paddy field have been investigated. The vehicle can be used and maintained by small size farm for paddy fields. The in-field performance of the vehicle and vehicle's wheels in terms of static and dynamic masses distribution, mobility numbers, rolling resistance, wheel slippage and the gross traction force in relation to vehicle tractive efficiency are discussed. Factors that affect the vehicle performance in paddy field such as soil moisture content, ground pressure, power to weight ratio, wheel type, wheel diameter, wheel contact area, front or rear drive, axle load and the operation speed are also highlighted.

Key words: High clearance, vehicle, paddy field, mobility number, rolling resistance, tractive performance

INTRODUCTION

A paddy field is a flooded parcel of arable land used for growing rice and other semi aquatic crops and is one of the most important land resources in the world. Paddy fields are a typical feature of rice-growing countries of East, South and Southeast Asia, including Bangladesh, China, India, Indonesia, Japan, Korea, Malaysia, Myanmar, Nepal, Pakistan, the Philippines, Sri Lanka, Taiwan, Thailand, and Vietnam. In those countries where rice is the staple food, dry land farming techniques are not possible. This dictates that vehicles must work in soils which are not only very soft but also very wet. Because of their peculiar water regime, paddy soils possess physical, chemical and biological properties which differ substantially from those of upland soils [1,2,3,4,5]. The most characteristic management practice in paddy rice cultivation is water logging, or submergence of the land surface. Aggarwal, [5] found that the maximum power which a medium power (46 kW) four-wheel (two-wheel drive) tractor could deliver in a flooded field was only about 40% of that which it could deliver when the soil was in its strongest state. With the development of agricultural mechanization, high clearance vehicles have become more useful in many field operations including tillage, planting, harvesting, and transportations. Sufficient clearance is necessary between the frame and the ground in order to leave crops undisturbed as the vehicle is driven over rows so that the vehicle undercarriage does not become hung on brush, small earth ridges, tree stumps or the like. In marshy conditions, high clearance often permits a vehicle to drive through shallow water and mud without flooding the engine and soaking the driver [3,4,5]. A high-clearance agricultural vehicle in use wound comprise the main frame extending longitudinally from the front to the rear of the upper portion of the vehicle, a pair of rear drive wheels disposed on opposite sides and connected to the rear portion of the frame, a tank suspended from the frame to be disposed laterally between the rear wheels, a front wheel connected to the forward portion of the frame to be pivotally movable about a steering axis, an engine supported under the frame to be forwardly of the tank and behind the front wheel, and a transmission and axle assembly drivingly connecting the engine to the rear wheels. The main frame is defined by a pair of laterally spaced apart, longitudinally extending side members as the primary structural members [3,6].

However, investigation should begin with the less complex relationships such as the vehicle, terrain, load, vehicle/terrain interface, vehicle/load interface, and terrain/load interface, thus leading to the most generalized model representing vehicle/terrain/load interface [5,6,7,8,9,10,]. The moisture content of paddy field soil is usually very high and sometimes the farm vehicles must be operated on saturated or flooded surfaces where the trafficability of the surface soil layer is very poor and this soft soil seems to be one of the largest sources of difficulty of mechanization of cultivation in paddy fields in the main rice production area in the world, South East Asia [3,5]. In most developing and least developed countries that produce

Corresponding Author: M.S. Abubakar, Department of Biological and Agricultural Engineering, Universiti Putra Malaysia.
E-mail: abubakarms@gmail.com

rice, transport methods of paddy from the field to processing areas are mainly by means of human and animal power. In the lowland areas, mobility in paddy field can be partially mechanized, that is by means of development of high clearance vehicles. Mobility over soft terrain is of considerable interest. This paper will review some concepts of developing of a high clearance vehicle for paddy fields which will serve as a guide in the development of the a high clearance vehicle and determination of the vehicle's tractive efficiency.

