Completing of modern energy-saving machine-tractor units

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Abstract. Labor productivity and crop production of a high quality directly depend on its equipment with the most advanced energy-rich machinery and the use of modern resource-saving technologies. Today, despite the difficult financial situation of agricultural enterprises, their technological infrastructure is implemented without necessary scientific justification, most often at the discretion of particular specialists or for other reasons, but without calculating the optimal composition and structure of the machine-tractor fleet. The units are completed according to the seller and manufacturer recommendations, relying only on the technical characteristics of the tractor and agricultural machine. The article focuses on the problem of completing machine-tractor aggregates, consisting of modern tractors and agricultural machines of domestic and foreign production, which are technically based production rates. For these units, a methodology for their completing, using the potential tractor thrust characteristics, has been developed. A graphic-analytical method for determining the technically based machine production rates is proposed.

1. Introduction
The crop production of a high quality largely depends on the applied modern resource-saving technologies, and also on the provision of the most advanced domestic and foreign energy-rich equipment. Analyzing the science achievements in the field of technologies for the agricultural crop cultivation [1, 2, 3, 4], we have proposed a strategy for the fundamental modernization of the crop production technical re-equipment. Firstly, it is necessary to replace the traditional tractor and combine fleets with already developed new generation equipment, based on calculations of the optimal composition and structure of the fleet, to replace the outdated soil cultivation technologies, the fertilization, plant protection, harvesting systems, to use new innovative solutions in modernizing the machine design, agrotechnical methods, the organization of new machinery use. Among the aforementioned areas of modernization of the crop production technical fit-out, it is necessary to point out on the use of new innovative solutions in the machine design. The main thing here is the use of multifunctional units, the novelty of technical solutions for which is confirmed by scientific developments and patents for inventions and useful models [5, 6] and the use of multifunctional units will improve the quality of the machines and their productivity [7, 8]. Multifunctional units allow to reduce the number of operations during the cultivation of agricultural crops, which accordingly reduces the cost of the resulting crop. However, the use of modern energy-rich technology does not always reduce operating costs. It is not enough to have high-quality modern equipment, it is necessary to use it rationally. At present, the heads of agricultural enterprises, when purchasing new equipment, rarely
think about how to use it rationally in the future. The units are completed at random on the farms, based on the recommendations of the equipment manufacturers. Such recruiting leads to numerous adjustments directly on the working site, unreasonable expenditures of labor, time and operating materials. And it is far from always that a unit assembled in this way can be called rational.

One of the main problems in the formation of the machine-tractor fleet is the lack of technically substantiated production and fuel consumption rates for new equipment, especially for foreign production. Irrationally assembled units have low productivity and increased fuel consumption. In this regard, the purpose of the work is to develop a methodology for completing machine-tractor aggregates (MTA) based on the tractor potential characteristics.

2. Materials and methods
Tractor haulage capacity is of decisive importance in the MTA formation and appliance in agriculture. In recent years, agricultural production has been replenished with new modern tractors of domestic and foreign production, which have not passed drawbar tests at Russian test stations. In light of this, it became necessary to theoretically develop tractors thrust characteristics based on widely known technical data. To develop potential traction characteristics, it is sufficient to have the following data: the effective engine power \( N^e \); the operating tractor weight \( G \); the mechanical transmission efficiency \( \eta_m \); the admissible thruster slip \( \delta_a \); the adhesion coefficient of the tractor thruster to the soil \( \mu \) and rolling resistance coefficient \( f \); the field gradient \( i \); the tractor working speed range \( \left( V_{\text{min}} \ldots V_{\text{max}} \right) \).

As is known [9, 10], the nominal tractor engine effective power \( N^e \) is first lost in the transmission \( (1-N^\eta) \), then it is spent on the thruster slipping \( (N^\delta) \) and the tractor overrolling movement \( (N^f) \), and with the field gradient, it is also spent on grade climbing (or is gained on descending) \( (N^i) \). The remaining effective output \( N^{en} \) can be used to carry out technological processes using the MTA, i.e. to overcome the machines traction resistance, included in the unit \( (N^t_p) \), and to drive their working bodies through the power-takeoff shaft \( (N_{PS}) \) or the tractor hydraulic system \( (N_{hs}) \).

\[
N^{en} = N^e \eta_m (1-\delta) - \frac{GV}{3.6} (f + \frac{i}{100})
\]  
(1)

where \( \eta_m \) – the mechanical transmission efficiency; \( \delta \) – the tractor thruster slip; \( G \) – the operating tractor weight, kN; \( f \) – the tractor thruster rolling resistance coefficient; \( V \) – the MTA motion speed, km/h; \( i \) – the field gradient, %.

