Proceedings of the International Conference for Agricultural Machinery & Process Engineering
October 19-22, 1993, Seoul, Korea

# A Proposal of a New Model of Wheel and Tractor Dynamics that Includes Lift Resistance

Jun SAKAI*, Jungseob CHOE*, Tadashi KISHIMOTO**, and Yeodoo YOON*

## ABSTRACT

The purpose of this study is to propose a new dynamic model of wheels and agricultural tractors through verification of the existence of "lift resistance" and "perpendicular adhesion" which also can be called "contra-retractive adhesion".

The existence of these forces was proved through experiments in which the forces acting on a wheel were measured. The influence of the ground contact pressure and the travel speed of the wheel on the perpendicular adhesion ratio was studied through the experiment including the development of a sensor which can measure the forces acting on a wheel accurately.

Consequently, "perpendicular adhesion ratio" which is defined as the ratio of the perpendicular adhesion to the distributed load was observed to be in the range of 0.05 to 0.3. This means the influence of the "lift resistence" is comparable to that of motion resistance in wheel dynamics. The perpendicular adhesion ratio was observed to decrease logarithmically with the increase of ground contact pressure, and to increase linearly with the increase of the travel speed of the wheel. Some examples to express the new dynamic model compared to the conventional dynamics are explained.

Key Words : wheel dynamics, perpendicular adhesion,
perpendicular adhesion ratio, lift resistance,
lift resistance ratio, tractor dynamics

## INTRODUCTION

The forces that act upon a towed wheel having no acceleration are a dynamic load, towed force, soil reaction and so on. We may resolve the soil reaction into a vertical component of soil reaction and a motion resistance equal to the towed force.

There are acting forces such as a dynamic load, net traction, torque transmitted from an engine, and soil reaction which consists of motion resistance, gross traction, and a vertical component of soil reaction on the wheel[2,11]. On the basis of such an conventional theory, the total vertical reaction acting on the four wheels of a tractor without acceleration is same as the total weight of the tractor whether the tractor is moving or stationary.

However, it is the opnion of the authors that a lift resistance may exists in addition to the known forces in the conventional dynamic model of a traveling wheel. This is because, the lug face bc in Fig.1 may receive adhesion, and the

* Department of Agricultural Engineering, Kyushu University, Fukuoka, 812 Japan
** Faculty of Agriculture and Vet. Medicine, Obihiro University of Agriculture and Vet. Medicine, Obihiro, 080 Japan

lower parts of lug sides ab and cd in Fig.1 may receive friction resistance when the
faces start to move upwards after moving downwards along a trochoidal trajectory. Therefore, the total vertical soil reaction acting on the wheels of a tractor that travels on sticky soil is not the same as the total weight of the tractor.

Consequently, the authors verify the existence of perpendicular adhesion and that its value is not negligible through its measurement. The influence of the ground contact pressure and traveling speed on the perpendicular adhesion is studied.

# PERPENDICULAR ADHESION AND LIFT RESISTANCE

1. Perpendicular adhesion and lift resistance

The study of the dynamic characteristics of vehicles, especially the interaction between the soil and traveling device has a long history. Usually, adhesion means frictional force in the tangential direction of a wheel or a crawler.

However, another adhesion whose direction is almost vertical relative to the travel direction acts on a traveling wheel in sticky soil shown in Fig.1. The authors would like to propose to call this force "contra-retractive adhesion" or "perpendicular adhesion", and to call the sum of the frictional resistance and this force the "lift resistance"[1,7].

2. Perpendicular adhesion ratio and lift resistance ratio

The ASAE standard[11] states that "The dynamic load is total force normal to the reference plane of the predisturbed supporting surface exerted by the traction or transport device under operating conditions. This force may result from ballast and/or applied mechanical forces". Also the gross traction ratio and the motion resistance ratio have been defined based on the dynamic load.

In general, the distributed load obtained from the dimensions and specifications of a vehicle has been used as the dynamic load in vehicle dynamics, the motion resistance and traction have been obtained by multiplying it by the motion resistance ratio and gross traction ratio. When the lift resistance does not exist, the actual dynamic load of a wheel will be the same as the distributed load obtained from the dimensions and specifications of a vehicle, but when the lift resistance exists as in sticky soil, the dynamic load ought to be larger by as much as the lift resistance, than the distributed load obtained from the dimensions and specifications of the vehicle.