2. Dynamic Behaviour of Wet Soil: A number of studies have been conducted to understand the dynamic behaviour of wet soil and to design and develop more efficient tillage implements and traction devices for wet land cultivation of rice. Traction problems in the saturated paddy soils have a major limitation to the adaptation of agricultural mechanization in rice producing Asian countries. Sinkage of agricultural machinery has been the topic of intensive research in the past and will continue to be in the future. The main problem in mechanizing paddy cultivation is the development of a suitable traction device for operation in the saturated soils. Soft soils with low trafficability have resulted in excessive sinkage of agricultural machinery. Considerable time and energy are lost in attempting to cultivate in soft soils. Because of the extra time necessary to remove sunken machinery from the fields. The drudgery involved, as well as the infeasibility of using agricultural machinery in soft marshy fields has led farmers to either under utilize or completely abandon the cultivation of paddy fields. Studies of dynamic properties of soil provide a method to systematically develop a characterization that will apply to the reaction of a soil applied forces and furnish a basis for machinery design. Resistance and strength properties characterize the reaction of the soil subjected to external forces. Shear strength, resistance to cone penetration, friction, adhesion, plastic flow and time dependent deformation represent the dynamic behaviour of the soil [8,9,10,11,12,13,14,15,16,17,18].

2.1 Shear Strength: Shear strength is defined as the maximum resistance offered by soil to shearing stresses. It is made up of two components: 1) internal friction due to inter-locking of particles and friction between individual particles at their contact points; and 2) cohesion due to inter-particle forces which tend to hold the particles together in a soil mass. An index of soil strength, called the cone index, is the force required to pass a 30° circular cone through the soil, expressed in pressure units (kPa) [12,13,14,15,16,17].

3. Traction on Wet Soil: The efficiency with which a tractor converts energy into pull is extremely poor when operating on wet soil. The top layer of wet soil has low shear strength so that sufficient thrust cannot be developed. Besides the slipperiness, stickiness and sinkage limit the available pull and forward speed of a tractor. In such situations the middle layer of the soil bears the traffic load of agricultural machinery. In wet fields, with a hard pan at considerable depth, the utility of agricultural machines is limited due to their bogging down in the soil. In agricultural operations, the effect of the vehicle on the soil is more important than the maximum traction that can be developed. A tractor that develops the desired pull at high efficiency may not be useful if it makes ruts in the soil so severe that subsequent cultural operations are adversely affected. Kokubun [19], Kisu [20], Ayub [21] and Kobuta [22] related machine trafficability of wet soil with cone penetrometers. In Japan, Kokubun [19] and Kisu [20] stated that a power tiller could possibly work on areas having a cone index between 196 and 284 kPa at 20 cm depth. Four wheel tractors and semi-crawler combine harvesters could possibly work on areas having a cone index value of 284-490 kPa at 20 cm depth.

4. Tractive Performance: Traction is a force derived from the interaction between a traction device (wheel or track) and the soil in order to facilitate motion. The magnitude and the nature of the force depend to a large extent on characteristics of both soil and the tractive device. The tractive efficiency of the tractor depends on the nature soil surface, contact area of the tyre or track and the wheel weight [16,17,18,19,23,24]. Bukhari *et al* [25] reported that the coefficient of traction is used for evaluation of the tractor tractive performance as affected by soil type and physical conditions, moisture content and soil distribution pressure. The coefficient of traction is relatively higher in hard soil than sandy soils. It increases with soil moisture content [20,21,26,]. Mohammed and Clough [27] concluded that to improve the tractive performance of a tractor is to reduce power losses at the soil-wheel interaction. The tractor tractive performance may be evaluated by means of a pull-slip test. The tractor must ensure small slip but large tractive force to be efficiently utilized through implement draught [23,24,25,27,28,29,30]. Shebi *et al* [31] indicated that the drawbar pull increases with the increase of static load, area of contact between the rear wheel and the soil and also with the tractor speed. However the maximum tractive efforts by tractor wheels can occur when Coulomb's equation for shear strength is satisfied [27,30,32]. Okella *et al* [33] reported modified equation for maximum tractive force as follows:

$$F_{max} = AC + W \tan Ø \quad (1)$$

Where:
Fmax = maximum tractive force (kN)
A = area of ground contact (m^2)
C = soil cohesion force (kN/m^2)
W = applied load on the wheels (kN)
Ø = angle of shearing resistance (°)

The total tractive force can be predicted by integrating the tangential stresses along the tyre soil contact area. Bekker [23] however generalized earlier equation into a single form applicable to homogeneous soil of any type.