At the same time, the aggregate mechanic effect implementation depends on the tractor thruster capacity, which is in contact with soil, for transmitting the required power for the unit operation \( N^u \).

\[
N^u_p = \frac{GV \left[ \lambda \mu (1-\delta_a) - \left( f + \frac{i}{100} \right) \right]}{3.6}
\]  
(2)

From the equality of the formulae (1) and (2), the boundary speed between insufficient and sufficient adhesion of the tractor thruster with a certain soil type \( V_{\mu} \), is determined.

\[
V_{\mu} = 3.6 \frac{N_u^{en} \eta_m}{G \lambda \mu}
\]  
(3)

In the zone from \( V_{\text{min}}^{en} \) to \( V_{\mu} \) (the insufficient adhesion of the tractor thruster to the soil), the tractive effort is limited by the tractor coupling properties and the admissible thruster slipping \( \delta_a \). Here, its value is constant and maximum.
The maximum tractive power $N_{tp}^{\text{max}}$ is achieved at the optimal speed $V_{\text{opt}}$, when the sum of power losses by thruster slipping $N_s$ and tractor overrolling movement $N_{fa}$ is minimal, i.e.

$$N_s^\eta_m \delta_{\text{opt}} + \frac{GV_{\text{opt}}}{3.6} \left( f + \frac{i}{100} \right) \rightarrow \min,$$

where $\delta_{\text{opt}}$ – the tractor thruster slipping coefficient at $V_{\text{opt}}$.

From this expression, finding the first derivative and making transformations, we obtain the calculated value of $V_{\text{opt}}^w$.

$$V_{\text{opt}}^w = \sqrt{\frac{3.6 N_s^\eta_m V_{\mu} \delta_a}{G(f \pm \frac{i}{100})}}$$

If it turns out that $V_{\text{opt}}^w \leq V_{\mu}$ (the slipping is out of allowable limits), then, $V_{\text{opt}} = V_{\mu}$ and $\delta_{\text{opt}} = \delta_a$. If $V_{\text{opt}}^w > V_{\mu}$, (the slip coefficient is less than $\delta_a$), then $V_{\text{opt}} = V_{\text{opt}}^w$.

The optimal tractor towing force $P_{tp}^{\text{opt}}$, corresponding to the maximum tractive power $N_{tp}^{\text{max}}$, is determined from the equation

$$P_{tp}^{\text{opt}} = \frac{3.6 (N_e - N_{\text{pr}} \eta_m) (1 - \delta_{\text{opt}})}{V_{\text{opt}}} - G(f \pm i/100),$$

The maximum tractive power is calculated by the expression:

$$N_{tp}^{\text{max}} = (N_e - N_{\text{pr}} \eta_m) (1 - \delta_{\text{opt}}) - \frac{GV_{\text{opt}}(f \pm i/100)}{3.6},$$

In the zone of thruster sufficient adhesion to the soil (from $V_{\mu}$ to $V_{\text{opt}}^w$), the nature of the change in parameters $N_{tp}^{\eta_m}$, $P_{tp}^{\eta}$, and $\delta$ is curvilinear. The specific values of these parameters are determined for various ($i$-th) motion speeds, included in the considered range, according to the formulas:

$$N_{tp}^{\eta} = N_e^\eta_m (1 - \delta_i) - \frac{GV_i \left( f \pm \frac{i}{100} \right)}{3.6},$$

$$P_{tp}^{\eta} = \frac{3.6 N_e^\eta_m (1 - \delta_i)}{V_i} - G \left( f \pm \frac{i}{100} \right),$$

$$\delta_i = \frac{V_{\mu}}{V_i} \delta_a,$$

Using these formulas, a tractor potential characteristic can be constructed (figure 1).
3. Results and discussions

When completing MTA, three criteria must be met

\[ \eta_{te} = \frac{N_{un}}{N_{e}} \rightarrow \eta_{ce} = \frac{N_{p}^{max}}{N_{e}} ; \quad \eta_{pof} = \frac{N_{un}}{P_{p}^{n}} \rightarrow 1 ; \quad \eta_{ref} = \frac{R_{un}}{P_{p}^{n}} \rightarrow \eta_{ref}^{opt} \]  \hspace{1cm} (11)

where \( N_{un} \) – the power required for the unit operation, kW; \( N_{p}^{max} \) – the maximum possible unit traction power under the given operating conditions, kW; \( N_{e}^{n} \) – the tractor engine nominal effective power, kW; \( \eta_{te} \) – tractor thrust efficiency; \( \eta_{ce} \) – tractor conditional thrust efficiency; \( \eta_{pof} \) – the tractor pulling power operation factor; \( \eta_{ref} \) – the tractive effort operation factor; \( \eta_{ref}^{opt} \) – the tractive effort optimal operation factor (in the calculations the average value \( \eta_{ref}^{opt} = 0.92 \) can be applied); \( R_{un} \) – the unit traction resistance, kN; \( P_{p}^{n} \) – the unit nominal tractive effort at a rational motion speed, kN. At the same time, the unit maximum performance will be achieved at the lowest operating costs.

