TEKA Kom. Mot. Energ. Roln., 2006, 6, 160–168

ENERGETIC ESTIMATION OF SOIL TILLAGE MACHINES

Arvids Vilde*, Wojciech Tanaś**

* Research Institute of Agricultural Machinery, Latvia University of Agriculture
** Department of Vehicles and Engines, Agricultural University of Lublin

Summary. Investigations are carried out, as well as a methodological foundation presented for the energetic estimation of machines with passive operating parts (ploughs, cultivators, harrows etc.) that are chiefly used in soil tillage. For unbiased energetic estimation of a soil tillage machine one should find out its static resistance and the coefficient of its dynamic resistance. On the basis of theoretical research methodology is worked out how to determine energetic characteristics of soil tillage machines.

Key words: soil tillage machines, energetic estimation, testing methods, specific draft resistance, static resistance, dynamic resistance.

INTRODUCTION

Soil tillage is one of the most power-consuming processes in field crop cultivation which requires a considerable part (20-25%) of the diesel fuel consumed in agriculture. The energy content of the process depends mainly on the energetic characteristics of the used machines. In order to give an unbiased energetic assessment of machines and find out possibilities how to decrease the power capacity of soil tillage, it is necessary to determine by experiment the energetic characteristics of machines as well as the relationships of their variations and the factors that affect them.

Investigations are carried out, as well as a methodological foundation presented for the energetic estimation of machines with passive operating parts (ploughs, cultivators, harrows etc.) that are chiefly used in soil tillage.

THEORETICAL BASIS

Energy capacity of soil tillage

The amount of energy consumed for soil tillage with machines having passive operating parts depends on their specific draft resistance [Vilde 1999b]:

$$E_m = K_{1,} \quad (1)$$

where:

E_m – specific energy capacity of soil tillage, Nm/m^2 ;
K_1 – specific draft resistance of the machine, N/m.

In terms of the units of measurement used in technical calculations the utilization of energy obtains the following expression:

$$E_m = 2.778 \cdot 10^{-3} K_1 \text{ , kWh/ha} \quad (2)$$

The draft resistance of the machine and its components

The total draft resistance R_x of the soil tillage machine is generally determined by four components [Vilde 1999a]:

– the resistance to the penetration of the blade of the operating part (ploughshare, tooth) into soil (cutting resistance) R_{px};
– resistance R_{Gx} caused by the gravity of the moved soil (raised soil);
– resistance R_{Jx} caused by the forces of inertia;
– resistance R_{Qx} caused by the proper weight of the machine from its movement.

$$R_x = R_{Px} + R_{Gx} + R_{Jx} + R_{Qx} \quad (3)$$

In a more expanded form:

$$R_x = k_p p_o iB + kaB + \varepsilon aBv^2 + fQ, \quad (4)$$

where:

p_o – soil hardness in its cutting zone with a ploughshare blade, Pa;
i – thickness of the ploughshare blade, m;
B – working width of the machine, m;
k_p – effect coefficient of the shape of the frontal surface ploughshare blade;
k – static resistance coefficient related to a unit the cross section area of the tilled soil, N/m^2;
ε – dynamic resistance coefficient related to a unit the cross section area of the tilled soil, Ns^2/m^4;
f – slip (movement of the machine) resistance coefficient;
a – working depth, m;
v – working speed, m/s;
Q – weight of the machine, N.

The specific draft resistance related to a unit of the working width:

$$K_1 = R_x B^{-1}; \quad (5)$$

$$K_1 = k_p p_o i + ka + \varepsilon av^2 + fQB^{-1}; \quad (6)$$

$$K_1 = k_{1p} + k_1 + \varepsilon_1 v^2 + k_{1Q}, \quad (7)$$

where:

K_1 – specific draft resistance related to a unit of working width (1 m), N/m;
k_{1p} – specific cutting resistance related to a unit of working width, N/m;
k_1 – static resistance caused by soil gravity related to a unit of the working width, N/m;
ε_1 – dynamic resistance coefficient related to a unit of the working width, Ns^2/m^3;
k_{1Q} – resistance caused by the weight of the machine for its movement related to a unit of the working width, N/m.