4.1 Tractive Performance Evaluation: Performance evaluation of attraction device first needs establishment of fundamental criteria. Certain basic measurements of pull, rate of angular rotation, forward speed, load and slip are required. Tractive performance of a tractor on soft paddy soil is affected by its fundamental specifications such as front and rear axle load ratio, total tractor weight and tyre size. The drawbar pull is large when the front axle weight is less and the ratio of front axle load to rear axle load is small as the travelling resistance of the front wheel is small and the thrust of the rear wheel is large [28,29,30.31,32,33]. Thus the front axle load should be as small as possible provided that steering stability is not. The softer, wetter and more slippery the ground the smaller the traction coefficient will be and greater the coefficient of rolling resistance. Lighter tractors perform better on soft soils because the driving force increases proportionally with the driving axle load but travelling resistance increases exponentially with tractor weight especially on soft wet soil. Consequently, drawbar pull is less when the tractor is heavy. Application of a drawbar load improves the performance of lighter tractors on wet soil because it increases the driving axle load by the effect of weight transfer [29,30,31,32,33,34,35,36,37].

Dwyer [37] in his study on the tractive performance of a wide-low pressure tyre compared with conventional tractor drive tyres used the following parameter and definitions:

$$\text{Coefficient of traction} = \frac{Tractiveforce}{Verticalload} \quad (2)$$

$$\text{Coefficient of rolling resistance} = \frac{Rollingresistance}{Verticalload} \quad (3)$$

$$\text{Coefficient of traction} = \frac{Drawbarpoweroutput}{Axlepowerinput} \quad (4)$$

Baloh *et al* [29] reported that according to Elwaleed *et al,* net traction is one of the pertinent measures of tyre tractive performance. An adequate knowledge and understanding of the basic principle of the tyre traction is essential to help managers and engineers for the proper designing of new machinery and the appropriate matching and selection of the tractor-implement system. Many research studies reported that about 20-55% of the energy developed to the drive tractor wheels is wasted in the tyre-soil interaction [29,34,37].

4.2 Factors Affecting Tractive Performance:

4.2.1 Mobility Number: Mobility number is used to predict the combined effect of soil-wheel parameters on the tractive performance. Godbole *et al* [34] reported that Freitag had developed two dimensionless ratios defined as mobility numbers to be used in the prediction of the tractive performance of pneumatic tyres on sand and clay soils as shown in the equations below;
For cohesive soils

$$N_C = \frac{CIbd}{W}\left(\frac{\delta}{h}\right)^{1/2} \quad (5)$$

For frictional soils:

$$N_S = \frac{G(bd)^{3/2}}{W}\left(\frac{\delta}{h}\right) \quad (6)$$

Where N_c, N_s, CI, b, d, δ, h, G, W
According to Brixius [38] mobility of wheeled vehicles on the wet land is influenced by the design of the wheel however the front and rear mobility numbers of a wheeled vehicle in paddy field (soft soil) are given by:

$$BNF_T = \left[\frac{2xDxC_n}{1+1.5\left(1x\dfrac{SWF_T}{URF_T}\right)}\right] \quad (7)$$

$$BNR_T = \left[\frac{2xDxC_n}{1+1.5\left(1x\dfrac{SWR_T}{URR_T}\right)}\right] \quad (8)$$

where:

BNF_T = front tyre mobility number, dimensionless
BNR_T = rear tyre mobility number, dimensionless
SWF_T = front tyre section width, cm
URF_T = front tyre static unloaded radius, cm
SWR_T = rear tyre section width, cm
URR_T = rear tyre static unloaded radius, cm
D = wheel configuration constant, dimensionless
C_n = wheel numeric, dimensionless

4.2.2 Weight Distribution and Stability: The location of the centre of gravity determines the weight distribution on the wheels, the distance ahead of the rear axle determines weight distribution under normal operations. Rear wheel drive tractors usually have 55-88% of the weight on the rear wheels. Front end weight on a two wheel drive tractor does not contribute directly to traction performance but provides a source for weight transfer to the rear wheels as the tractor pulls and is necessary for steering. Excessive front weight would decrease both the tyre efficiency and dynamic ratio (coefficient of traction) obtained from the tractor tyres. The rear tractor weight improves tractive performance [24,27,34,37].

