SIMULATION OF THE IMPACT OF THE ENERGETIC CHARACTERS OF TRACTORS AND MACHINES ON THE WORKING EFFICIENCY OF THE SOIL TILLAGE UNITS

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ABSTRACT
For soil tillage only those tractor-machine units (aggregates) should be used which ensure their 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 design and applications parameters. Analytical relationships, deduced as a result of theoretical studies and confirmed by experimental data, allow simulation performance of soil tillage depending on the energetic characters of tractors and tillage machines that determine optimal parameters, such as the design, working speed and working width of the soil tillage tractor-machine aggregates, providing maximum labour efficiency at minimum fuel consumption and costs. During soil tillage the optimum speed of contemporary energy-saturated high-speed wheeled tractors 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^{-1}).

Keywords: analytical relationships, soil tillage aggregates, optimal working speed, optimal working width.

1. INTRODUCTION

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 (Lazarev 1967). The application intensity of tractors and machines, as well as their aggregates is characterized by their working capacity per unit of time. 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 (Cesnieks et al. 2003; Vilde 1999; Witney 1996). One of the ways how to raise labour efficiency, 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 (Witney 1996; Vilde 1976, 1997).

The purpose of this study is, by applying simulation methods, to determine the favourable design of tractor-machine units for soil tillage and their optimal parameters: working speed and width.

2. MATERIALS AND METHODS

The objects of research are: the design of the tractor-machine units (aggregates), their parameters and working regimes. Theoretical and experimental studies are carried out in order to determine the energetic characteristics of tractors and tillage machines and simulation their effect on labour efficiency, energy (fuel) consumption, costs and optimal parameters of soil tillage aggregates (Vilde 2004; Rucins et al. 2005).

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 (Cesnieks et al. 2003; Vilde 1976, 1998). These methods are applied to optimise the parameters of the tractor-machine aggregates.

The energetic characteristics of the tractors are determined by engine power N_e, it specific power $N^/$ related to the unit of the tractor mass and specific fuel consumption g_e, by the tractor draft power N_v and their available changes of the working speed and conditions (Vilde 1976, 1997).

The energetic characteristics of the soil tillage machines with passive working parts are determined by their static and dynamic resistance coefficients (Vilde 1976, 1998).

3. RESULTS AND DISCUSSION

3.1. The energetic characteristics of tractors

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, g(kWh)$^{-1}$ and the coefficient of its employment for the useful work k_u (soil tillage). 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) (Vilde 1997), 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.

An important factor in fuel consumption is the engine loading. Figure 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) (Vilde 1997). 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 (Fig. 1).

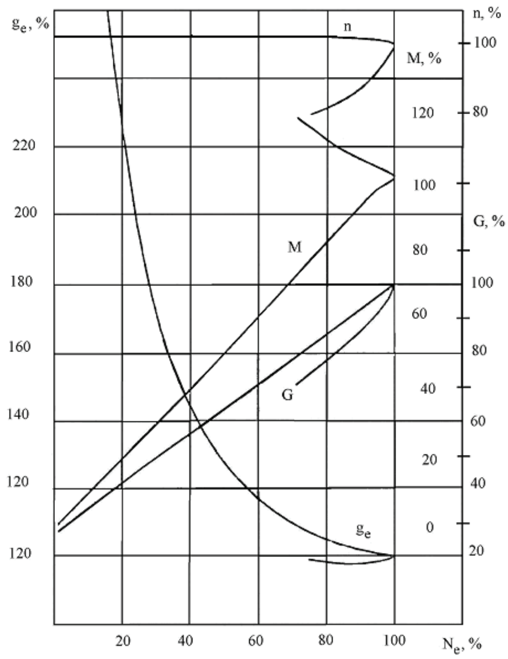

Figure 1: Generalised load curves of the tractor diesel engines: N_e – the efficient power, %; n – the rotational speed of the crankshaft, %; M – the moment of rotation, %; g_e – the specific fuel consumption related to a unit of work of engine, %; G – the total fuel consumption per unit of time, %

Running underloaded engine decreases correspondingly the efficiency of the aggregate, increases the time spent on tilling, as a result of it, salaries, which makes soil tillage still more expensive.

$$g_{ei} = g_{el}\, k_{ui}^{-1}, \qquad (1)$$

where g_{el} – the specific fuel consumption at a 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 (Cesnieks et al. 2003; Vilde 1976, 1997).