Consequently, the authors define the perpendicular adhesion ratio $R_{PA}$ and the lift resistance ratio $R_{LR}$ respectively as follows;

$$R_{PA} = A_P / ( R_D - R_L ) = A_P / L_D \qquad (1)$$

$$R_{LR} = R_L / ( R_D - R_L ) = R_L / L_D \qquad (2)$$

where,

$A_P$: perpendicular adhesion

$R_L$: lift resistance

$R_D$: vertical soil reaction

$L_D$: distributed load obtained from the dimensions and specifications of a vehicle

The definition for these ratios $R_{PA}$ and $R_{LR}$ are based on the system used to define the ratios of the motion resistance and the gross traction.

## EXPERIMENTAL DEVICES AND METHOD

1. Experimental devices

The experimental devices consisted of a carriage, trailing arms, a wheel mounting frame and a test wheel. Fig.2 shows a schematic diagram of the devices.

(1) Carriage

The carriage with a motor to pull the test wheel travels on a rail. Traveling speed of the wheel can be changed by a variable-speed motor on the carriage.

(2) Test wheel

Fig.3 shows the test wheel. This wheel consisted of spokes(1), a rim(2), sensors(A, B). The rubber facing(5) is bonded onto the lug connected to a sensor(B). The diameter of the test wheel is 600mm, and the width of the rim is 120mm.

The rim has two holes of size 96x56mm as shown in Fig.3, and the steel plate lug and the rubber lug of size 90x50mm are installed in the holes. The perpendicular adhesion is measured by the sensors which are the load cells with duplicate octagonal rings fastened to the lug.

(3) Load cell with duplicate octagonal rings

As the perpendicular adhesion that occurs instantaneously when a wheel lug retracts from the soil is small compared with the ground contact pressure, a sensor capable of measuring the small adhesion as well as the big loading force is necessary.

Considering this point, unique load cell with duplicate octagonal rings was developed as shown in Fig.4. The ground contact pressure is measured by the strong part A, and the perpendicular adhesion is also measured by the sensitive part B. The special slit was formed in part B of the sensor to protect the load cell from destruction due to too big forces like traction and ground contact pressure.

2. Methods and soil condition

Experiments were conducted on an open-air soil bin. The soil was light clay composed of 33.3% clay, 30.5% silt, and 36.2% sand. The soil surface was reformed to be flat by a roller after rotary tillage of 30mm depth.

The moisture content of the test soil was kept at 35%d.b throughout the experiment. The effective length of the soil bin for the experiment was 8m.

## RESULTS AND DISCUSSIONS

1. Perpendicular adhesion ratio and ground contact pressure

Experiments were done in order to evaluate the influence of the ground contact pressure of the wheel on the perpendicular adhesion ratio. The load on the test wheel was varied from 120N to 620N, and the traveling speed was kept at 0.5m/s throughout the experiments. Assuming the perpendicular adhesion acts on the whole width of the test wheel, its value was calculated from the experimental data. The contact area was obtained by multiplying the width of the wheel by the contact length of the wheel. The sinkage of the wheel became large on increasing the load acting on the wheel, and it was 8mm and 23mm when the loads on the wheel were 120 N and 620 N respectively.

Fig.5 and Fig.6 show measurement results for steel and rubber facings on a circular wheel. These two Figures show that the perpendicular adhesion ratio decreases logarithmically with the increase of ground contact pressure for both steel and rubber facings. And the perpendicular adhesion itself increases with the increase of ground contact pressure.

It is also ascertained from Fig.5 and Fig.6 that the perpendicular adhesion ratio is about 0.1 when the ground contact pressure is 40kPa, the ground contact pressure of a wheel used on general paddy fields. The ratio is about 0.15 when the ground contact pressure is 20 to 30kPa which are the ground contact pressures of a wheel used on swampy fields.

The regression equations and the coefficients of correlation r of the perpendicular adhesion ratio $R_{PA}$ and the ground contact pressure $P_{GC}$ are shown in Fig.5 and Fig.6 respectively.

The relation between soil reaction and the perpendicular adhesion ratio may be expressed as follows from the experimental results.

$$R_{PA} = a + b \ln ( P_{GC} ) \qquad (3)$$

Many experiments must be done in order to obtain constants a and b in Eq.(3), because they vary depending upon the shape of the lug, the composition and moisture content of the soil, and so on.

