Traction-speed properties of wheeled mobile power equipment for agricultural purposes

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Abstract. The studies were carried out to determine the compliance of traction-speed performance of the tractor as part of the machine-tractor unit with aggregation requirements, taking into account the random nature of changes in external factors. The work was carried out using the example of the assembly Fendt 936 Vario + AVA-12.6 “Agropitatel” in Leninsk-Kuznetsk district of Kemerovo region in 2017. Using the control dynamometer method, the probabilistic characteristics of the traction resistance of the machine, its dependence on the speed of movement in the operations of the main tillage and intra-soil liquid fertilizer application were determined. The studies were carried out on medium humus on stubble background with depth of soil treatment and fertilizing of 21 cm and the average length of run 1100 m. The tractor Fendt 936 Vario does not ensure compliance with the requirements for operating speed and slipping of propellers when working within the range of average specific drag. Power equipment with the estimated parameters will improve the traction coefficient of performance for 4.7...13.6 % in comparison with the tractor Fendt 936 Vario, which will increase the average working traction on the hook, which is implemented without violation of the established requirements. The result will be an increase in the average operating speeds of the unit and an increase of its net hourly productivity.

1. Introduction

Analysis of trends in the development of methods of tillage and seeding shows that in the future, a mechanical method using tractor power remains the main one. However, due to the improvement of agricultural production, the requirements to the tractor are constantly increasing [1], and its functionality is expanding. In accordance with the modern concept, tractor in the composition machine-tractor aggregate (MTA) is considered not simply as a traction energy unit (EU), but as an energy-technology complex, allowing, along with a high traction load, maximizing the potential load-carrying ability of its suspension system, the rational loading of the power take-offs and on-board hydraulic systems [2, 3].

Thus, the provision of high values of traction efficiency of the tractor and the productivity of the unit is possible with a scientifically based approach to the assessment and justification of traction-speed indicators of EU when aggregated with modern energy-intensive agricultural machines and tools [4, 5]. This approach should be based on the results of experimental studies [6] and techniques of mathematical modelling involving elements of probability theory, allowing a high degree of reliability to consider and evaluate the many external factors affecting the unit under operating conditions [7, 8].

The purpose of the study is to determine the compliance of traction-speed indicators of the tractor as part of the unit for the introduction of anhydrous ammonia aggregation requirements, in relation to
specific natural and industrial conditions of its use, taking into account the random nature of changes in external operational factors.

To achieve this goal, we solved the following tasks:
- to hold control dynamometrical of unit for anhydrous ammonia and to determine statistical estimates for the main traction energy and agronomic performance of MTA and tractors;
- to reveal the influence of high-speed and load modes of MTA operation on the change of traction resistance of the agricultural machine using the basic theoretical provisions formulated on the basis of the mathematical model of MTA functioning as a system of “soil – agricultural machine – propeller – transmission – engine” (“S-M-P-T-E”) [7, 9, 10].
- to determine the rational values of the operating weight, engine power and to assess the required level of energy-saturation of the tractor for aggregation with the tested agricultural machine, in relation to the conditions of the experiment.

2. Conditions, materials and methods
Field tests of MTA were performed on fields of Peasant farm “Pecherin C.V.” of Leninsk-Kuznetsk region of Kemerovo region in 2017 (figure 1).

The program of experimental investigations was developed in accordance with the requirements of existing regulatory documents (Russian State Standard GOST R 52777-2007, GOST 7057-2001) and included a control dynamometrical test of agricultural machine as part of MTA to determine the effect of working speed on the traction resistance of the working machine and the dynamics of its changes, to assess the compliance of the slipping of propellers with the set requirements, and to determine statistical characteristics of the studied parameters [11].