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

$$G_i = f\,(k_{ui})\,. \qquad (2)$$

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.

$$w = W N_e^{-1}\,. \qquad (3)$$

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

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

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

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

$$N_a = f(R_a, v) \quad \text{and} \quad N_p = f(R_p, v)\,. \qquad (5, 6)$$

But there are occasions when a part of the engine power may be used for devices which require a certain 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 the draft coefficient η_v of the tractor, which is not a constant value, but depends on the working speed (Vilde 1997, 1976; Kolobov et al. 1972):

$$N_v = N_e\, \eta_v = \eta_{v\,max}\, e^{-c\,(v_o - v)^2}, \qquad (7)$$

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 the working capacity (gripping with soil, resistance to movement) of the tractor undercarriage (wheels, caterpillar track);

$\eta_{v\,max}$– the maximum draft coefficient of the tractor.

The tractor has the maximal draft power $N_{v\,max}$ at a speed which ensures a maximum draft coefficient.

The values of $N_{v\,max}$, c , v_0 *and* $\eta_{v\,max}$ were determined by testing.

3.2. The 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 (Vilde 1998):

$$E_m = K_1 = k_1^{/} + \varepsilon_1 v^2, \qquad (8)$$

where E_m - the specific energy capacity of soil tillage, Nm m^{-2}; K_1 - 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, Nm^{-1}; ε_1 - the dynamic resistance coefficient related to a unit of the working width, N s^2 m^{-3}; v - the working speed of the machine, m s^{-1}.

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

$$E_m = 2.778 \cdot 10^{-3} K_1 , \quad \text{kWh ha}^{-1}. \qquad (9)$$

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.

3.3. 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 1 m working width) (Vilde 1997, 1976):

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

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:

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

$$N_1 = 2.778 \cdot 10^{-3} (k_1^{1} v + \varepsilon_1 v^3), \qquad (12)$$

where: $N_{v\,max}$ - the maximum draft power of the tractor working 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 W (ha h^{-1}) changes too, as shown in the formula:

$$W = 366.8\, N_{v\,max} k_{af} k_n e^{-c\,(v_o - v)^2} (k_1^{1} + \varepsilon v^2)^{-1} \qquad (13)$$

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:

$$k_n e^{-c\,(v_o - v)^2} (k_1^{1} + \varepsilon v^3)^{-1} = w \qquad (14)$$

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:

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

The specific fuel consumption Q_0 (kg ha^{-1}) for soil tillage (ploughing, cultivation, harrowing, etc.) can be determined according to the formula (Vilde 1997):

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

Direct costs I are formed from the sum of labour costs a (salaries for the workers with transfers), the expenditure on fuel and lubricants d, the expenses R on repairs of the tractor and machines and technical maintenance, as well as the amortisation deductions A (of the tractor and machines), i.e. deductions for the purchase of new machinery (Vilde 1997):

