

Rationale for Measurements to be Selected for Tractors to Perform Agricultural Activities Differing in Energy Intensity

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Abstract. The topic is relevant due to the need to improve basic measurements of tractors, considering a major contribution they make to crop production, not only during separate technological operations, but also during a whole sequence of technological operations performed. The paper analyzes the limits to which the basic measurements of tractors (weight and engine power), which are used to perform a combination of technological operations requiring different energy consumption, can be altered and to identify practical limits to perform a combination of low and high energy-consuming activities. The key research method used is mathematical modeling based on system analysis and computational experiments that are carried out using models of implements during various technological operations. The results of calculations analyzed for technological operations that differ in the amount of energy consumed suggest that for each of the groups of technological operations that require similar amount of energy (soil resistivity per meter of working width, kN/m), there are fairly stable values of the basic measurements of tractors. A reasonable weight for tractors to perform operations such as harrowing, continuous cultivation of soil with a resistivity of 1 to 4 kN/m is 35-60 kN. For soil preparation with a resistivity of 4 to 8 kN/m it is 100-120 kN, for plowing with a resistivity from 10 to 16.25 kN/m – equal to 160 kN, for tillage with subsoilers with a resistivity from 8 to 16 kN/m – equal to 240 kN. Once put to practice, the findings will lead to a decrease in total energy consumption to 10,000 MJ/ha. The amount of saved energy costs depends on the type of technological operation, the parameters of tractors used, the characteristics of agricultural implements, soil properties, etc.

1 Introduction

The farming system aligned with the conditions of the Republic of Tatarstan [1-9] divides farming technologies by the rate of crop production into extensive; basic (normal); intensive and high with a non-linear sequence of technological operations. Any agricultural technology includes absolutely mandatory technological operations based on the use of tractor-implement system, presently, sowing. Another group of technological operations is relatively mandatory, including soil cultivation, fertilization, etc. The last group of technological operations refers to a variable group implying techniques of plant protection, root feeding, etc. The authors here are primarily interested in a large variety of once-over tillage operations featuring in most of the listed agricultural technologies. It is here that tractors are widely used as power sources, and considerable financial and energy resources are consumed. Due to various reasons, all types of agricultural technologies mentioned are currently exploited in the agrarian sector of the Republic of Tatarstan and the Russian Federation. The extensive technologies rely on moldboard variable-depth tillage – ploughing, pre-sowing, packing, etc. The basic

technologies employ soil-protecting combined, variable-depth tillage with ploughshares, cultivators, disc harrows and combined implements. Intensive technologies should be employed for differentiated minimized variable-depth tillage, alternating processing depth by crops and years. Crop cultivation operations can be conditionally classified into three groups subject to the amount of energy consumed, namely: low-input operations (harrowing, sowing on prepared soil, packing, etc. with a specific resistivity of 1 to 4 kN/m); medium-input technological operations (shallow variable-depth tillage, sowing with combined aggregates, etc. with a resistivity of 4 to 8 kN/m); high-input technological operations (plowing, chiseling, etc. with a resistivity of 8 to 16 kN/m).

The paper is an offshoot of a series of research towards improving technical parameters, with some of the findings to be presented in the papers [10-12].

The paper proposes some findings towards a rationale for sustainable basic measurements of tractors and implements for technological operations, classified by energy intensity, measured in kN/m and for a combination of operations featuring in different groups. With no effective methods to address this challenge, sensitive to the parameters of tractors and tractor-

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implements systems that have an impact on grain crops produced, it turns from a mere production issue into a scientific problem.

2 Materials and Methods

The study was based on a mathematical model describing tractor-implement systems, compiled using theoretical and experimental findings, by-and-large enunciated in [9-11].

To get an idea of those impacts that machinery measurements are likely to have on yield losses, the authors reiterate the criterion for improving equipment measurements in an energy mathematical model [9].

“The criterion for improving the measurements of tractors and implements is total energy consumption per hectare of operations performed:

$$E = E_{m.t.} + E_{m.aci} + E_{rm} + E_{a.d.} + E_c + E_f + E_{agr} + E_{pack} \rightarrow \min, \quad (1)$$

where E is the specific total energy consumption, MJ/ha; $E_{m.t.}$ and $E_{m.aci}$ is the amount of energy consumed, respectively, on the manufacture of a tractor and an agricultural implement per 1 ha, MJ/ha; E_{rm} is the energy consumed for all types of repair and maintenance practices to keep a tractor and agricultural implement operational, MJ/ha; $E_{a.d.}$ is the energy consumed for assembly and disassembly of a seed drill, MJ/ha; E_c is the energy consumed by an operator to control a machine (turning, stopping and starting off and shifting gears), MJ/ha; E_f is the energy spent on fuel consumed, MJ/ha; E_{agr} is the energy of harvest lost due to violated agrotechnical terms for a technological operation, MJ/ha; E_{pack} is the energy of harvest lost due to soil packing by tractor propellers, MJ/ha” [9].

