CRITERIA FOR THE ESTIMATION OF THE EFFICIENCY OF AGRICULTURAL TRACTORS IN FIELD CROP CULTIVATION

Arvids Vilde, Edmunds Pirs
Latvia University of Agriculture, Research Institute of Agricultural Machinery
vilde@delfi.lv

Abstract. The efficiency of tractors and machines applied in agriculture is usually estimated as an integrated value including the indices of their intensive and extensive use. The application intensity of tractors and machines is characterized by their working capacity per unit of time but its extensity - by the length of the consumed time in a season (year). However, in order to obtain more objective estimation data for the used tractor aggregates, their performance should be evaluated by optimal parameters: their working width and their speed. One of the ways how to raise labour efficiently, to cut the fuel consumption and the production costs, as well as to improve the ecological situation is to improve the tractor loading and aggregation patterns. Only those aggregates should be used for soil tillage and other works which ensure its performance with minimum fuel consumption and costs. This can be achieved by aggregates completed with efficient up-to-date tractors and tillage machines that are suitable for local conditions and have optimal parameters. In order to estimate the application intensity of the tractor, its engine loading (fuel consumption per unit of time) should be measured and fixed in the data logger; to estimate its extensity - the length of time consumed for its application should be determined.

Key words: efficiency of tractors, energetic characteristics of tractors, energetic characteristics of machines, intensive use, extensive use, efficient use.

Introduction

In the Latvian agriculture the transition process from the old tractors and machines made in the former Soviet Union (now – the Commonwealth of Independent States, CIS) to new ones coming from the West European countries is going on. The new machinery is more progressive but more complicate and expensive too. This may raise the costs of agricultural production. Therefore measures should be taken for efficient maintenance of the new machine fleet. The data of the previous investigations [2, 9, 12, 17] are now obsolete and useless for the purchase of the new machinery. The purpose of this investigation was to find out criteria for the efficiency estimation of agricultural tractors in field crop cultivation.

Materials and methods

There was a great amount of different methods and normative technical documents used to estimate the efficiency of the farm machines of the previous time [2-6, 8-16]. At present the former normative data are out of date, yet some methods, when revued with a critical eye, may still be useful. The capacity of tractors can be calculated multiplying their draft force and take-off force by their shaft power. The energy requirement for soil tillage and other traction operations (pull technologies) may be determined by the specific static and dynamic resistances [2-6, 8, 18, 19]. These methods are applied to optimise the parameters of the tractor-machine aggregates [2, 6]. This work also deals with some of the contemporary methods and normative data used to choose and calculate the efficiency of the farm machines in other countries [1, 7].

Results and Discussion

A brief review is given of the methods and criteria to assess the efficiency of agricultural tractors, machines and aggregates in field crop cultivation, the basic ones being:

- efficiency characteristics of the tractor and their application;
- energetic characteristics of the machines used;
- the modes of aggregation, optimisation of the parameters of the aggregates;
- indices for the choice and efficient use of tractors, farm machines and aggregates.

Application of more efficient tractors and their rational usage

The specific fuel consumption of correctly aggregated machines performing agricultural operations does not depend on the capacity of the tractor but on its economy, which is determined by the specific fuel consumption of the engine for the production of a unit of energy g_e (kWh) and the coefficient of its employment for the useful work k_u (soil tillage, manure spreading, sowing, transport, etc.) [2].

The last coefficient k_u characterises which part of the energy produced by the engine is used up in the technological operations. The lower is the specific fuel consumption of the engine and higher the coefficient k_u of the useful work (for example, the draft coefficient [2, 3]), the more economic may be the work of the tractor. Therefore, in order to save fuel, the tractors with the most economic engines should be used. In addition, to avoid excessive consumption of fuel, due attention should be paid also to a correct setting of the tractor fuel system, its timely control and adequate maintenance.