According to Makela *et al* [39] the factors which cause transfer from the front axle to the rear axle of agricultural vehicle are the torque of the front and rear wheels, the distance between the front and rear axle and the angle of inclination. Weight transfer appears to be a fairly reliable measure of vehicle mobility because it varies with the motion resistance coefficient [35,36,37,40,41].

According to Liljedahl *et al* [42] the static mass distribution and dynamic mass distributions of both front and rear axles are given by the equations below;

$$DFA_M = SFA_M - WTF \tag{9}$$

$$DRA_M = SRA_M - WTR \tag{10}$$

$$DFW_M = DFA_M/A \tag{11}$$

$$DRW_M = DRA_M/B \tag{12}$$

Where;

DFA_M = dynamic front axle mass, kg
DRA_M = dynamic rear axle mass, kg
WTF = weight transfer from front axle, kg
WTR = weight transfer from rear axle, kg
DFA_M = dynamic front wheel mass, kg
DRA_M = dynamic rear wheel mass, kg
SFA_M = static front axle mass, kg
SRA_M = static rear axle mass, kg
A = number of wheels at front axle, dimensionless
B = number of wheels at rear axle, dimensionless

4.2.3 Rolling Resistance: Rolling resistance refers to the resistance to motion of a wheel caused by the absorption of energy in the contacting surfaces of the wheel and the soil upon which the wheel rolls.

Rolling resistance is directly proportional to the front and rear dynamic masses and inversely proportional to the mobility numbers. Gee-Clough [43] reported that measurements of the rolling resistance of rigid wheels on soft ground were made by German agricultural engineers as far back as 1907, and later by Voelter in 1927 and by Meyer in 1934. Gee-Clough [43] also reported that rolling resistance decreases rapidly with increase in wheel diameter. Decrease in rim width increases the rolling resistance progressively and this is particularly so when the wheel penetrates into the ground. Bekker and Semonin [44] proposed that the motion resistance of a free rigid wheel can be expressed in terms of motion resistance components.

$$R = R_c + R_b + R_t, \tag{13}$$

where R is the total motion resistance force; R_c is the component of motion resistance due to vertical soil deformation or compaction; R_b is the component of motion resistance due to bulldozing effect or horizontal soil displacement effect; R_t is the component of motion resistance due to tyre deformation. For vehicle operating on a hard surface, R_t constitutes the largest percentage of the motion resistance force and can be slightly reduced by increasing the inflation pressure and the effective stiffness of the tyre. Bekker and Semonin [44] also considered that the shape of the tyre contact area should be oblong. McAllister [45] proposed that tyres should be wider in wetland conditions that in dryland conditions provided that bulldozing does not occur. Gee-Glough [43] reported that an increased tyre width does not solve all mobility problems on soft soil but increasing the diameter of a tyre is a better way of reducing motion resistance. In extremely soft soil, the top layer of soil begins to pile up at the front of the tyre, causing the so-called effect. The bulldozing effect occurs mostly in frictional soils and rarely in cohesive soils. In cohesive soils, when the tyre width increases, vertical displacement of the soil occurs on either side of the tyre track. This phenomenon seems to increase the motion resistance [40,41,43]. The tyre stiffness and inflation pressure have a significant effect on the motion resistance [41,43,46,47,48,49,50,51,52,53,].

Plackett [18] proposed that the relationship between tyre stiffness, soil strength, and sinkage and tyre deflection be described as a triangle where the sides represent these features. According to Brixius [38] the front and rear tyre rolling resistances can be determined from the two equations below:

$$ROF_W = \left[\left(\frac{1.0}{BNF_T} + 0.04\right) x DFW_M\right] \qquad (14)$$

$$ROR_W = \left[\left(\frac{1.0}{BNR_T} + 0.04\right) x DRW_M\right] \qquad (15)$$

where, ROF_W and ROR_W are front and rear wheels rolling resistance; DFW_M and DRW_M are the dynamic front and rear wheels masses; BNF_T and BNR_T are mobility numbers of front and rear wheel respectability. This agrees with definition given by [26,32].