A calculation algorithm consists in finding by a numerical method an efficient ratio of the weight of a tractor M_{opt} and the power of its engine N_{opt} for various groups of technological operations, depending on factors – i , with the condition of obtaining the minimum total energy consumption – E .

$$M_{opt} = f(i); N_{opt} = f(i) \text{ if } E \rightarrow \min. \quad (2)$$

Novelty and inventive step of the approach is that it is sensitive to the impacts the machinery measurements have on the volume of yields. Due to improper parameters and operating modes selected for tractors and tractor-implement systems, part of yields is lost. The longer the operation the more the crop yields lost. To eliminate this reason of crop losses, it is necessary to use high-performance implements and heavy-weight high-drawbar tractors. However, in this case soil is packed more, which leads to an increase in yield losses due to suppression of living plants, deterioration of water-air regime in the soil. Hence, it becomes possible to choose the efficient (optimal) parameters for tractors and implements [13-20]. The energy of harvest lost is up to 75-85% of the total energy consumption for technological operations performed in early spring (harrowing, cultivation, sowing, etc.), so it is simply criminal to ignore it.

The main research method is computational experiments based on mathematical models for

implements performing various technological operations united into groups according to energy intensity expressed in kN/m.

Mathematical models of agricultural implements have been verified [10-11].

3 Results

The findings determining the efficient parameters and operating modes selected for drawbar tractor implements to perform various technological operations are partially touched upon in the papers [10, 11] and summarized in Table 1. Table 1 summarizes the findings by splitting technological operations into groups by energy intensity.

The results of computational experiments are shown in Fig. 1,2,3,4,5,6,7,8 in the form of graphs of changes in the parameters of the tractor and the implement, as well as the total energy consumption for technological operations differing in energy intensity, depending on specific resistance of working components of agricultural implements, expressed in kN/m. The resistance of working components turned out to have the greatest impact on the value of parameters preferred for the tractor and the TIS.

As the resistance of an agricultural implement K used for all operations increases, the total energy input E increases too. The working width of B_P implements decreases or remains constant, while the optimal tractor weight M and its engine power N increase (sowing Fig. 1,3,4,5) or remain unchanged (cultivation Fig. 2). The output computation for an Agrator Ancer combine sowing system is shown in Fig. 1.

Belarus MTZ 1000 and 1200 tractors with a weight of 40 to 60 kN and engine power of up to 120 kW are most suitable for the 1st group of technological operations.

The tractors weighing from 7 to 12 tons are most efficient for the second group of technological operations. However, due to the fact that the Lemken Solitair and DMC combine seed drills are manufactured to enable a maximum working width of 12 m, and the Agromaster and Agrator Ancer combine seed drills – 16 m, there is a leap in optimal tractor weight from 12 to 16 tons at high values of specific resistance of seeders (high density, hardness, soil moisture, etc.) (Table 1 and Fig. 3,4,5).

In this regard, for the second group of technological operations, two brands of tractors are recommended, namely K-424 to be combined with agricultural implements enabling a working width of up to 12 m and K-744R-R3 for working as part of combinations with a working width of up to 16 m.

As calculations show, the largest tractor weight (13-24 tons) and its engine power (380-436 kW) are required for plowing and chiseling being the third group of technological operations. The higher the drawbar category, the more productive the tractor, the yield losses from violated agrotechnical terms for these operations decrease, and a growing negative impact of tractor propellers is compensated by deep tillage by 0.25-0.35 m (Table 1 and Fig. 6,7).

The Kirovets K-744R-P4 tractors are recommended for plowing, while for chiseling – 9000 series tractors from various manufacturers are most preferred, including the Kirovets K-9400, New Holland-9060 or John Deere-9430.