The energy rating of the unit was performed using instrumentation and recording equipment produced at the Novokubanskiy branch of Federal State Budget Scientific University “Rosinformagroteh” (Kuban Research Institute for Testing of Tractors and Agricultural Machines), which included measurement information system SM-302 with set of primary converters of the signal (sensors) (figure 2).
Figure 2. General view of the sensors installed on the unit: a - strain gauge sensor for measuring the tractive effort of K-R-20G-20-C1; b – speed sensor of the driving wheels of the tractor IP-268; c – sensor of the travel IP-266.

During the tests of the unit, the following performance indicators were registered and measured: traction resistance of the agricultural machine (force on the tractor hook) ($P$, kN), operating speed ($V_o$, m/s), slipping of the tractor drive wheels ($\delta$, %).

For installation of control and measuring equipment and sensors on the MTA, there were specially designed and manufactured devices that allow reliably fixing the sensors at the time of measurement, as well as quickly changing their position depending on the design features and layout of a particular EU, working as part of the MTA [12].

Test conditions unit were as follows: agriculture conditions – steam clean (cereal stubble) prior to treatment – cultivation of sowing complex SC-8.5 “Kuzbass” (5...8 cm), type and mechanical composition of soil – humus, medium-humic, the average length of the run – 1094.2 m, depth of tillage – 21 cm, the average absolute humidity of the soil in the horizon from 0 to 30 cm is 37.5 %.

The dynamometrical test of the unit was carried out while moving within the range of agrotechnically permissible operating speeds: 7...10 km/h for the operation of strip loosening, 6…8 km/h for the operation of fertilizing.

Simulation of traction load under operating conditions in a trailed container with a liquid fertilizer, provided with the help of the tow in the unit cargo onboard car KAMAZ-65115 operating weight 9300 kg, which corresponded to a potential download of the staffing capacity of the unit material by 70 %. Use of the car during testing was a coercive measure, as provided to the test pre-production sample of the machine was not fully completed by the time of tests conduct. However, due to the fact that the implementation of experiments as the main tasks were the definition of the statistical characteristics of traction resistance of the unit, for information about the rolling resistance trailer capacity in its structure was sufficient to estimate the coefficient of rolling resistance of pneumatic tire on agricultural conditions and differences of the parameters of the propellers and the layout of the car from the regular capacity of the unit had no significant influence on the final measurement results.

The experiments were implemented in the form of separate block plans, where the operating speed of the unit was a variable factor [13]. Measurements were carried out at working and idle strokes of the unit in the paddock (table 1).

### Table 1. Parameters of the experiment organization.

| Working stroke | Idle stroke and turns | Duration of the experiment |
|----------------|-----------------------|----------------------------|
| in the mode “cultivator” | 23 | 13 | 30.0 | 61.65 |
| in the mode “plant feeder” | 22 | 15 | 30.3 | 46.47 |

The results of measurements for the calculation of such statistical evaluation characteristics as the expectation $M(x)$, the maximum $x_{max}$ and the minimum $x_{min}$ values, the standard deviation $\sigma(x)$ and the variation $\nu(x)$ were processed by the method of dispersion analysis [11].
Table 2. Descriptive statistics of performance indicators, defined during dynamometrical.

| Indicator | M(x) | x_max | x_min | σ(x) | v(x), % |
|-----------|------|-------|-------|------|--------|
| In the mode of cultivator | | | | | |
| P, kN | 68 | 70.71 | 65.37 | 1.46 | 2.14 |
| V_o, m/s | 2.08 | 2.29 | 1.68 | 0.13 | 6.18 |
| δ, % | 17.56 | 21.1 | 15.5 | 1.25 | 7.1 |
| In the mode “plant feeder” | | | | | |
| P, kN | 78.85 | 83.77 | 71.01 | 2.73 | 3.46 |
| V_o, m/s | 1.61 | 1.83 | 1.44 | 0.073 | 4.56 |
| δ, % | 27.05 | 34.7 | 20.5 | 3.86 | 14.27 |