An important factor in fuel consumption is the engine loading. Fig. 1 presents generalised curves of the diesel engine loads that show the variations in the values of indices characterising the operation of the engine: the total fuel consumption G, the torsional moment (the moment of rotation) M, the number of crankshaft revolutions n and the specific fuel consumption g_e depending on the effective power N_e developed by the engine (also in percentage). It is obvious from the picture that if the engine loading falls, the specific fuel consumption rises, at first, at a slower rate (up to about 80 % loading), but further it increases more and more rapidly.

For instance, at full engine loading of the Belarus tractor the specific fuel consumption is 250 g/kWh, whereas at an 80 % loading it is 260 g/kWh, i.e. by 4 % higher, but at a 50 % loading it is 322 g/kWh, that is, by 29 % higher. The specific fuel consumption changes in a similar way also during the work. For example, in soil tillage, if, working at full loading, the specific fuel consumption in ploughing is 16 kg/ha, then at an 80 % loading it is 16.6 kg/ha, but at a 50 % loading (insufficient gripping, low speed) it is 20.6 kg/ha (by 4.6 kg/ha higher).

This extra fuel consumption raises the cost of ploughing by 2 Ls/ha [2]. Yet that is not all. Running underloaded engine decreases correspondingly the efficiency of the aggregate, increases the time spent on ploughing and, as a result of it, salaries, which makes ploughing still more expensive. A similar picture is observed also with other ways of soil tillage.

$$g_{ei} = g_{e1} k_{ui}^{-1}, \tag{1}$$

where g_{e1} – the specific fuel consumption by total (100 %) engine loading.

It follows from what was said before that efficient tractors should be used in order to ensure efficient work, and they should be loaded in a proper way by running them at an optimum speed with machines of proper width [6, 8].

It is evident from the graphs (Fig. 1) that the total fuel consumption of the engine per unit of time G_i is function of the engine loading coefficient:

$$G_i = f\, k_{ui}. \tag{2}$$

Further, it follows from this correlation that the ratio of the engine loading k_{ui} may be determined by measuring the fuel consumption G_i in a corresponding moment of time and the data saved in the data logger, and their interpretation using an appropriate computer programme.

The next important characteristic of tractors is the productivity of its work. It can be characterised by specific working efficiency w determined as an amount of the performed work W related to a unit of power.

$$w = W N_e^{-1}. \tag{3}$$

The power N_e of contemporary tractors is generally used for driving the machines with both active and passive working parts:

$$N_e = N_a \eta_a^{-1} + N_p \eta_p^{-1}, \tag{4}$$

where N_a and N_p – the power, correspondingly, for driving the machines with active and passive working parts;
η_a and η_p – coefficients of the power transmissions efficiency.