Calculations to identify the optimal basic measurements of a tractor designed to perform both low-input and high-input technological operations show that there are optimal measurements that largely depend on

the energy intensity of a technological operation. A certain dependence of total energy consumption on the main measurements of the tractor (weight and engine power) when the tractor is exploited in sowing with a seeder resistance of 4 kN/m and plowing with a specific resistance of 70 kN/m² is shown in Fig. 2. It can be seen from the graph that there is a minimum of total energy consumption for a certain combination of tractor weight (15 t) and its engine power (400 kW).

Table 1. Optimal parameters of machine and tractor units in groups of technological operations, divided by their energy intensity

Group of operations	Technological operation / Brand of agricultural machine	Unit specific resistance, kN/m	Tractor weight, t	Engine power, kW	Recommended tractor brand	Operating width of the unit, m	Unit operating speed, km/h	Total energy costs, MJ/ha
I	Sowing on a prepared surface / SZ-3,6	0,8-2,4	2,6-6,0	60-150	MTZ-800-MTZ-1221	10,8-14,4	8-14 (12)	3800-7400
	Presowing cultivation / KKS	2,4-4,4	3,5-4,2	95-110	MTZ-800-MTZ-1221	5,5-6	11-12	2200-2800
II	Seeding / Lemken Solitair (single disc opener)	3-5	7-12	130-235	BELARUS-3022DV, Kirovets K-424	12	8-14 (12)	8800-15000
	Seeding / DMC (chisel opener)	3,2-5,2	7,2-11,8	154-224		12	8-14 (12)	5000-18000
	Sowing / Agromaster (cultivator opener)	3,2-5,2	10,3-16,7	270-410	Kirovets K-744P1-P4	16	8-14 (12)	5000-16500
	Sowing / Agrator anker (anchor opener)	3,2-5,2	10,3-16,6	265-410		16	8-14 (12)	8000-14200
	Combined tillage / KPIR	4-8	10-11	240-292	BELARUS-3022DV, Kirovets K-424	6,5-13	10-11	4830-9500
	Tillage with disc implements / BDM	4-8	10-12	272-346		7,5-12,5	10,5-12	4500-8900
III	Plowing / PLN, PLP	11,2-18,2	13-16	380-436	Kirovets K-744P2-P4	4,2-5,25	10-12	1600-2400
	Deep loosening of the soil / PGP	8-16	24	382-436	Kirovets K-9400 New Holland - 9060, John Deere - 9430	6-11,5	8,5-10	2900-5500
I - III	Sowing SZ-3,6 + plowing PLP	1-4/ 10-20	7-15	220-410	Kirovets K-744P, P1, P2, P3	10-18/ 3,15-4,2	12-13/ 11-13	7728,2- 16494,7
II - III	Cultivation KPIR + plowing PLP	3-6/ 10-20	8-19	210-400	Kirovets K-744P2-P4, New Holland - 9060 or John Deere - 9430	15-18/ 3,85-4,2	9/ 10-11	18746,7- 54950,5
II - III	Sowing Agromaster + PGP	3-5,4/ 8-16	11-19	286-415		16/ 5-7	9-12/ 10-11	12001,6- 26754,3

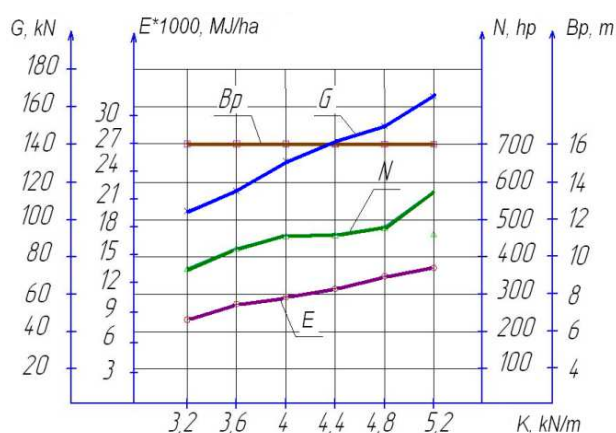


Figure 1. Influence of change in resistance of operating parts of the farm vehicle on optimum values of critical parameters of the sowing unit with the sowing Agrator Ancer system and its total energy consumption

The way the efficient (optimal) measurements of the tractor change as soon as the resistance of the seeder and the plow changes is shown in Fig. 3.

With increasing resistance of agricultural implements by 1 m of working width (K_S – seeders; K_P – plows), the optimal values of the tractor weight M , the power of its engine N and the total energy consumption E grow. The speed of the V_{PS} seeder and V_{PP} plow reduces to a resistance of $K_S=4$ kN/m and $K_P=70$ kN/m², and then increases.