Also Brixius [38] used the equations below to determine the front and rear wheel slips of vehicle in soft ground:

$$SLIPF_W = -\frac{1}{7.5}\ln\left[1 - \frac{\left(\frac{HTF_a}{AxDFW_M} - 0.04\right)}{0.88\left(1 - \exp\left[-0.1xBNF_T\right]\right)}\right] \qquad (16)$$

$$SLIPR_W = -\frac{1}{7.5}\ln\left[1 - \frac{\left(\frac{HTR_a}{BxDRW_M} - 0.04\right)}{0.88\left(1 - \exp\left[-0.1xBNR_T\right]\right)}\right] \qquad (17)$$

where:
$SLIPF_W$ = front wheel slippage, decimal
$SLIPR_W$ = rear wheel slippage, decimal
HTF_a = front axle gross traction, kg
HTR_a = rear axle gross traction, kg

Brixius [38] developed equations through dimensional analysis to predict the tractive performance of bias-ply tyres operation in cohesive-frictional soils. Wheel torque, motion resistance, net pull and tractive efficiency are predicted as a function of soil-strength, wheel load, slip, tyre size and tyre deflection. The rolling radius is said to be nearly constant and equivalent to 0.475 for most agricultural and earthmoving tyres.

Therefore equations predicting traction performance of a wheel driven through the soil were developed in the forms:

$$\frac{Q}{r_o W}, \frac{TF}{W} = f\left\{\frac{CIbd}{W}, \frac{b}{d}, \frac{\delta}{h}, s\right\} \qquad (18)$$

According to Brixius [38] torque ratio, motion resistance, net traction ratio and tractive efficiency are given by equation below

$$\frac{Q}{r_o W} = 0.88(1 - e^{-0.1Bn})(1 - e^{-7.5s}) + 0.04 \qquad (19)$$

$$\frac{TF}{W} = \frac{1.0}{Bn} + 0.04 + \frac{0.5s}{\sqrt{Bn}} \qquad (20)$$

$$\frac{P}{W} = 0.88(1 - e^{-0.1Bn})(1 - e^{-7.5s}) - \left(\frac{1.0}{Bn} + \frac{0.5s}{\sqrt{Bn}}\right. \qquad (21)$$

$$TE = \left[\frac{P/W}{Q/r_o W}\right](1 - s) \qquad (22)$$

Pneumatic and Rigid Wheels: Pneumatic wheels are tyres that worked by air under pressure and are classified either the dial-ply tyres or biased-ply tyres. Various researchers have conducted studies to compare the tractive performance of the radial-ply tyres with the biased-ply tyres in different soils at different tyre inflation pressures and shown that the radial-ply tyres developed more drawbar pull than the biased-ply tyres [43,45,49].

Rigid and Cage Wheels: Rigid wheels are wheels made by welding a sheet metal of a particular thickness round the circumference of the rim or made by covering the welded sheet metal by rubber having similar surface and look like pneumatic tyres but do not require any inflation. Such wheels have similar characteristics like that of pneumatic wheels of high inflation pressure. Cage wheels are made of steel but not covered with rubber, rather, have steel lug placed at a predetermined angle round the circumference of the steel wheel to aid traction. Both wheels are used as traction members of agricultural machines especially in swampy areas where pneumatic wheels have low tractive efficiency as a result of rut formation. [43,44,45,49].