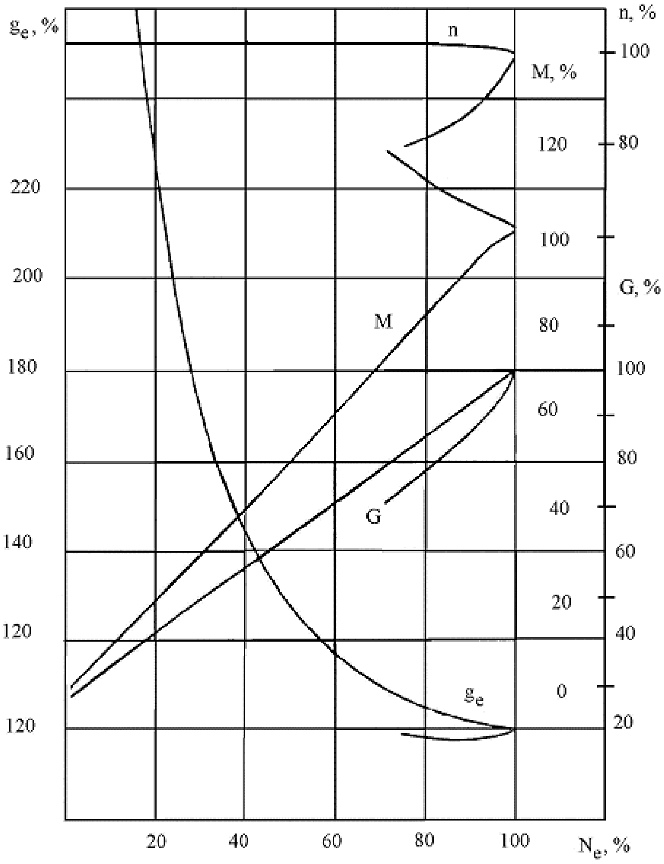

Fig. 1. **Generalised load curves of the tractor diesel engines:** N_e – efficient power, %; n – rotational speed of the crankshaft, %; M – moment of rotation, %; g_e – specific fuel consumption related to a unit of work of engine, %; G – total fuel consumption per unit of time, %

The power for driving machines is a function of resistance R and the working speed v:

$$N_a = f(R_a, v), \tag{5}$$

$$N_p = f(R_p, v). \tag{6}$$

But there are occasions when a part of the engine power may be used for devices, which require a determined driving power irrespective of the working speed of the tractor (for example, the power needed for driving a ventilator, or blowhole). Then there remains less power for driving the machines.

If the tractor is used, for example, only for soil tillage with machines having passive working parts (ploughs, cultivators, etc.), the draft power N_v depends on draft coefficient η_v of the tractor, which is not a constant value, but depends on the working speed [2, 6, 18]:

$$N_v = N_e\,\eta_v = \eta_{vmax}\,e^{-c(v_0 - v)^2}, \tag{7}$$

where e – 2.718 (the basis of the natural logarithm);
v – the working speed of the aggregate;
v_o – the speed corresponding to the maximum draft capacity, (i.e., the speed corresponding to $\eta_{v\,max}$),;
c – a coefficient that depends on the physical and mechanical properties of soil and working capacity (gripping with soil, resistance to movement) of the tractor undercarriage (wheels, caterpillar track);
η_{vmax} – maximum draft coefficient of the tractor.

The tractor has the maximal draft power N_{vmax} at a speed, which ensures maximum draft coefficient.

The values of N_{vmax} , c , v_0 *and* η_{vmax} were determined by testing.

Energetic characteristics of the machines used

The efficiency of tractors depends, to a great extent, on the energetic characteristics of the machines used with this tractor.

The amount of energy consumed for soil tillage with the machines having passive operating parts depends on their specific draft resistance [5]:

$$E_m = K_1 = k_1^{/} + \varepsilon_1 v^2, \tag{9}$$

where E_m – the specific energy capacity of soil tillage, Nm m^{-2};
K – the specific draft resistance of the machine, N m^{-1};
$k_1^{/}$ – a generalised (total) specific static resistance related to a unit of the working width, N m^{-1};
ε_1 – the dynamic resistance coefficient related to a unit of the working width, Ns^2 m^{-3};
v – the working speed of the machine, m s^{-1}.

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 the machines with active working parts in addition to these draft resistance one must determine the resistance moment (torque moment) too.

Modes of aggregation, optimisation the parameters of aggregates

Only such aggregates are to be used that ensure the work with a maximum efficiency and minimum fuel consumption. For example, in soil tillage this can be achieved by aggregates of optimum width working at optimum speed. The pure (net) efficiency of the aggregate W is determined by the ratio of the draft efficiency N_v developed by the tractor and the specific efficiency N_1 required to operate the machine (related to the 1 m working width) [2, 5, 18, 19]:

$$W = B\,v = v\,k_n N_v N_1^{-1}, \tag{10}$$

where k_n – the loading coefficient of the engine (the use of power) (k_n = 0.75-0.95);
B – the working width of the aggregate.

The value of the draft power N_v and of the specific power N_1 required for running the machine varies with the speed of the movement:

$$N_v = N_{v\,max}\, k_{af}\, k_n\, e^{-c\,(vo-v)^2}, \tag{11}$$

$$N_1 = 2.73 \cdot 10^{-3}(k_1^{1} v + \varepsilon_1 v^3), \tag{12}$$

where $N_{v\,max}$ – the maximum draft power of the tractor in the stubble under standard conditions, kW;
k_{af} – a coefficient that characterises the impact of soil conditions on the maximum draft power of the tractor.