The working width of the B_{PS} seed drill is stable up to $K_S=3$ kN/m (18 m) and then decreases. The working width of the B_{PP} plow steadily increases up to the plow resistance value $K_P=60$ kN/m², and then stabilizes around 3.85 m. The recommended tractors for a combination of these technological operations are the Kirovets K-744R-R3 tractors.

The same calculations carried out when one tractor performs technological operations of the second and third groups show that the type of technological

operation and their combination affects the main measurements of the tractor (Fig. 4.5).

At both combinations of technological operations, with an increase in specific resistance of agricultural implements, the weight of the tractor, its engine power and total energy consumption grow. The power stabilizes at the level of 400 kW, weight – at the level of 190 kN. A recommended range of tractors involves Kirovets K-744R2-R4, New Holland-9060 or John Deere-9430, with the last two tractors to be necessarily used with track scarifiers when they cultivate and sow. An example of a mounted track scarifier, routinely used with the tractor, with adjustable working components is shown in Fig. 6

[17]. The use of this scarifier will compensate for a negative impact that a high tractor weight has on the soil and reach maximum utilization of tractor's capacity when performing the second group of technological operations in early spring, when the risk of soil overpacking is high. The total traction resistance of the track scarifier ranges from 6 to 16 kN. It depends both on the condition of the soil and on the speed of the tractor. The harder the soil and the higher the speed of the machine, the higher the traction resistance of the scarifier. The upper limit of the recommended speed is 12 km/h.

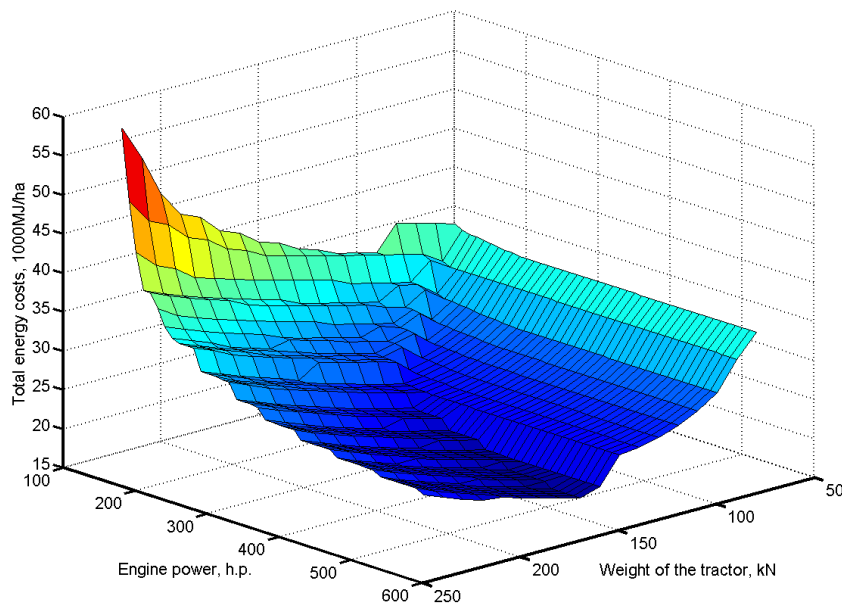


Figure 2. Changes in total energy consumption vs the main measurements of the tractor (weight and engine power) used for sowing and plowing