It follows from formulas (3)-(7) that for the purpose of energetic characteristics of the machine (its operating parts) in a particular situation it is necessary to determine the values which characterize all the four components of its specific resistance k_{1p}, k (k_1),ε (ε_1) and k_{1Q}, i.e., four unknown values. With this aim, during the tests, a system of four independent equations must be obtained.

Sometimes it is sufficient to have a characteristic of the machine only in its basic sphere of performance, e.g., for the ploughs working on grassland and stubble-fields at normal humidity without indicating all the resistance components. This makes it possible to reduce considerably the amount of the testing work.

A simplified energetic estimation of the machine

To estimate energetic capacity of the machine using a simplified method, two components of its specific resistance are determined: **static resistance** that practically is not dependent on speed and **dynamic resistance** which is functionally related to the working speed according to formula [Vilde *et al.* 2004]:

$$K_1 = k_1' + \varepsilon_1 v^2 , \tag{8}$$

where:

k_1' – generalized (total) specific static resistance, N/m.

The comparison with formulas (6) and (7), shows that

$$k_1' = k_p p_o i + ka + fQB^{-1} , \tag{9}$$

$$k_1' = k_{1p} + k_1 + k_{1Q} . \tag{10}$$

For a simplified energetic estimation of the machine for a particular case by testing, it is necessary to determine its specific static resistance k_1' and the coefficient of dynamic resistance ε_1 which are obtained from the system of two specific draft resistance equations at different working speeds.

The commonly practiced energetic estimation of machines by their specific fuel consumption is not correct since it depends not only on the design of the machine but largely also on the loading of the tractor engine. Such an estimation method would be allowable if, under equal testing circumstances at an equal speed, the loading of the tractor engine were at least approximately equal and sufficient, which usually is not the case.

Guided by this theoretical consideration methodology was worked out for energetic estimation of soil tillage machines.

METHODOLOGY FOR THE ESTIMATION OF ENERGETIC INDICES OF SOIL TILLAGE MACHINES

The energetic indices of the soil tillage machine are determined by measuring its draft resistance at various settings of the operating parts and working speeds of the machine.

For the machines with plough-type operating parts (ploughs, sweep-type cultivators) the estimation of their four principal draft resistance components (formula 3) requires to set up a system of four independent equations. It can be achieved by finding the draft resistance of the machine at the same speed and four different working depths:

$$\begin{cases} R_{x1} = k_p p_{o1} iB + ka_1 B + \varepsilon a_1 B v_1^2 + fQ \\ R_{x2} = k_p p_{o2} iB + ka_2 B + \varepsilon a_2 B v_1^2 + Fq \\ R_{x3} = k_p p_{o3} iB + ka_3 B + \varepsilon a_3 B v_1^2 + fQ \\ R_{x4} = k_p p_{o4} iB + ka_4 B + \varepsilon a_4 B v_1^2 + fQ \end{cases} \quad (11)$$

Similar systems of equations are formulated for the other speeds, v_2, v_3, v_4.

The solution of this system of equations produces the numerical values of the draft resistance components (coefficients) k_p, k, ε and f at all the working speeds used. This, in its turn, allows to determinate the correlations between the variations of these coefficients depending on the working speed.

In cases when soil hardness p_o (by the readings of the hardness meter) within the range of depth variations at which the draft resistance is determined remains constant ($p_{01} = p_{02} = p_{03} = p_{04}$), the finding of values k_p and f is complicated.

In such situations it is essential to carry out additional draft resistance measurements at one or more (if necessary) working depths a_i having a different working width B_i, or with an altered mass of the machine (additional loading), e.g.:

$$R_{xi} = k_p p_o iB_i + ka_i B_i + \varepsilon a_i B_i v_1^2 + fQ, \quad (12)$$

$$R_{xj} = k_p p_o iB + ka_i B + \varepsilon a_i B v_1^2 + f(Q + \Delta Q), \quad (13)$$

where:

ΔQ – weight of the load, N.

For the ploughs equipped with disk or knife coulters used to cut off the arable strips in a vertical plane, the draft resistance is measured separately. This gives a possibility to determine more exactly the ploughshare resistance when cutting off the arable strips in a horizontal plane.