When the adhesion between soil and the wheel becomes unusually larger than the cohesion of the soil particles, it happens that soil attaches onto the wheel as an irregular phenomena.

2. Perpendicular adhesion ratio and traveling speed

In order to evaluate the influence of the traveling speed on the perpendicular adhesion ratio, experiments were done with varying traveling speeds from 0.3m/s to 1.1m/s. The sinkage of the wheel decreased with the increase of traveling speed, it was 14mm and 5mm when the traveling speeds were 0.3m/s and 1.1m/s respectively.

Fig.7 and Fig.8 show results for steel and rubber facings on a circular wheel. These two Figures show that the perpendicular adhesion ratio increases almost linearly with the increase of traveling speed for both steel and rubber facings, and its values become more than 0.1 when the traveling speed exceeds 0.1m/s.

The regression equations and the coefficients of correlation r of the perpendicular adhesion ratio $R_{PA}$ and the traveling speed V are shown in Fig.7 and Fig.8 respectively.

The relation between traveling speed and the perpendicular adhesion ratio may be expressed as follow from the experimental results.

$$R_{PA} = c + d\,V \qquad (4)$$

The constants c and d in Eq.(4) also vary according to the shape of the lug, the composition and moisture content of soil, and so on.

3. Examples of application of the lift resistance to tractor dynamics

The difference between the conventional model of tractor dynamics and the new model of tractor dynamics applying the lift resistance will be explained as follows;

The free body diagram according to the conventional model of tractor dynamics for a four-wheel-drive tractor moving at constant speed on a horizontal plain, is represented in Fig.9. Drawbar pull is excluded here.

where,

$R_1$ and $R_2$: Vertical soil reaction at the front wheel and rear wheel respectively

$f_1$ and $f_2$: Motion resistance at the front wheel and rear wheel respectively

$P_1$ and $P_2$: Gross traction at the front wheel and rear wheel respectively

$r_1$ and $r_2$: Radius of front wheel and rear wheel respectively
$W_T$: Weight of the tractor

Summing forces in the vertical direction,

$$W_T = R_2+R_1 \quad (5)$$

Considering moment equilibrium about the point O,

$$(b+e_1)W_T = (a+b+e_1-e_2)R_2 \quad (6)$$

Letting $e_1=\mu_1 r_1$, $e_2=\mu_2 r_2$[13], $\mu_1=\mu_2=\mu$, and substituting these in Eq.(6),

$$R_2 = (b+\mu r_1)W_T/\{a+b+\mu(r_1-r_2)\} \quad (7)$$

Fig.10 is the free body diagram according to the new model of tractor dynamics applying the lift resistance for a four-wheel-drive tractor moving at constant speed on a horizontal plain.

Where, $R_{L1}$ and $R_{L2}$ are the lift resistances at the front wheel and the rear wheel, respectively.

Letting $R_{LR}=R_{L1}/(R_{D1}-R_{L1})=R_{L2}/(R_{D2}-R_{L2})$ according to the definition of the lift resistance ratio, and summing forces in the vertical direction,

$$W_T = (R_{D1}-R_{L1})+(R_{D2}-R_{L2})$$
$$= (R_{D1}+R_{D2})(1-R_{LR})+R_{LR}(R_{L1}+R_{L2}) \quad (8)$$

Considering moment equilibrium about the point O,

$$(b+e_1)W_T+(e_1+\varepsilon_1)R_{L1}+(e_1+a+b+\varepsilon_2)R_{L2} = (a+b+e_1-e_2) R_{D2} \quad (9)$$

Letting $e_1=\mu_1 r_1$, $e_2=\mu_2 r_2$, $\mu_1=\mu_2=\mu$, $\varepsilon_1=\varepsilon_2=0$ because $\varepsilon_1$ and $\varepsilon_2$ is very small, and substituting these in Eq.(9),

$$R_{D2}=\{(b+\mu r_1)W_T+\mu r_1R_{LR}(R_{D1}-R_{L1}) +(\mu r_1+a+b)R_{LR}(R_{D2}-R_{L2})\}$$
$$/\{a+b+\mu(r_1-r_2)\} \quad (10)$$

Comparing this $R_{D2}$ in Eq.(10) with $R_2$ in Eq.(7), we can see that the vertical soil reaction on the rear wheel is bigger by as much as $\{\mu r_1 R_{LR}(R_{D1}-R_{L1}) +(\mu r_1+a+b) R_{LR}(R_{D2}-R_{L2})\} /\{a+b+\mu(r_1-r_2)\}$ when the lift resistance acts on the wheel of a tractor traveling in paddy fields than when it does not act in dry fields.