3. Results and discussion

Processing of experimental data (table 2) allowed obtaining graphical dependencies (figure 3), as well as the equation of connection of the average traction resistance of the unit (P, kN) with the operating speed (V_o, m/s):

in the mode of a cultivator

$$P = 59.91 + 1.86V_o^2, R = 0.735,$$

(1)

In the mode of a plant feeder

$$P = 65.12 + 3.14V_o^2, R = 0.534.$$

(2)

After the transformation of the equation for the average specific traction resistance of the unit (k, kN/m) we have the following dependencies:

in the mode of a cultivator

$$k = 4.15 + 0.15V_o^2,$$

(3)

in the mode of a plant feeder

$$k = 5.16 + 0.25V_o^2.$$

(4)

The obtained data (table 2 and figure 3) indicate the failure of the test unit requirements of agricultural machinery for operating speed and slipping tractor propellers within the study range of traction resistance. The average speed of the unit in the performance of operations of loosening the soil and fertilizing, below the recommended by agricultural machinery, respectively, by 16.8% and 17.3%, and slipping tractor propellers exceeds the permissible level by an average of 20.3% and 49.3%, respectively.
Figure 3. The dependence of the average operating speed and slipping of propellers of the tractor from the traction resistance of the unit a - in the mode of the cultivator; b - mode “plant feeder”.

On the basis of regression equations (1)...(4) was determined as given to the reference speed \(V_0 = 1.39\) m/s = 5 km/h the coefficient of proportionality \(\varepsilon_0\) and the specific traction resistance of the unit \(k_0\), and descriptive statistics of their changes (table 3).

Table 3. Descriptive statistics of the given (to \(V_0 = 1.39\) m/s) energy performance of the unit.

| Size of the sample N | M\((P_0)\), kN | \(\sigma(P_0)\), kN | \(\nu(P_0)\), % | M\((k_0)\), kN/m | \(\varepsilon_0\), s²/m² |
|---------------------|----------------|-----------------|----------------|-----------------|-----------------|
| 23                  | 63.49          | 1.46            | 2.14           | 5.04            | 0.034           |
|                     |                |                 |                |                 |                 |
| 22                  | 77.36          | 2.73            | 3.46           | 6.14            | 0.030           |
The obtained generalized data on the energy indicators of the unit allowed, using the developed probabilistic model of the MTA functioning as a system of ("S-M-P-T-E") [7, 9, 10], with the calculated probability to predict the values of parameters and output performance indicators of EU for a specific soil-climatic zone under conditions of unsteady external influences.

Operating weight of tractor required to ensure compliance with agrotechnical requirements of propellers slipping:

\[ G_{tr}' = \frac{P_{max}}{\lambda(\delta_{max} - \delta)_{\text{exp}^{-b}}[\delta_{\text{max}}]} \]  

(5)

where \( P_{max} \) - the maximum value of the average tractive effort of the tractor (traction resistance unit) specified in the test conditions, kN; \( [\delta]_{\text{max}} \) - the maximum allowed, according to the agrotechnical requirements, the amount of slipping of the drive wheels of the tractor, %; \( \lambda \) - coefficient of the redistribution of the operating weight of the tractor between its axles; \( A, B, \phi \) - function coefficients approximating the curve of slipping of the propellers during testing the traction of the tractor.

The maximum value of the average traction resistance of the unit was determined by the formula:

\[ P_{max} = k_{0\text{max}}[1 + \varepsilon_0(V_o^2 - V_0^2)]B, \]  

(6)

where \( k_{0\text{max}} \) - corrected value the maximum average specific traction resistance of the unit, kN/m; \( [V_o]_{\text{max}} \) – the maximum operating speed of the unit in accordance with the requirements of farming, m/s; \( B \) – working width of unit capture, m.