As shown above, the presented methodology for the estimation of the draft resistance components is applied mainly to the machines with a ploughshare-mouldboard or sweep-type tooth operating parts (ploughs, cultivators) for which it is possible to distinguish sufficiently clearly these four main resistance components. For the machines (harrows, drags, rollers etc.) that have no possibility to use this method, or resistance components, their static resistance and the coefficient of dynamic resistance, that is, two resistance components are defined using formula (8). They are derived from a system of two resistance equations:

$$\begin{cases} R_{x1}B^{-1} = k_1' + \varepsilon_1 v_1^2 \\ R_{x2}B^{-1} = k_1' + \varepsilon_1 v_2^2 \end{cases} \quad (14)$$

Solving this system of equations one can obtain expressions for the calculation of static resistance and dynamic resistance coefficients:

$$k_1' = B^{-1}(R_{x1}v_2^2 - R_{x2}v_1^2)(v_2^2 - v_1^2)^{-1}; \quad (15)$$

$$\varepsilon_1 = B^{-1}(R_{x2} - R_{x1})(v_2^2 - v_1^2)^{-1}. \quad (16)$$

Expressions (15) and (16) allow obtain the average values of k_1' and ε_1 in the range of speeds applied $v_1 ... v_2$ under particular testing circumstances for a particular setting of the operating parts of machines.

In order to detect the variations of the static resistance coefficient k_1' and the dynamic resistance coefficient ε_1, depending on the working speed, their values are to be determined on several-level speed ranges. For this purpose the draft resistance of the machine is estimated at least at four working speeds, thus obtaining three systems of equations:

$$\begin{cases} R_{x1}B^{-1}=k'_{1(12)}+\varepsilon_{1(12)}v_1^2 \\ R_{x2}B^{-1} = k'_{1(12)} + \varepsilon_{1(12)}v_2^2, \end{cases} \quad (17)$$

$$\begin{cases} R_{x2}B^{-1} = k'_{1(23)} + \varepsilon_{1(23)}v_2^2 \\ R_{x3}B^{-1} = k'_{1(23)} + \varepsilon_{1(23)}v_3^2, \end{cases} \quad (18)$$

$$\begin{cases} R_{x3}B^{-1} = k'_{1(34)} + \varepsilon_{1(34)}v_3^2 \\ R_{x4}B^{-1} = k'_{1(34)} + \varepsilon_{1(34)}v_4^2. \end{cases} \quad (19)$$

These systems of equations are solved in the same way as the previous system of equations (14).

As shown above, such a solution can be applied also to a simplified energetic estimation of mouldboard-like machines. In this case, as it is obvious from formula (9), the generalized static resistance k_1' is the sum of the resistances caused by cutting the arable strip, by weight of the soil raised and the weight of the plough related to a unit of working width.

The resistances that are caused by cutting the strip and the weight vary in proportion with the working width, the proper weight of the machine and the resistance caused by it generally not proportional to the working width but changing in accordance with other relationships. As a rule, they grow more rapidly than the working width. This should be considered in the energetic estimation of machines having different working widths.

By using automatic systems to control the operation of the mounted equipment of the tractor the weight of the machine (or its part) not needed to perform the technological process can be transferred to the tractor. In this case:

$$fQB^{-1} \approx 0 , \tag{20}$$

and

$$k_1' = k_p p_o i + ka , \tag{21}$$

i.e., the static resistance of the machine is proportional to its working width.

Consequently, the relationships given above serve as energetic characteristics of the machines to be tested.

To carry out comparative energetic estimation of soil tillage machines, the values of their static and dynamic resistance coefficients are compared, as well as the character of their variations. From the energetic point of view, those machines are better for which the values of the resistance indices are lower.

For a complete energetic assessment of the machine its energetic features are determined in operation on the basic most typical soils at a different degree of humidity, hardness, humus content, soddiness of the soil and by various fore crops.

Besides, this task is complicated by the circumstance that in a general case the factors which determine the values of components (p_o, k, ε, f) are not constant but may vary for each particular soil with the working depth (p_o), speed (k, ε, f), soil non homogeneity etc. This requires a specific approach to the solution of this problem matching any particular situation.

The energetic indices of soil tillage machines are affected also by the design of the applied mounted equipment of the tractor. The use of their automatic control systems (hydraulic loading, automatic regulation of the working depth) may be considerably (to 15%) decrease their draft resistance, chiefly, at the expense of the components caused by the weight of the machine and soil. Therefore, it would be advisable in the test to determine the energetic characteristics of the machine by running it not only in the floating but also in the automatic control modes.