Since the values of the draft power developed by the tractor and the power that is necessary to run the machine vary with the speed, the labour efficiency changes too, as shown in the formula:

$$W = 366.8\, N_{v\,max} k_{af}\, k_n\, k_n\, e^{-c\,(v_o - v)^2}(k_1^{1} v + \varepsilon v^2)^{-1} \quad [\text{ha h}^{-1}]. \tag{13}$$

By calculating the labour efficiency according to formula (13) at different speeds one can find optimum speed v_{opt} at which the efficiency of the aggregate is the greatest. In this formula the ratio:

$$k_n\, e^{-c\,(v_o - v)^2}\,(k_1^{1} v + \varepsilon v^2)^{-1} = w \tag{14}$$

indicates the specific working efficiency w of the soil tillage aggregate determined as an amount of the performed work related to a unit of the tractor draft power.

Knowing the optimum working speed it is possible to determine from this same relationship (13) the corresponding (optimum) working width of the machine B_{opt} in metres:

$$B_{opt} = 366.8\, N_{v\,max}\, k_{af}\, k_n\, e^{-c\,(v_o - v_{opt})^2}\, (k_1 + \varepsilon_1 v^2_{opt})^{-1}\, v^{-1}_{opt} \text{ [m]}. \qquad (15)$$

The specific fuel consumption Q_0 for soil tillage (ploughing, cultivation, harrowing, etc.) can be determined by the formula [2-4]:

$$Q_0 = 2.778 \cdot 10^{-6}\, g_e\, \eta^{-1}_{v\,max}\, (k_1 + \varepsilon_1 v^2)\, e^{c\,(v_o - v)^2} \text{ [kg ha}^{-1}\text{]}. \qquad (16)$$