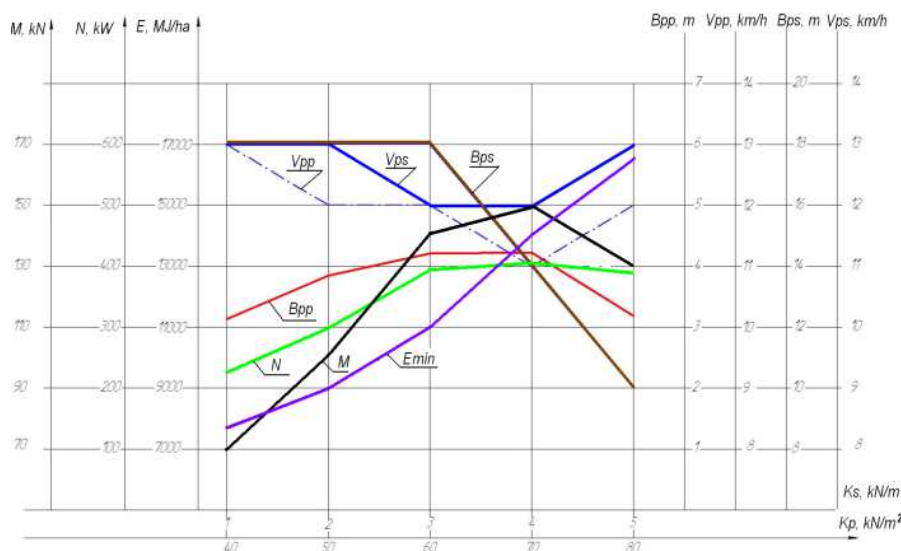


Figure 3. Changes in optimal measurements of implement assembled with standard tractor for combined sowing with SZ seeders and plowing

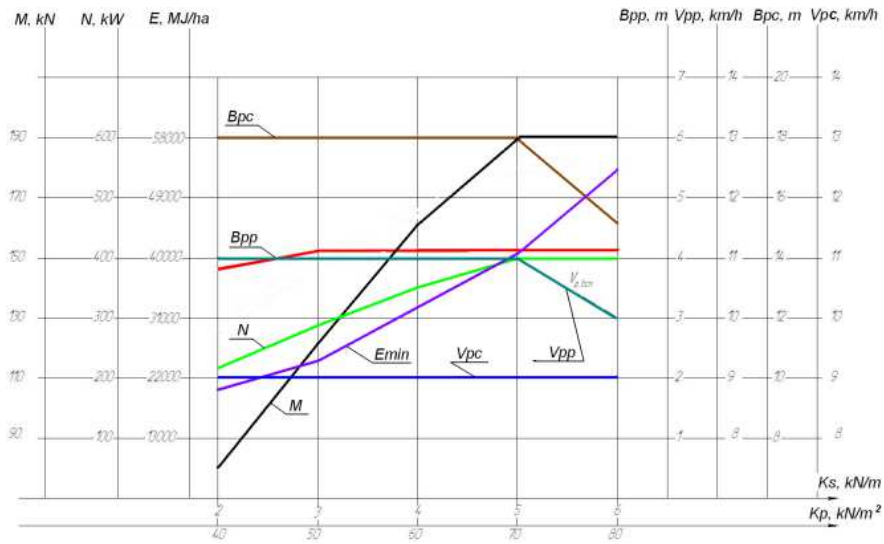


Figure 4. Changes in optimal measurements of implement assembled with standard tractor for combined cultivation with a KPIR cultivator and plowing

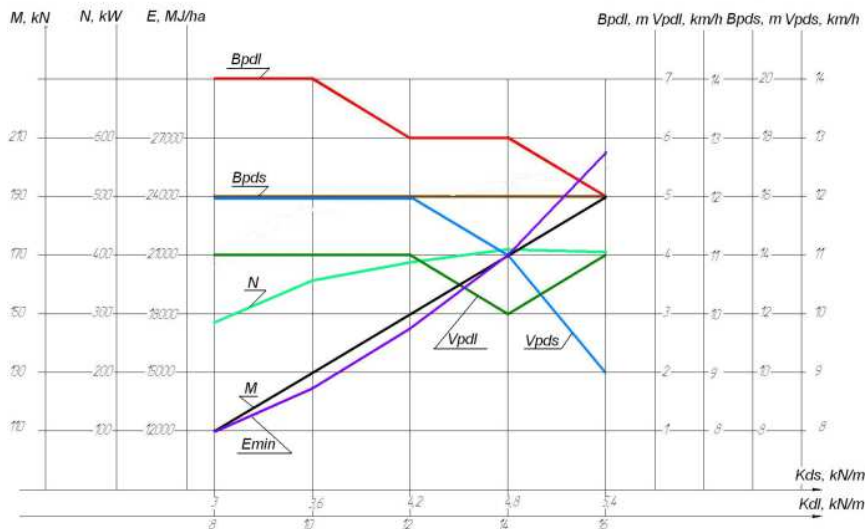


Figure 5. Changes in optimal measurements of implement assembled with standard tractor for combined direct sowing with an Agromaster seeder and chiseling