Possible values of corrected specific traction resistance of agricultural machinery while working on a separate field are limited by permissible (tolerance) limits:

\[ k_{0\text{min}} = M(k_0)[1 - \nu(k_0)t_{\alpha1}]; \]  

(7)

\[ k_{0\text{max}} = M(k_0)[1 + \nu(k_0)t_{\alpha2}], \]  

(8)

where \( M(k_0), \nu(k_0) \), respectively the mathematic expectation (kN) and coefficient of variation of the average corrected the specific traction resistance of agricultural machinery; \( t_{\alpha1}, t_{\alpha2} \) - deviation from \( M(k_0) \), expressed as average standard deviations \( \sigma(k_0) \) for a given confidence probability \( \alpha \) and a fraction of the sign \( \Delta \).

On the basis of the operating parameters of the unit, installed during dynamometry (see table 2), according to formulas (7) and (8), the calculated range of the average corrected specific traction resistance \( k_0 \) was determined for soil testing conditions (table 4). Data indicate an increase in the average tractive resistance is given by 17.9% and expanding the range of changes by 49.4% when the unit is operating in the mode of a plant feeder compared to tillage, as well as allow to estimate with a given probability on the basis of the calculation, the potential range of changes in operational performance of the unit.

Table 4. The calculated range of the average corrected specific traction resistance of the unit when working on a separate field (at \( \alpha=0.95 \) and \( \Delta=0.05 \)).

| \( M(k_0) \), kN/m | \( \nu(k_0) \) | \( t_{\alpha1} = t_{\alpha2} \) | End of the range \( k_0 \), kN/m |
|-----------------|----------------|----------------|-----------------------------|
| 5.04            | 0.021          | 1.96           | 4.83                        | 5.25                        |
|                 |                |                | In the mode of a cultivator |                             |
| 6.14            | 0.035          | 1.96           | 5.73                        | 6.56                        |
|                 |                |                | In the mode of a plant feeder|

Taking into account the upper limits of the range of variation of average specific corrected the traction resistance of the unit \( k_{0\text{max}} \) by the formula (8), determined the actual traction resistance \( P_{max} \) at the maximum operating speed in accordance with the requirements of the agricultural machinery by the formula (6).

According to the formula (5) calculated the average value of the operational weight of a tractor \( G_{tr}' \), necessary for compliance with agrotechnical requirements for slipping its propellers (table 5). When
working within the range of acceptable agricultural technology speeds the MTA, a minimum operating weight of EU, should be 221.3 kN that more than a third (34.5%) exceeds the weight of the tractor Fendt 936 Vario (144 kN). Operation of the unit in the mode of a plant feeder, due to higher traction resistance, requires an additional increase in the weight of the EU by 30.5 kN (12%).

Table 5. Calculation of the required operating weight of the tractor when aggregating with UCA-12.6.

| [\(V_{o}\)] max, m/s (km/h) | P max, kN | Coefficients | \(\lambda\) | [\(\delta\)] max, % | G tr, kN |
|-----------------------------|-----------|--------------|---------|---------------------|---------|
|                             |           | A | B | \(\phi_{max}\) |              |         |
| in the mode of cultivation   |           |    |    |                    |          |         |
| 2.78(10)                    | 79.18     | 0.71 | 5.87 | 0.67             | 1.0     | 14     | 221.3 |
| In the mode of a plant feeder|           |    |    |                    |          |         |
| 2.22(8)                     | 90.1      | 0.71 | 5.87 | 0.67             | 1.0     | 14     | 251.8 |

According to [6, 7], the following formula was used to determine the traction power of the unit (the hook power of the tractor):

\[ N_{hook} = N_{t} \lambda_{N} \eta_{t} \eta_{f} \eta_{D}, \]  \hspace{1cm} (9)

Where \(N_{hook}\) is the rated power of the tractor engine, kW; \(\lambda_{N}\) is the coefficient of use of the rated power of the tractor engine.