The authors think that the new model of wheel or tractor dynamics applying the lift resistance must be studied to improve their accuracy, especially in Asia.

## CONCLUSION

The influence of the ground contact pressure and the traveling speed of the wheel on the perpendicular adhesion ratio was studied through experimentation including the development of a sensor which can measure the forces acting on a wheel-lug accurately. The main results were as follows;

1) A wheel experimental device that can measure the force acting on the lug face of a wheel was developed by designing a sensor which can measure the forces accurately.

2) A wheel-lug ought to receive a special resistance force in downward direction which resists the lug's upward motion on wet sticky soil surface. The authors propose a new academic name of "lift resistance" for such a force which resists retraction of a lug of wheel from the soil in the upward trochoidal motion of a lug. This force is mainly composed of the frictional force acting on the trailing and the leading lug side, and the "perpendicular adhesion" acting on the lug face and the undertread face on adhesive soil.

3) The "perpendicular adhesion ratio $R_{PA}$" and the "lift resistance ratio $R_{LR}$" are defined and proposed considering the conventional system of definition of the motion resistance ratio and the gross traction ratio in the wheel dynamics.

4) It is ascertained that the perpendicular adhesion ratio is about 0.1 when the ground contact pressure is 40kPa, the typical ground contact pressure of a wheel used on general paddy field. The ratio is about 0.15 when the ground contact pressure is 20 to 30kPa which are the ground contact pressures of a wheel used on swampy fields.

5) The perpendicular adhesion ratio was observed to decrease logarithmically with the increase of ground contact pressure, and to increase linearly with the increase of the traveling speed of the wheel.

6) A simple example showing the difference between the conventional model of tractor dynamics and the new model of tractor dynamics applying the lift resistance was presented.

## REFERENCES


1)Sakai, J. : The lift resistance acting on a wheel(I), Abstracts of the 50th annual conference of the JSAM, 45-46, 1991

2)Sakai, J., Kishimoto, T. : Translation and proposal on ASAE terminology for traction and transport devices, JSAM J., 49(6), 605-610, 1987

3)Sakai, J., Kishimoto, T., Inoue, E. and Matsuo, T.: Basic studies on design theories of agricultural wheels(part 4), JSAM J., 53(3), 25-34, 1991

4)Kishimoto, T., Sakai, J. and Inoue, E. : Basic studies on design theories of agricultural wheels(part 3), JSAM J., 53(2), 3-11, 1991

5)Sakai, J., Kishimoto, T. and Phongsupasamit, S. : Basic studies on design theories of agricultural wheels(part 1), JSAM J., 50(6), 11-18, 1988

6)Sakai, J. : Motion of a wheel lug and the measurement of contra-retractive adhesion, Abstracts of the 51th annual conference of the JSAM, 19-20, 1992

7)Sakai, J., Kishimoto, T. and Taniguchi, T. : A proposal of lift resistance on wheel dynamics, Proceedings of international agriculture mechanization conference, Beijing, 2(116) - 2(133), 1991

8)Koolen, A. J., H. Kuipers : Agricultural soil mechanics, Springer-Verlag, 1983

9)Bekker, M. G. : Theory of land locomotion, 75,333, Birmingham, Michigan, 1955

10)Dwyer, M. J. : The tractive performance of wheeled vehicles, Journal of terramechanics, Vol.21, No.1, 19-34, 1984

11)ASAE Standard : ASAE S 296.2 "Uniform terminology for traction of agricultural tractors, self-propelled implements, and other traction and transport devices", ASAE standard 1989, 118-120, 1989

12)Sineokov, G. N. : Design of soil tilling machines, Izdatelstvo "Mashinosttroenie", Moskva, 164-173, 1965

13)Sakai, J. : A theoretical approach to the mechanism and performance of the hand-tractor with a rotary-tiller, together with practical application, Shin-norinsha Co.,Ltd., 1962