For illustration a figure (see below) is presented that shows a general scheme for testing machines in order to obtain their complete energetic estimation (Fig. 1).

It is obvious from the scheme that, in order to obtain full energetic characteristics of a soil tillage machine (plough, cultivator, rotary knife harrow etc.), a great amount of testing work is to be done. So for the energetic estimation of a single machine on the same soil background after one fore plant and at the same soil humidity, at three settings of the machine, as well as at three speeds and three repetitions 27 tests must be carried out (draft resistance measurements). Doing this on three soil types after three different fore-plants and at three soil humidity conditions the number of tests is 729.

When the number of working speeds is increased by one, the number of tests reaches 972. If the number of machine settings is increased by one setting, the number of tests rises to 1296.

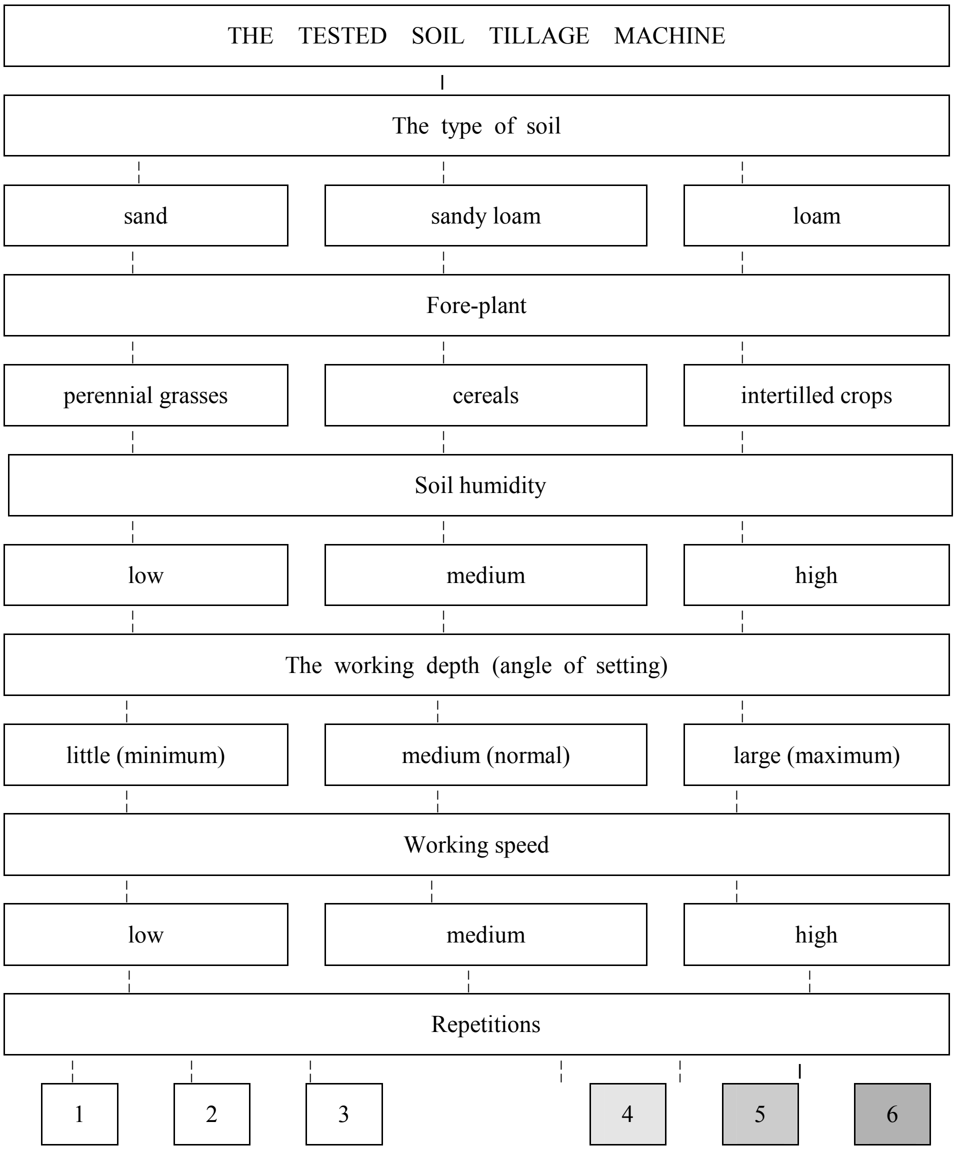

Fig 1. General testing scheme of soil tillage machinesfor their energetic estimation

For a comparative energetic estimation of several machines, testing should be carried out under equal conditions.