The coefficient \(\lambda_{N}\), depending on the technical characteristics of the tractor, the test conditions of the unit and the statistical characteristics of the traction resistance of the working agricultural machine, can be determined using a highly significant regression dependence established by the test results [8]:

\[ \lambda_{N} = 114 - 13.85q + 157.3v(P_{0}) - 161.3qv(P_{0}) - 162.7v(P_{0})^2, \]  \hspace{1cm} (10)

where \(q\) is the average value of the denominator in geometric series to the main transmission range of the tractor; \(v_{0}\) is the constant of proportionality, \(s^{2}/m^{2}\); \(v(P_{0})\) is the coefficient of variation of the average corrected of the traction resistance of the unit.

Traction efficiency factor of the tractor:

\[ \eta_{tr} = \eta_{t} \eta_{f} \eta_{D} \eta_{D}, \]  \hspace{1cm} (11)

where \(\eta_{t}\), \(\eta_{f}\), \(\eta_{D}\) – efficiency factor of mechanical losses in the drivetrain of the tractor of losses at rolling of the tractor and slipping its propellers, respectively.

Efficiency factor of the losses at the rolling of the tractor:

\[ \eta_{fr} = 1 - \frac{P_{r}}{P_{r} + P_{f}} \]  \hspace{1cm} (12)

Efficiency factor of the losses for slipping of propellers of the tractor:

\[ \eta_{D} = 1 - \delta, \]  \hspace{1cm} (13)

Where \(\delta\) - is the slipping of the tractor drive wheels.

The estimated value of propellers slipping of the tractor with an operating weight of \(G_{tr} \prime\), obtained by expression from the formula (5)

\[ \delta = B^{-1} \ln \left( \frac{A}{P_{max} \frac{P_{fr}}{\lambda_{tr'}}} \right), \]  \hspace{1cm} (14)

Resistance force to rolling of the tractor

\[ P_{r} = fG_{tr} \prime, \]  \hspace{1cm} (15)

where \(f\) – coefficient of rolling resistance of tractor wheels.

The coefficient of resistance to rolling of the tractor, characterizes the state of the conditions and is determined on the basis of data obtained during the dynamometrical of unit on idling (table 6).
where $P_{xx}$ – traction resistance of the unit when performing the idle passages, kN; $G_m$ is the weight of the tested agricultural machinery.

**Table 6.** Descriptive statistics of energy performance of the unit when performing idle passes.

| Agricultural conditions | Size of the sample N | $M(P_{xx})$, kN | $\sigma(P_{xx})$, kN | $\nu(P_{xx})$, % | $f$ |
|-------------------------|----------------------|------------------|---------------------|------------------|-----|
| Clear vapor             | 13                   | 7.10             | 0.26                | 3.60             | 0.095 |

Since, according to the results of studies [7, 8, 14], there is no established relationship between the idle traction resistance of the agricultural machine and the speed of the unit, the corrected values of energy indicators were not determined.

The traction power of the unit, according to the results of the control dynamometrical, can also be calculated by the formula:

$$N_{hook} = PV_0$$  \hspace{1cm} (17)

By substituting expressions (17) into formula (9) and its solution taking into account formulas (10)...(15) with respect to $N_n'$, was determined the estimated range of the average values of the rated motor power EU, $N_n'$ necessity to use it in the aggregate with respect to specific testing conditions, characterized by the limits of change corrected the specific traction resistance of the soil $k_{0min}$-$k_{0max}$ (7)-(8) without violation of the established requirements at the operating speed and the slipping of the propellers [10] (table 7). Despite the fact that the unit working in mode of a plant feeder is characterized by higher average tractive resistance of 9.9%, exceeding the same indicator of the dealer, the required motor power of EU, on average, on 10.6% (37.2 kW) is lower owing to the lower operating speed of the unit, according to the requirements of farming, when performing feeding.