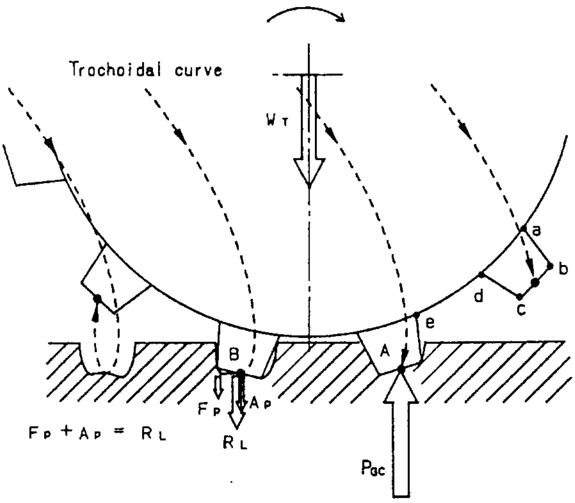


Fig.1 The lift resistance and the perpendicular adhesion

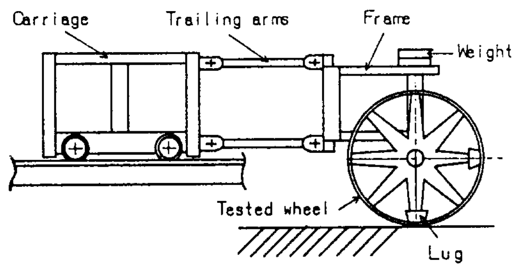


Fig.2 Experimental device

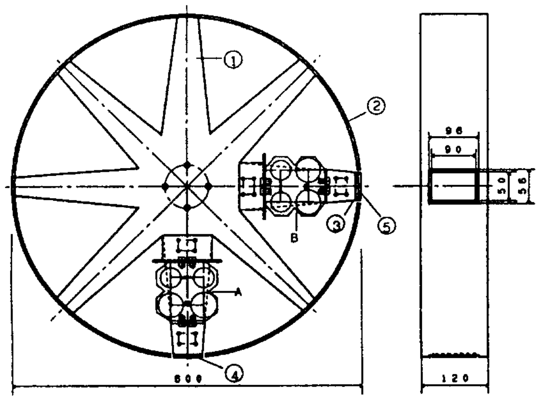


Fig.3 Tested wheel

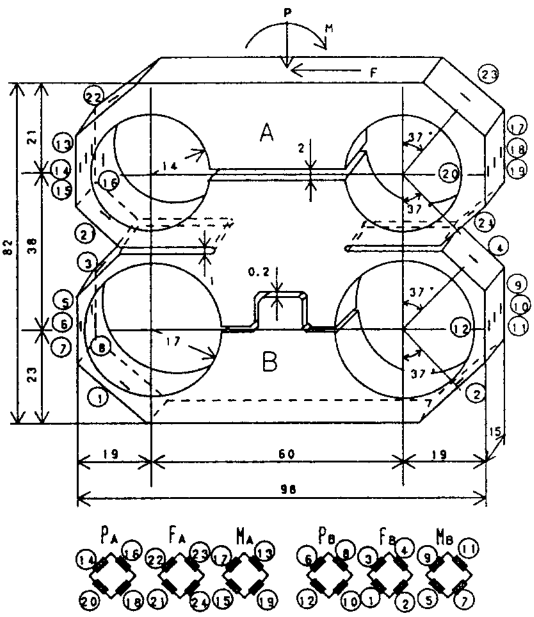


Fig.4 A load cell with duplicate octagonal rings