Based on the criteria (11), the rational composition and the MTA high-speed operating mode are calculated (modeled) for performing a particular agricultural work. The main parameters, determining the rationality of the selected (modeled) unit are its grasp width \( B \) and speed \( V \). The method for calculating these parameters depends on the task and has several directions. As an example, let us consider the first direction, when it is necessary to select an agricultural machine for a specific operation (plowing, disking, cultivation, etc.) for a given tractor. First, the unit motion speed range, permissible
in performing the considered agricultural operation (technologically permissible speeds) \( V_{\text{min}} \leq V \leq V_{\text{max}} \), is determined.

The unit traction resistance \( R_{\text{un}} \) is determined by the formula:

\[
R_{\text{un}} = B_{\text{un}} k_{\text{n}} + G_{\text{n}} n_{\text{m}} i / 100 + R_{\text{v}},
\]

where \( G_{\text{n}} \) – the weight of selected agricultural machine, kN.

The rational speed of the selected unit is determined. If \( \mu_{\text{r}} > \mu_{\text{max}} \), (the speed range is in the zone of insufficient thruster coupling with the soil), then \( V_{\text{rat}} = V_{\text{max}} \), since the unit maximum performance is achieved.

If \( V_{\text{opt}} \) is within the speed range \( V_{\text{min}} \leq V_{\text{opt}} < V_{\text{max}} \), then the calculated value \( V_{\text{rat}} \) will be determined by the formula:

\[
V_{\text{rat}} = \frac{M + \sqrt{M(M - 4CV_{\mu}\delta_{\mu})}}{2C}
\]

(13)

To simplify mathematical calculations, the following designations have been introduced:

\[
M = 3.6N_{\text{e}} \eta_{\text{m}}, \quad C = R_{\text{un}} + G (f \pm i/100).
\]

Next, the calculated speed value should be compared with the permissible unit motion speed range. At \( V_{\text{rat}} \leq V_{\text{max}} \), the rational speed is equal to the calculated value, i.e. \( V_{\text{rat}} = V_{\text{rat}}^{e} \) (figure 2). At \( V_{\text{rat}} > V_{\text{max}} \) the rational speed is limited by the maximum permissible unit motion speed, i.e. \( V_{\text{rat}} = V_{\text{max}} \). If \( V_{\text{opt}} < V_{\text{min}} \), then the calculated rational speed is also determined by the formula (13).

\[\text{Figure 2. Graphical determination of } V_{\text{rat}} \text{ at } V_{\text{min}} \leq V_{\text{opt}} < V_{\text{max}} \text{ and } V_{\text{rat}}^{e} \leq V_{\text{max}}.\]

And in this case at \( V_{\text{rat}}^{e} \leq V_{\text{max}} \), the rational speed is equal to the calculated value, i.e. \( V_{\text{rat}} = V_{\text{rat}}^{e} \), and at \( V_{\text{rat}}^{e} > V_{\text{max}} \), the rational speed is limited by the unit maximum permissible motion speed, i.e. \( V_{\text{rat}} = V_{\text{max}} \).

Next, the tractor thrust efficiency \( \eta_{\text{te}} \), the maximum tractive power operation factor \( \eta_{\text{pof}} \) and the nominal tractor pulling power operation factor \( \eta_{\text{tef}} \), are calculated according to the formulas (11).

Under production conditions, the determination of the rational speed can be performed graphically using the potential characteristic of a given tractor on a specific agricultural background. To determine
the unit output per shift or the production rate per shift, we need to know the unit grasp width and its rational speed. The unit rational speed is determined from the tractor potential characteristics as the point of intersection of the unit traction resistance and the tractor potential characteristics (figure 3).

Thus, with simplified graphic-analytical calculations, we can determine the unit rational speed based on the potential traction characteristic of the corresponding tractor. So, for the MTZ1523 + APK-2.5 unit, it is 7 km/h, for the MTZ1523 + BD-6.6 unit, it is 8 km/h. The speed obtained, graphically, must be compared with the maximum permissible one, according to the agricultural requirements for a given operation and the operating speed must be selected according to the calculation algorithm (figure 4).

The obtained operating speed is used in calculating the hourly and shift unit productivity, as well as the specific fuel consumption. The units completed according to this method have the highest possible performance and reduced fuel consumption under the given agrotechnical conditions.

4. Conclusion
The developed methods of completing energy-saving machine-tractor aggregates [9] allow not only to select a power unit for performing a specific technological operation with a specific agricultural machine, but also to choose the most optimal version of a working machine for a known tractor (power unit). Using these techniques, it is possible to determine or clarify the output per shift of units, existing in the MTA fleet, establish the fuel consumption rates, as well as the unit costs of labor and heat energy for performing the work under consideration with a specific machine-tractor aggregate.

new high-performance varieties, new sowing and harvesting technologies.

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