**Table 7.** Calculating range of the average values of the rated motor power of the energy when used with UCA-12.6

| $k_0$, kN/m | $P_{max}$, kN | $P_0$, kN | $\eta_f$, % | $\delta$, % | $\eta_s$, % | $\eta_t$, % | $N_{hook}$, kW | $\lambda$, | $N_n'$, kW |
|-------------|---------------|-----------|-------------|-------------|-------------|-------------|----------------|-----------|------------|
| 4.83        | 72.80         | 0.78      | 12.5        | 0.88        | 0.62        | 202.2       | 335.4          |           |            |
| 5.04        | 75.99         | 0.78      | 13.2        | 0.87        | 0.62        | 211.1       | 349.8          |           |            |
| 5.25        | 79.18         | 0.79      | 14.0        | 0.86        | 0.62        | 219.9       | 364.5          |           |            |
| 5.73        | 78.66         | 0.77      | 11.7        | 0.88        | 0.62        | 174.8       | 292.3          |           |            |
| 6.14        | 84.38         | 0.78      | 12.8        | 0.87        | 0.62        | 187.5       | 312.6          |           |            |
| 6.56        | 90.10         | 0.79      | 14.0        | 0.86        | 0.62        | 200.2       | 333.7          |           |            |

Matching the tractor to its purpose for traction and speed properties were evaluated by the coefficient of energy saturation:

$$N_{tr} = \frac{N_n}{G_{tr}}$$  \hspace{1cm} (18)

The energy saturation of the EU is calculated on the basis of tables 5 and 7 for the entire design range of the rated engine power.

Using the dependences (9)...(17), as well as the guidelines of probabilistic mathematical models of the functioning of the MTA, as a system of “S-M-P-T-E” was executed the comparative assessment of medium-output indicators of EU $[M(k_0)]$ with the estimated parameters $G_{tr}'$, $N_n'$ and the tractor is being tested in the aggregate (figure 4).
Figure 4. Comparison of average energy and operational performance of the MTA on the basis of EU with the estimated parameters and the tractor Fendt 936 Vario during the work on a separate field: a – in the mode of cultivator \([M(k_0)=5.04\, \text{kN/m}]\); b – in the mode of plant feeder \([M(k_0)=6.14\, \text{kN/m}]\).
Thus, it is clear that in real operating conditions to achieve a rational level of energy saturation of EU within the entire range of change of working resistance of unit (7)...(8), in case of its unchanging composition, is possible only by ballasting of EU and consideration of its operating weight as a variable parameter ($G = \text{var}$, when $N_4 = \text{const}$). As an example, indicators of EU were added to the comparison with parameters $N_4 = 349.8$ kW and $G = 251.8$ kN (figure 4b).

From the presented dependences it is evident that EU with the estimated parameters reduces the slipping of the propellers (depending on the performed operation – “tilling/fertilizing”) an average of 42.3/58.5% and the increase in tractive efficiency is 4.7/13.6%, compared to the tractor Fendt 936 Vario, which leads to an increase in average worker traction effort on the hook, which is implemented without violation of the established requirements for 8.1/8.2%.

The use of EU with rational energy saturation in the aggregate by increasing its average working speeds up to 20.2/27.5% provides an increase in net hourly production to 16.6/22.8%, while ballasting of EU up to 22.8/27.3%.

4. Conclusions

The tractor Fendt 936 Vario in the configuration presented on the test has an energy saturation of 1.87 kW/kN, and its traction-speed properties do not comply with the conditions of aggregation with tested agricultural machine for working speed and the slipping of the propellers.

The calculated average value of the required nominal power of the engine EU is 349.8 kW (476 HP). Required operational weight of EU to perform the unit operation of loosening is 221.3 kN with ballasting to 251.8 kN under the work of MTA in mode of a plant feeder, in the area of high specific traction resistance of the soil $-5.73...6.56$ kN/m.

Energy saturation of EU with design parameters will be 1.39...1.58 kW/kN, depending on executed field operations, at the same time, it will demonstrate consistently high performance across a range of medium corrected specific traction resistance of the assembly of $4.83 \leq M(k_0) \leq 6.56$ kN/m with consideration of the limitations based on technology and agronomic standards.

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