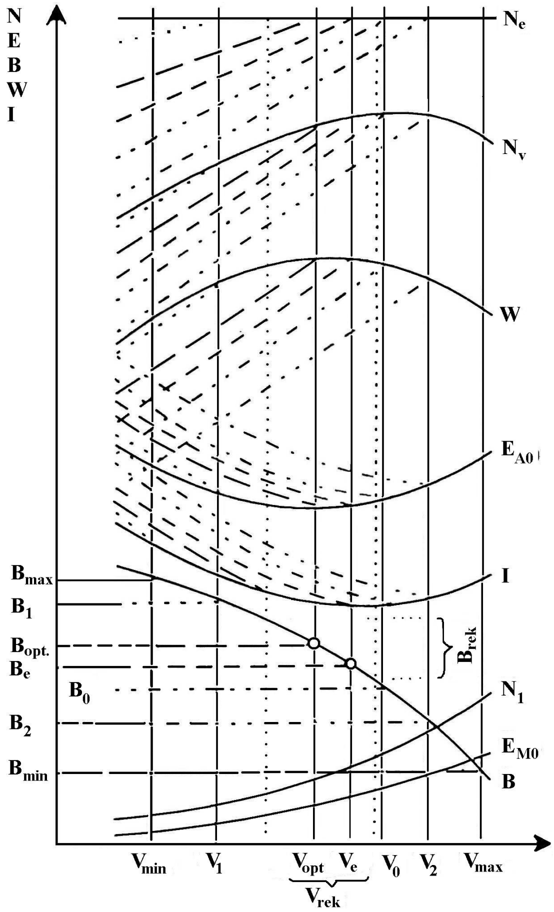

Fig. 2. **Variations of the energetic and economical characteristics of soil tillage aggregates depending on the working speed and width of the machine:** N_e – the efficient power of the tractor engine; N_v – the tractor draft power; N_1 – specific power required to run the machine (related to 1 m of its working width); B – the working width of the aggregate; W – working efficiency of the aggregate; E_{Mo} – specific energy consumption of the machine (for tilling a unit of area); E_{Ao} – specific energy consumption of the aggregate (for tilling a unit of area); I – soil tillage costs; v_{min}, v_{max} – the working speeds (minimum and maximum) corresponding to agrotechnical requirements; v_0 – the speed at which the tractor develops maximum draft power; v_{opt} – the optimum working speed of the aggregate that ensures maximum working efficiency at minimum energy (fuel) consumption ($v_{opt} < v_0$); the economic working speed of the aggregate at which the soil tillage costs are minimal; ($v_e > v_{opt}$); B_{opt} – the optimum working width of the aggregate; B_e – the economic working width of the aggregate; v_{rek} – the range of recommended working speeds for the aggregate; R_{rek} – the range of recommended working widths of the aggregate; $v_1 ... v_2$ – the range of available working speeds of the tractor.

----------- – variations of the characteristics of the aggregate at a full loading of the tractor engine;

. . . . . . , -- -- --., - - - - , -..-..-.. - , -...-...-… – variations of the characteristics of the aggregate at a partial loading of the tractor engine

Direct costs I are formed from the sum of labour costs a (salaries for the workers with transfers), expenditure on fuel and lubricants d, expenses R on repairs of the tractor and machines and technical maintenance, as well as amortisation deductions A (of the tractor and machines), i.e. deductions for the purchase of new machinery [2, 7]:

$$I = a + d + R + A. \tag{17}$$

Variations of the energetic and economical characteristics of soil tillage aggregates depending on the working speed and width of the machine are given in Fig. 2.

The optimum speed of contemporary energy-saturated high-speed wheeled tractors during soil tillage that ensures maximum labour efficiency with minimum consumption of fuel and means is 7-9 km h^{-1}. It is by 25-30 % lower than the speed at which these tractors develop maximum draft power (10-12 km/h) [2, 6].

The economic working speed at which the costs of soil tillage are the lowest is a little greater (10-15 %) than the optimum one. The more expensive the machine and the cheaper the labour and fuel force are, the greater is this speed [2, 6].

Under Latvian conditions the best are mounted (hang-up) aggregates, also multisection wide aggregates during the operation of which it is possible to transfer their extra weight (in order to perform technological operations) to the tractor using the automatic control system of the tractor hydraulic hitch-up device, hydraulic loaders or other analogous means (the support of the frontal part of the machine on the wheels of the tractor) [2, 3, 6, 8].

Indices for the choice and efficient use of tractors, farm machines and aggregates

The efficiency of choosing and using the farm tractors and machines may be defined by several coefficients, such as the coefficient of extensive usage k_{ex}, the intensive usage k_{int} and the effective usage k_{ef} [9, 17] and presented by the following expressions:

$$k_{ex} = T_f\, T_m^{-1}, \tag{18}$$

$$k_{int} = W_f\, (W_{opt}\, \tau)^{-1}, \tag{19}$$

$$k_{int} = k_{ef}\, k_{int}\,, \tag{20}$$

where T_f and T_m – the actual working time and the maximum available working time;
W_f and W_{opt} – the actual labour productivity and the available productivity by optimal parameters;
τ – coefficient of the usefulness of time for fulfilling the work.

$$\tau = T_n\, T_f^{-1}, \tag{21}$$

where T_n – the net working time.

Conclusions

As a result of the studies of the references, a series of criteria were found out how to estimate the efficiency agricultural tractors used in the field crop cultivation. These criteria are:

- the specific fuel consumption of the tractor engine;
- the load coefficient of the engine;
- the power of the engine;
- the specific working efficiency;
- coefficients of the power transmission efficiency;
- the draft coefficient of the tractor;
- the energetic characteristics of machines: the coefficients of the static and the dynamic resistances;
- indices of the optimal parameters – the working speed and width of the soil tillage aggregates;
- specific fuel consumption;
- coefficients of extensive, intensive and effective usage of tractors and machines;
- the efficiency coefficient of the time consumed for work;
- the costs of the fulfilled operations.