$$I = a + d + R + A\ . \qquad (17)$$

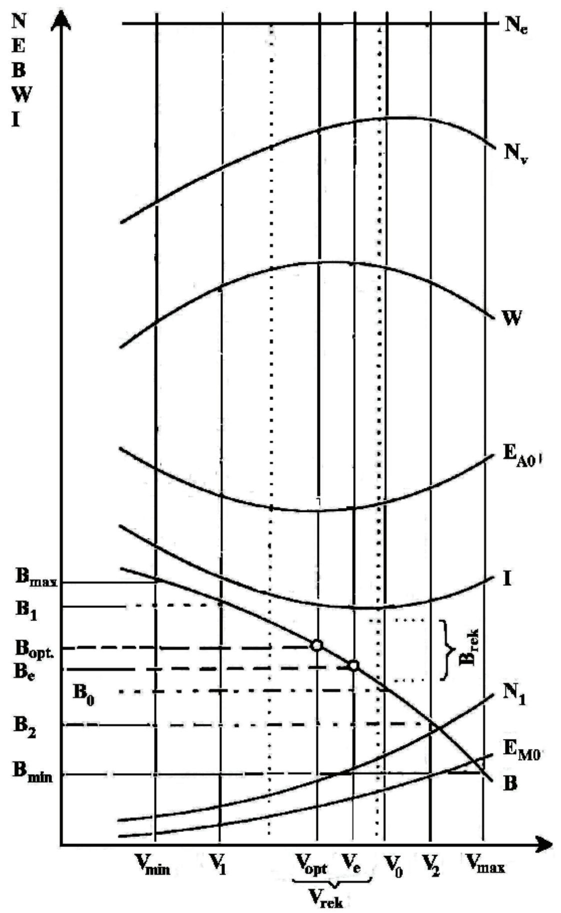

Figure 2: The scheme of variations of the energetic and economical characteristics of soil tillage aggregates (at a full loading of the tractor engine) depending on the working speed and the width of the machine: N_e – the efficient power of the tractor engine; N_v – the tractor draft power; N_1 – specific power required to run the machine (related to 1 m of its working width); B – the working width of the aggregate; W – the working efficiency of the aggregate; E_{Mo} – the specific energy consumption of the machine (for tilling a unit of area); E_{Ao} – the specific energy consumption of the aggregate (for tilling a unit of area); I – the 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 a minimum energy (fuel) consumption ($v_{opt} < v_0$); v_e-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; B_{rek} – the range of recommended working widths of the aggregate; $v_1...v_2$ – the range of available working speeds of the tractor.

The scheme of variations of the energetic and economical characteristics of the soil tillage aggregates depending on the working speed and width of the machine are given in Figure 2.

It is evident from Figure 2 that the specific power required to operate the machine N_l and the specific energy requirement E_{Mo} increase with the increase in the speed of work v. Increasing the speed, the draft power N_v developed by the tractor rises reaching its maximum, after that it decreases. The specific energy requirement E_{Ao} of the aggregate needed for tilling soil falls with the rise in speed and reaches its minimum, then it rises again (at a full loading of the engine). The soil tillage costs *I* vary in a similar way. At an optimum speed when the aggregate reaches maximum efficiency the energy requirement and, consequently, fuel consumption and costs of soil tillage are minimal (at a full loading of the engine).

It is also clear from Figures 1 and 2 that, in case the tractor is not loaded (it works with a small width and at a low speed), the efficiency of the aggregate decreases but the energy (fuel) requirement for soil tillage and costs increase correspondingly. Therefore one should work in the range of recommended speeds v_{rek} with the corresponding working widths B_{rek} of the machine at a full loading of the engine.

The optimum speed of contemporary energy-saturated high-speed wheeled tractors that ensures maximum labour efficiency with minimum consumption of fuel and means during soil tillage 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^{-1}) (Vilde 1997, 1976).

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 is, and the cheaper the labour force and fuel are, the greater is this speed (Cesnieks et al. 2003).

The best aggregates under Latvian conditions are the mounted (hang-up) aggregates, including the wide multi-sectional 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) (Vilde 1997).

The results obtained by simulating the operation of the soil tilling units are confirmed in experimental tests. They show a close relationship among the parameters of aggregation, the mode of operation (speed, engine loading), the efficiency of the soil tilling aggregates, the specific fuel consumption and the expenses.

As an example, variations of energetic and economic indices of ploughing rocky soils with ploughs of different working widths depending on the speed are shown in Figure 3.

It is evident from diagrams (Figure 3) that at a low working speed ($v \approx 5$ km h^{-1}) with a plough of insufficient working width the labour productivity of the aggregate decreases almost by half, but the specific fuel consumption increases by 20-30% (3-4 kg ha^{-1}), and the costs rise by 20-30% (3.70-7.40 € ha^{-1}), in contrast to the work at an optimum speed with a machine of an optimum width.

It is evident from diagrams (Figure 3), too, that, by their energetic characteristics (the values and alteration of the specific draft resistance K_l), both of 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 2-body plough ATA-2-40 with the KAUR-40 AGS bodies (with the specific fuel consumption of ~20 kg ha^{-1}) is much worse than the other 3-body plough PGP-3-35 with the Kverneland bodies No 8 (with the specific fuel consumption of ~17 kg ha^{-1}) at approximately the same speed ~ 1.5 m s^{-1}.