A great many vehicles which have to work in flooded, puddle soils use cage wheels, These have been found, in practice, to be greatly superior to rubber tyre in this environment [43,44,54,55,56]. Experiments were carried out by Jayasundera [57] to investigate this phenomenon and also the effect of lug angle on wheel forces. He used a small (11 kW) four-wheel (two-wheel drive) tractor in these experiments. The results showed that initially, as the number of lugs was increased from 6 to 9 to 12 there was a continuous increase in power transmitted. As the number was increased from 12 to 18, however, there was a rapid decrease. The best combination was found to be 12 lugs at a 30 degree lug angle. Jayasundera found, however, that the limiting factor appeared not to be lug interference but lug blocking. The wheels with 18 lugs, at every lug angle, quickly became blocked with mud and this markedly reduced their ability to transmit power. Similar experiments were carried out by Wimalawansa [58] on a medium power (46 kW) four wheel tractor with cage wheels 1.6 m in diameter. The results showed that as the number of lugs was increased from 12 to 15, power transmitted increased at every lug angle. As the number was increased further from 15 to 18 power transmitted also dropped. Jayasundera [57] and Wimalawansa [58] observed that 30° lugs on cage wheels gave maximum tractive performance. They found that the optimum number of lugs on a cage wheel should be 12-15 depending on the size of the wheel. They also reported similar observation by Hossain that under similar conditions, the performance of a 4.47 kW power tiller with cage wheels was better than one with rubber tyres. He observed that the performance of the wheels was higher than the high lugged tyres and conventional cage wheels. Once again the main reason appeared to be lug blocking at medium to high slip values. As the number of lugs was increased further from 18 to 24 none of the wheels, with the exception of those with a 40 degree lug angle, could even propel the tractor across the field in no-load conditions. The best lug angle in these experiments was 30° [57,58]. The overall level of power transmitted was very low in these experiments. The experiments were carried out at low speed (1 m/s) in order to avoid engine stall and also for the sake of safety, since backward overturning is not uncommon in these field conditions as wheels become bogged down. The circumferential spacing between lugs at best power transmission was 23 cm in Jayasundera's experiments and 29 cm in Wimalawansa. These are quite similar and suggested that in a given soil condition, there is a minimum lug spacing below which wheels will block with mud. Neither this minimum spacing, nor the effect of lug interference, can yet be predicted theoretically and these are urgently required before cage wheel design can be optimized [59,60,61,62].

Elwaleed [60] formulated two models for tyre net traction ratio; one in terms of wheel numeric and travel reduction (wheel slip) and the other in terms of mobility number and travel reduction (wheel slip) to describe the tested tyre performance at different soil strength and at nominal tyre inflation pressure (221 kPa).

$$\frac{Q}{r_o W} = \ln(Cn)[0.0214\ln(S) + 0.208] \quad (23)$$

$$\frac{Q}{r_o W} = \ln(Bn)[0.0196\ln(S) + 0.189] \quad (24)$$

Another model was used to described the tyre torque ratio for different strength in term of wheel numeric and mobility at 193 kPa tyre inflation pressure as shown in equations below [60]

$$\frac{Q}{r_o W} = \ln(Cn)[0.0247\ln(S) + 0.215] \quad (25)$$

$$\frac{Q}{r_o W} = \ln(Bn)[0.0224\ln(S) + 0.196] \quad (26)$$

New models for the Riceland tyre motion resistance at the nominal tyre inflation pressure in terms of wheel and mobility numbers are presented as follows [60]

$$\frac{TF}{W} = 0.0682\ln(\frac{1}{Cn}) + 0.3719 \quad (27)$$

$$\frac{TF}{W} = 0.0682\ln(\frac{1}{Bn}) + 0.3617 \quad (28)$$

The new motion resistance ratio models at 193 kPa inflation pressure which was found to be better in performance than the nominal inflation pressure for both the wheel numeric and mobility number are given as

$$\frac{TF}{W} = 0.0627\ln(\frac{1}{Cn}) + 0.3443 \quad (29)$$

$$\frac{TF}{W} = 0.0627\ln(\frac{1}{Cn}) + 0.336 \quad (30)$$

Conclusions: The present state of research on the development of a high clearance vehicle for paddy fields have been reviewed, and the information required to develop the vehicle in terms of soil factors and the nature of the tyres such as rolling(motion) resistance, mobility numbers, wheel slip, tractive force and efficiency have been discussed. Existing models used to determine the tractive performance of off-road vehicles have also been stated.

Nomenclature

b = tyre width, cm
d = tyre overall diameter, cm
h = tyre section height, cm
N_t = tyre rotational speed, rpm
S = tyre travel reduction (slip), dimensionless
δ = tyre deflection, cm
r_o = rolling radius, cm
B_n = mobility number, dimensionless
C_n = wheel numeric, dimensionless
C_s = moving carriage speed, cm/s
CI = cone index, kPa
P_r = inflation pressure, kPa
M = motion resistance, N
TF = towed force (motion resistance), N
W = vertical load on tyre, N

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