References

1. Witney Brian. Choosing and using farm machines. Land Technology Ltd, Edinburgh, Scotland UK, 412 p.
2. Vilde A. Cost-Efficient Soil Tillage. Ulbroka, Latvia, 1997, 49 p.
3. Vilde A. Energetic and economic estimation of soil tillage systems. Folia Universitatis Agriculturae Stetinensis 195. Szczecin, 1999, pp. 213-222.
4. Vilde A. More-environment-friendly cost-efficient soil tillage. Field technologies & environment. Proceedings of the International Conference EurAgEng. Raudondvaris, 1998, pp. 42-61.
5. Vilde A. Energetic estimation of soil tillage machines by testing. Theoretical motivation and methods. Proceedings of the Latvia University of Agriculture, Vol. 13 (290), 1998. Jelgava, 1998, pp. 39-47.
6. Cesnieks S., Vilde A., Rucins, A., Cesnieks A. Economical efficiency of the parameter optimisation of soil tillage aggregates. International Scientific Conference “Motor Vehicle, Logistics, Alternative Fuels.” Proceedings April 24, 2003. Jelgava, Latvia, 2003, pp. 146–151.
7. Betriebsplanung Landwirtschaft 2006/07. KTBL-Datensammlung 20. Auflage 2006. Herausgeber Kuratorium für Technik und Bauwesen in der Landwirtschaft e. V (KTBL) Darmstadt, 672 S.
8. Vilde A. Lieljaudas traktoru izmantošana. Rīga: Liesma, 1976. - 144 lpp.
9. Lazarevs A. Racionāli vadīsim mehanizatoru darbu. Gr.: Jaunākās atziņas lauksaimniecības mehanizācijā. Rīga: ZTIP, 1974, 54-68. lpp.
10. Иофинов О.А. Эксплуатация машинно-тракторного парка. Москва: Колос, 1974, 480 с.
11. Кацыгин В.В. Основы теории выбора оптимальных параметров мобильных сельскохозяйственных машин и орудий. В кн.: Вопросы сельскохозяйственной механики, т. XIII. Минск: Урожай,1964, с. 5-147.
12. Колобов Г.Г., Парфенова А.П. Тяговые характеристики тракторов. Москва: Машиностроение, 1972, 153 с.
13. Копик Н.П., Виестурс Д.Э. Определение эксплуатационных показателей загрузки двигателя комбайна. В кн.: Механизация и электрификация сельского хозяйства (Труды Латв. НИИМЭСХ), т. I (VIII). Рига: Звайгзне, 1975., с. 194-199.
14. Копик Н.П. Определение загрузки трактора Т-150К сприцепом 1 ПТС-9 на транспортной работе. В кн.: Механизация и электрификация сельского хозяйства (Труды Латв. НИИМЭСХ), т. II (IX). Рига: Звайгзне, 1976, с. 83-88.
15. Копик Н.П. К вопросу колебания загрузки двигателя трактора при работе в производственных условиях. В кн.: Механизация и электрификация сельского хозяйства (Труды Латв. НИИМЭСХ), т. IV (XI). Рига: Звайгзне, 1978, с.83-88.
16. Копик Н.П., Путан Х.Э. Устройство для регистрации и нанесения параметров работы мобильного агрегата на машинные носители информации. В кн.: Механизация и электрификация сельского хозяйства (Труды Латв. НИИМЭСХ), т. VI (XII). Рига: Звайгзне, 1980, с. 58-64.
17. Лазарев А.А. Состояние и пути дальнейшего внедрения комплексной механизации в сельскохозяйственное производство республики. Труды Латв. НИИМЭСХ, т. I, Рига, 1967, с. 262–313.
18. Вилде А.А. К теории определения оптимальной ширины захвата и скорости движения почвообрабатывающих агрегатов. В кн.: Механизация и электрификация сельского хозяйства (Труды Латв. НИИМЭСХ), т. I (VIII). Рига: Звайгзне, 1975., с 20–42.
19. Вилде А. А. О подборе ширины захвата и скорости работы почвообрабатывающих агрегатов. В кн.: Механизация и электрификация сельского хозяйства (Труды Латв. НИИМЭСХ), т. II (IX). Рига: Звайгзне, 1976, с. 3–14.