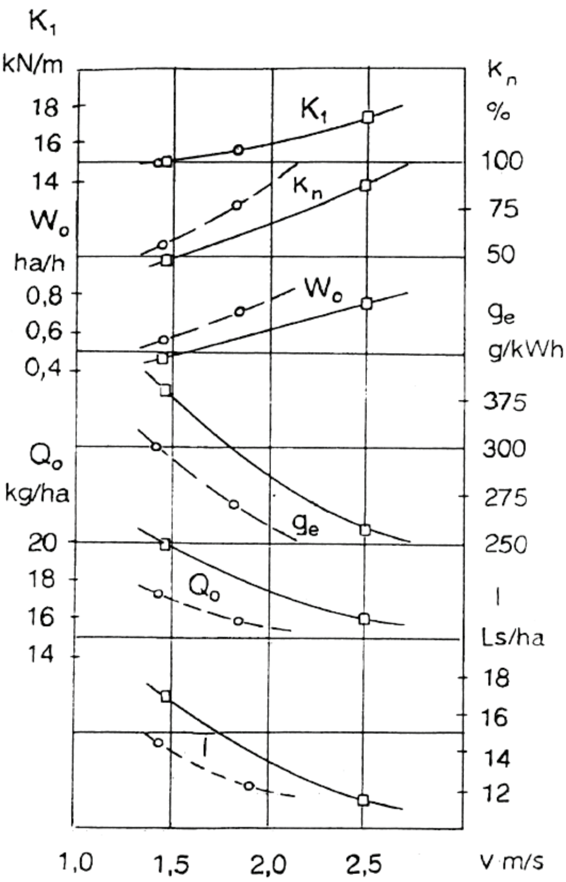

Figure. 3. Variations in energetic and economic characteristics of ploughs for rocky soils with different working widths depending on the speed of ploughing:

K_l – the specific resistance of the plough, kN m^{-1};

k_n – the loading of the tractor engine, %;

W_0 – the efficiency of the direct work, ha h^{-1};

g_e – the specific fuel consumption of the engine, g (kWh)$^{-1}$;

Q_o – the specific fuel consumption, kg ha^{-1};

l – the ploughing costs, Ls ha^{-1} (1Ls ≈ 1.5 €);

□ - a 2-body plough ATA-2-40 with the KAUR-40 AGS bodies;

○ - a 3-body plough PGP-3-35 with the Kverneland bodies No. 8.

The field tests of the improved plough PGP-3-35 on the peasants' farms show the following agro-technical and economical results:

- By replacing the bodies PGC 61000 of the plough PGP-3-35 with the KAUR-40 AGS bodies (the working width of each body 50 cm) and rebuilding it into a 2-body variant (PGP-2-50 with the working width 1.0 m) for more rational work with the tractor MTZ-82 (55 kW), the fuel economy is 15-20%.
- Increasing the working width of the plough bodies by 50 cm (PGP-3-50 with the working width 1.5 m) the fuel consumption of the tractor MTZ-952 (66 kW) decreases by 25-30%.
- There is a possibility of qualitative (up to 96%) and cheap (without previous shredding) introduction of the siderate (catch crop) plants and long-stalk stubble into soil thus saving 1.4-1.8 man h ha^{-1}, fuel 6-8 kg ha^{-1}, the financial resources – 8…11 USD ha^{-1}.
- Rebuilding the ploughs reduces the expenditure of the ploughshares by 30%.

The other bigger ploughs of the PGP family have been rebuilt by a similar scheme (for PGP-7-40 the working width increases from 2.8 m to 3.2…3.6 m).

Similar results are obtained with the cultivation aggregates (Vilde 1998).

The experiments, carried out with the soil tillage tractor-machine aggregates, confirmed the results obtained by simulating their operation.

CONCLUSIONS

1. Analytical relationships deduced as a result of theoretical studies and confirmed by experimental data allow simulation of the operation of soil tillage tractor-machine units in order to determine their optimal parameters, such as the design, working speed and working width, providing maximum labour efficiency at a minimum fuel consumption and costs.

2. The best soil tillage aggregates under the Baltic conditions are tractors with mounted machines, also wide multi-section aggregates during the operation of which it is possible to transfer extra weight of the machines (in order to perform technological operations) to the tractor using the automatic control system of its hydraulic hitch-up device.

3. Improvements of 3-7 body ploughs for rocky soils by equipping them with high-speed semi-helicoidal bodies having an increased operating width up to 50 cm, and the corresponding increase in the total working width of the whole plough for the work with more powerful tractors are technically and agro-technically possible and profitable. This reduces the specific draft resistance of ploughs by 14…26%, raises their efficiency by 25…42%, decreases the specific fuel consumption by 16…24% (3…4 kg ha^{-1}), and lowers correspondingly the ploughing costs.

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A. Vilde has received several medals and diplomas at the Exhibition of Economic Achievements in Moscow. In 1985 he received the Lavian State Prize. He was named a Merited Inventor of Latvia in 1990, International Man of the Year for 2000-01 and a Latvian State Emeritus Scientist 2001. He is an expert of promotion councils and a publicist who has written more than 800 publications including eighteen monographs. He enjoys orchards and stenography. With his late wife Velta, he has four children and eleven grandchildren. His e-mail address is vilde@delfi.lv

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