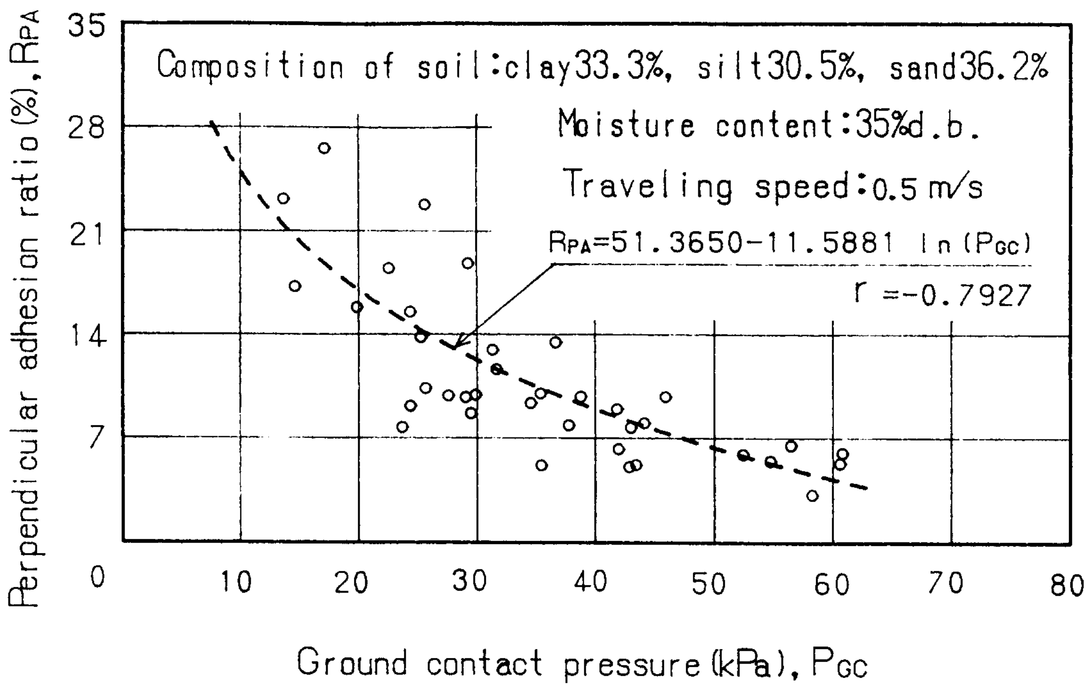


Fig.5 The perpendicular adhesion ratio and the ground contact pressure of the steel wheel

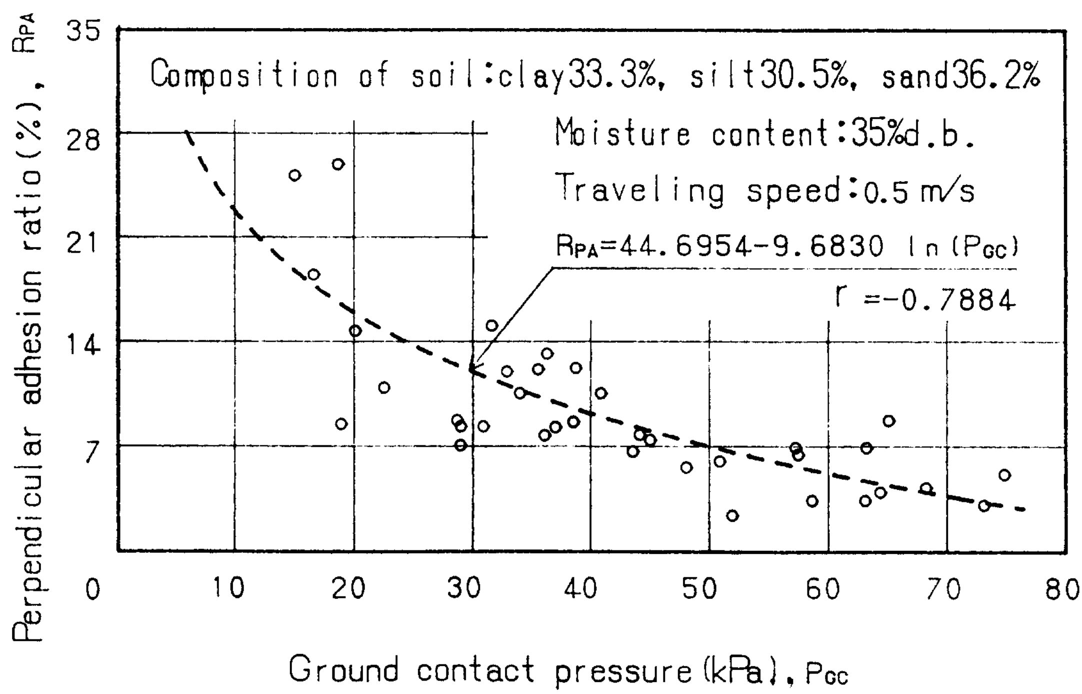


Fig.6 The perpendicular adhesion ratio and the ground contact pressure of the wheel with rubber facing