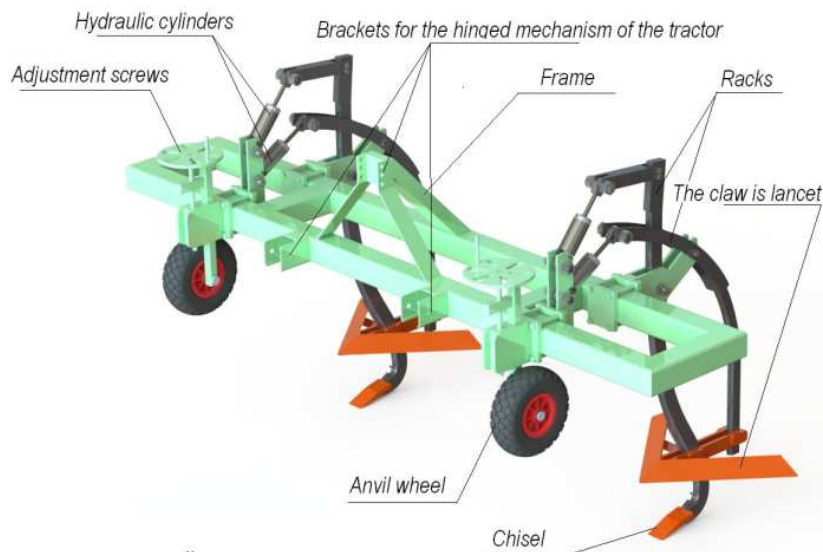


Figure 6. 3D image of a track scarifier with adjustable working tools

4 Conclusion

To provide a rationale for the main measurements to be selected for the tractor and the implement, it is necessary to strive to increase the efficiency of the tractor and the implement not only by maximizing the use of engine power, increasing the tractive efficiency of the tractor, increasing the productivity of the implement, reducing operating costs, but also taking into account that the parameters of the tractor and the implement affect the yield of crops produced, which means that the parameters of the tractor must be selected with due account of the need to reduce the amount of the lost crop. The proposed criterion for improving the measurements of the tractor and the implement, the total energy consumption, allows this work to be systematic.

The proposed method for justifying the weight and power of the tractor and the measurements of the implement made it possible to reveal the efficient values of these measurements both in separate groups of technological operations and when a combination of technological operations varying in energy intensity is performed by one tractor in a single path.

The optimal weight of a tractor used in low-input operations such as harrowing, continuous soil cultivation, sowing with a specific resistance of agricultural implements from 1 to 4 kN/m is 40 kN with a possibility of filling incremental capacity up to 50 kN and above, engine power ranges from 60 to 120 kW.

The second group of technological operations with a specific resistance of agricultural implements from 4 to 8 kN/m can be made up of two subgroups, including operations using implements with a working width of up to 12 m and operations using implements of 16 m or more. To work the soil with combined implements, disc harrows and direct sowing with seeders with a working width of up to 12 m, the optimal tractor weight is 90-100 kN, and the engine power is in the range of 160-300 kW. In this case, tractor weight can be filled up to 120 kN. When utilizing wide-cutting implements with a working width of 16 m and more, it is advantageous to use more massive and powerful tractors with a weight of 140-150 kN and with an engine power of 310-400 kW. Additional filling of the tractor weight up to 170 kN is possible.

The third group of technological operations is represented by plowing and chiseling. For plowing, the most acceptable tractor weight is 160 kN. This weight is maintained when the resistivity of the plow changes in the range from 50 to 70 kN/m². The efficient engine power ranges from 360 to 420 kW.

When soil is cultivated with subsoilers with a traction resistance of working components from 8 to 16 kN/m, the rational weight of the tractor is 240 kN or more, and the engine power is in the range of 382-436 kW.

To perform a combination of technological operations of the first and third groups, the tractor must have a weight of 100 kN with a possibility of filling incremental capacity up to 140-150 kN, the engine power ranges from 220-380 kW.

To perform a combination of technological operations of the second and third groups, the rational

weight of the tractor should be 140 kN with a possibility of filling incremental capacity on heavy soils up to 190 kN, and the engine power should be 290-420 kW.

Due to the fact that the optimal measurements of the tractor are influenced by many factors, including physical and mechanical properties of the soil, the features of technological operations, the speed of the operation, the design parameters of the agricultural implements and other factors, prior to establishing a machine and tractor fleet on farms, it is imperative to provide optimization calculations in order to select the most rational tractors and agricultural implements, taking into account the size of the farm fields, soil properties, cultivated crops, etc.

The recommendations proposed in the paper can be used by large agricultural enterprises in order to reduce the varieties of the machine and tractor fleet, reduce the cost of maintaining equipment in a working condition. The developed recommendations help the manufacturer reduce direct and indirect energy consumption, including the energy of the crop lost.

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