It is possible to carry out such an immense amount of testing only with a corresponding measuring equipment and automated fixing of readings already in the course of measuring (by means of summators and self-recorders of draft resistance).

However, not always such a range and amount of testing is possible and necessary. Hardly ever there is a need to determine all the four components of draft resistance. As a rule, they characterize machines with mouldboard-type operating parts (ploughs, sweep-type cultivators) whereas to isolate the cutting resistance component for other machines (spring-tooth cultivators, harrows with tines, rotary knives and disks, rollers) is not easy, or this component does not exist at all.

The testing of machines is carried out by standardized methods including characteristics of the conditions (GOST 20915-75), determination of draft resistance (OST 10.2.2-86) and the assessment of the machine performance (OST 70.4-80: OST 70.4.2-80) with the necessary specifications and supplements in them.

RESULTS

Table 1. Comparative energetic and economic characteristics of ploughs for rocky soils working in loamy soils of perennial grasslands

Characteristics	Unit of measure-ment	The value of the characteristics			
Tractor		MTZ – 82 (55.5 kW)			
Plough		ATA 2-40 with KVU 10000 LR SIA "AGS" bodies		PGP-35 with Kverneland Nr.8 bodies	
Technical characteristics:					
the number of bodies		2	2	3	3
the width of the body	cm	42	42	35	35
the width of the plough	m	0.87	0.84	1.07	1.1
the depth of ploughing	cm	21.4	21.7	22.1	21.8
the working speed	m/s	1.47	2.5	1.43	1.81
efficiency in the basic time	ha/h	0.46	0.76	0.55	0.71
Energetic characteristics:					
the loading of the tractor engine	%	48	87	57	77
specific draft resistance	kN/m	15	17.3	14.9	15.7
	N/cm^2	7	8	6.7	7.2
specific energy consumption	kWh/ha	57.9	63.9	57.4	59.6
specific fuel consumption	kg/ha	19.8	16.1	17.3	15.9
static resistance k_1^1	kN/m	13.8		13.7	
the coefficient of dynamic resistance ε_1	kN/m^3	0.56		0.59	
Testing conditions:					
soil humidity	%	1 0-14		1 0-14	
soil hardness	MPa	1-3.5		1 -3.5	

The data obtained from the Baltic Machine Testing Station.

On the basis of the obtained data a versatile energetic estimation of the machine is undertaken, recommendations worked out for the choice of machines, their rational aggregation and use.

The elaborated methodology is applied to the energetic estimation of soil tillage machines (ploughs, cultivators, harrows etc.) at their testing obtaining their sufficiently exhaustive and unambiguous energetic characteristics [Vilde 1999b, Vilde *et al.* 2004].

For example, energetic characteristic of two ploughs obtained by their testing are given in Table 1.

It is evident from the data in the Table 1 that energetic characteristics (the values of the static and dynamic resistances), both the tested ploughs are almost equivalent. However, in case the energetic estimation, is given, as it is often erroneously done, according to the specific fuel consumption at a speed which does not load the tractor engine, one can draw a false conclusion that the first plough (with the specific fuel consumption of 19.8 kg/ha) is much worse than the other one (with the specific fuel consumption of 17.3 kg/ha at approximately the same speed).

CONCLUSIONS

1. For unbiased energetic estimation of a soil tillage machine one should find out its static resistance and the coefficient of its dynamic resistance.
2. On the basis of theoretical research methodology is worked out how to determine energetic characteristics of soil tillage machines.

REFERENCES

Vilde A., 1999a: Dynamics of the soil tillage machines operating parts and their elements. Proceedings of Latvia University of Agriculture, Vol. 1 (295), pp. 36-44.

Vilde A., 1999b: Energetic and economic estimation of soil tillage systems. Folia Universitatis Agriculturae Stetinensis 195, Agricultura 74, pp. 213-222.

Vilde A, Cesnieks S., Rucins A., 2004: Minimisation of soil tillage. Polish Academy of Sciences Branch in Lublin. TEKA Com. Mot. Pow. Ind. Agricult., IV, 237–242.