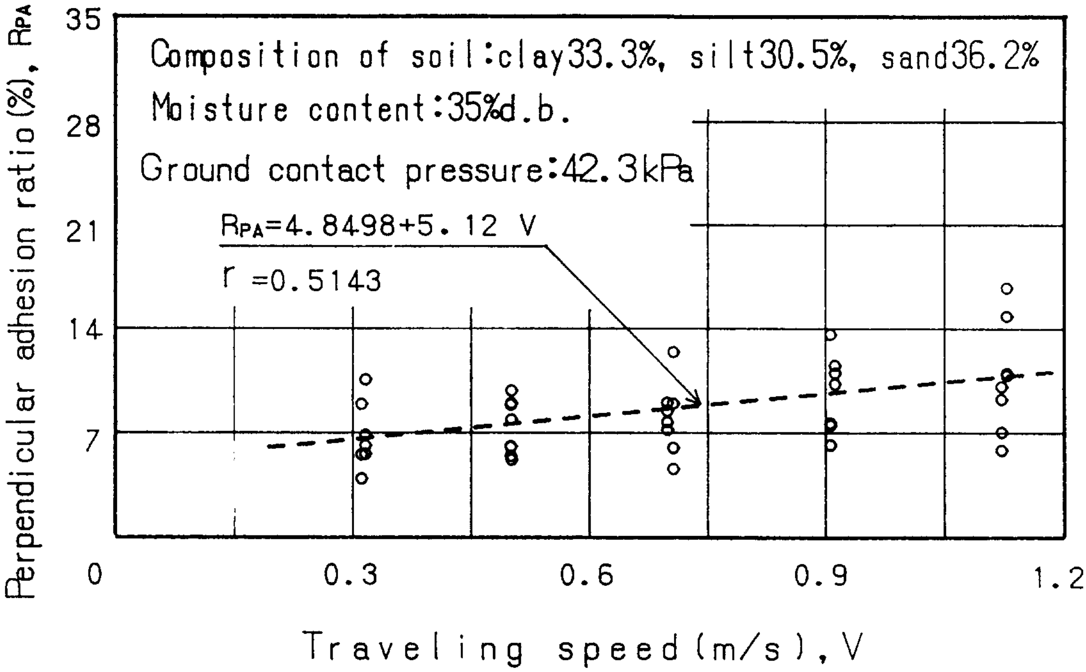


Fig.7 The perpendicular adhesion ratio and the traveling speed of the steel wheel

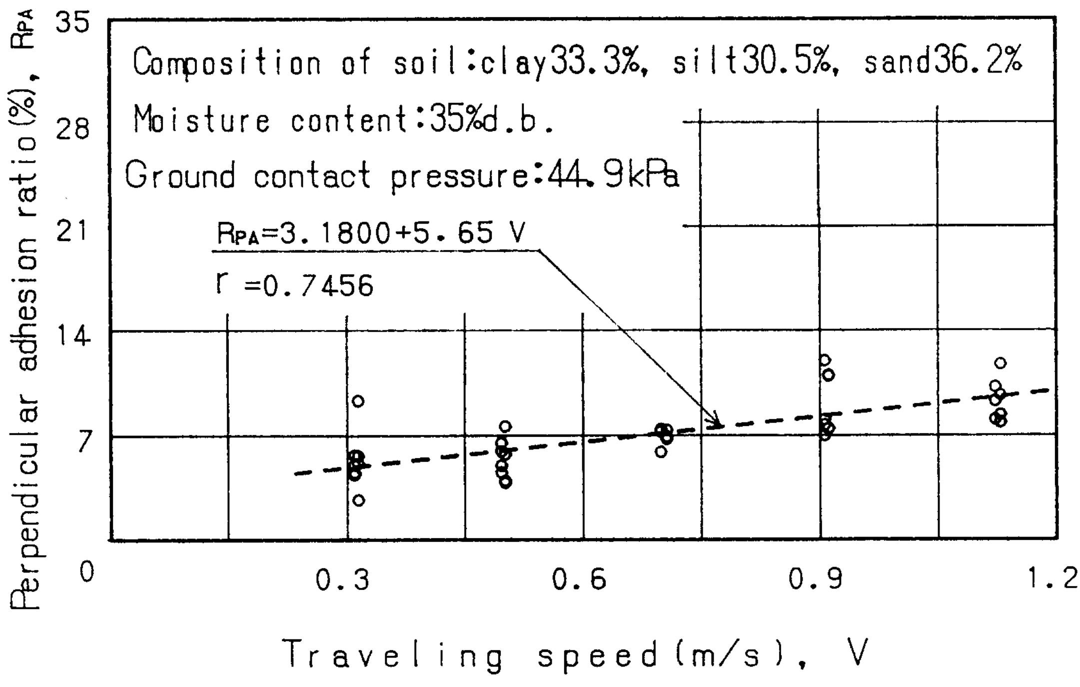


Fig.8 The perpendicular adhesion ratio and the traveling speed of the wheel with rubber facing

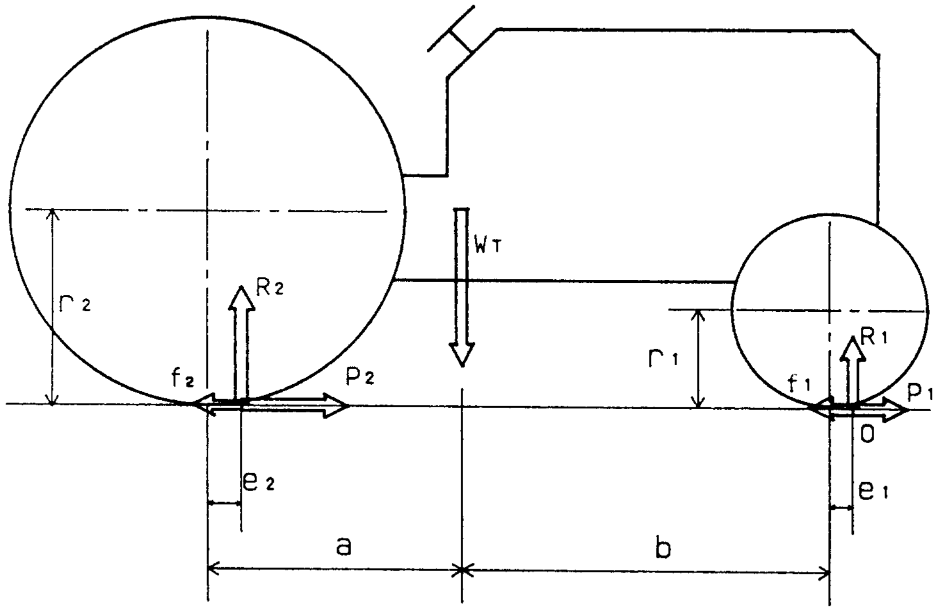


Fig.9 The free body diagram of a four-wheel-drive tractor driven at constant speed on a horizontal surface according to conventional model of tractor dynamics

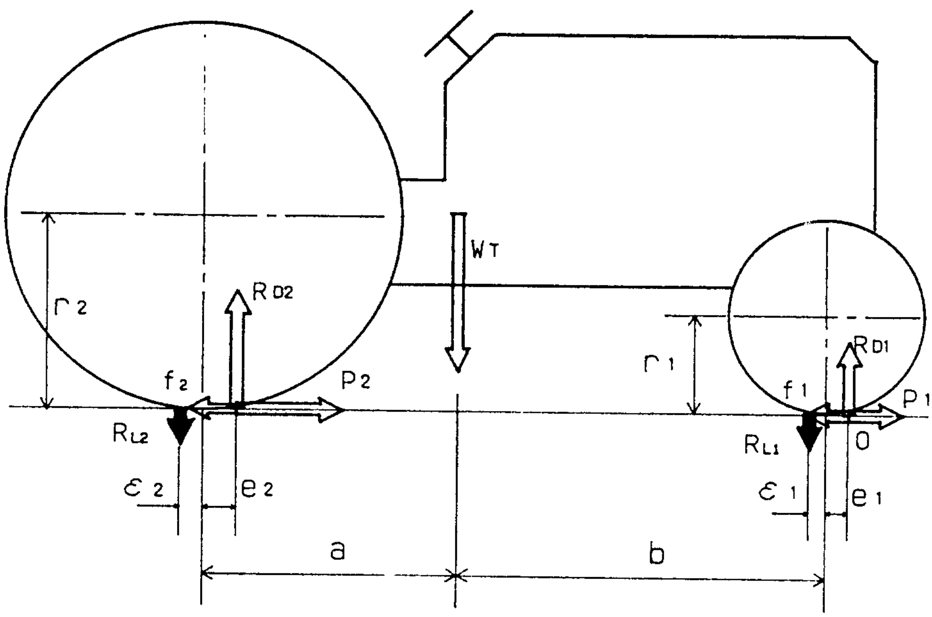


Fig.10 The free body diagram of a four-wheel-drive tractor driven at constant speed on a horizontal surface according to new model of tractor dynamics