OPTIMIZATION OF TRACTION PROPERTIES THE ELECTRIC TRACTOR BASED ON THE SIMULATION DLG-POWERMIX TEST CYCLES

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Abstract - One of the promising steps to improve the environment in various industrial sectors is the transfer of specialized technical means to alternative clean energy. Agriculture is not an exception, because the introduction of an electric drive on tractors of small traction classes, which are designed to perform traction, as well as small transport work, is relevant today. Such an implementation is implemented by replacing the internal combustion engine with an electric drive, in connection with this; the task of observing the traction properties of the tractor arises. Therefore, the material of this type aims to increase the traction efficiency of the wheeled low-power tractor by optimizing its design features. The implementation of the outlined goal occurs due to the use of multi-criteria optimization when conducting a simulated numerical experiment of traction test cycles. When solving the set goal, the method of dynamic tests of the German Agricultural Society DLG-PowerMix is used, this includes 12 traction tests of an agricultural tractor. The result is a justified selection of the distribution of the total weight of the low-power tractor in combination with the tire pressure in conditions of compliance with the maximum average integral values of the speed and efficiency of the tractor, as well as the minimum average integral value of skidding, as those that should be implemented in an electric tractor. The practical significance of the work consists in providing specific values of weight distribution on the axle of the low-power tractor and tire pressure when aggregating with a plow, a cultivator, a rotary cutter and a hay mower, as well as taking into account the operation of a manure spreader and a hay baling. The scientific novelty of the work is the establishment of a relationship between the design parameters of the low-power tractor and the change in traction indicators during traction work, namely between the tractor weight distribution, tire pressure, speed, tractor efficiency and wheel slip.

Keywords: Electric wheeled low-power tractor, Traction indicators, Weight distribution, Tire pressure, Speed, Slipping, Efficiency, Traction cycles.

1. Introduction

During the last decade, the electrification of vehicles, both cars and tractors, has become widespread in the world. This, first of all, is intended to solve the problems of environmental degradation by polluting emissions and the reduction of fossil fuel reserves. Electrification has reached a high point in the automotive industry, which became an impetus for its spread to the tractor industry. Equipment manufacturers around the world are experimenting with various electric drive technologies to improve modern machinery. Most car manufacturers are mass switching to electric or hybrid power drives. Tractor builders are not far behind, because the introduction of electric power plants on agricultural machinery ensures an increase in energy efficiency and allows the creation of universal machinery for agricultural activity [1].

The introduction of an electric drive on heavy agricultural machinery is currently impossible, because the relatively low level of technical development of electric motors and batteries [2] negatively affects the popularization of purely electric heavy vehicles. However, the use of electric drive on low-power tractors, which should provide rapid development of farming, is gaining great popularity. Compared to traditional (combustion engine equipped) tractors, exclusively electric tractors have a compact structure, maximum torque at low revolutions and high efficiency.

The use of low-power tractors is due to their versatility, because they are used in a complex with variable mounted, semi-mounted and trailed agricultural units, so the design of the electric tractor must take into account the operation of the power take-off shaft. Such versatility of low-power tractors should ensure the implementation of traction indicators.

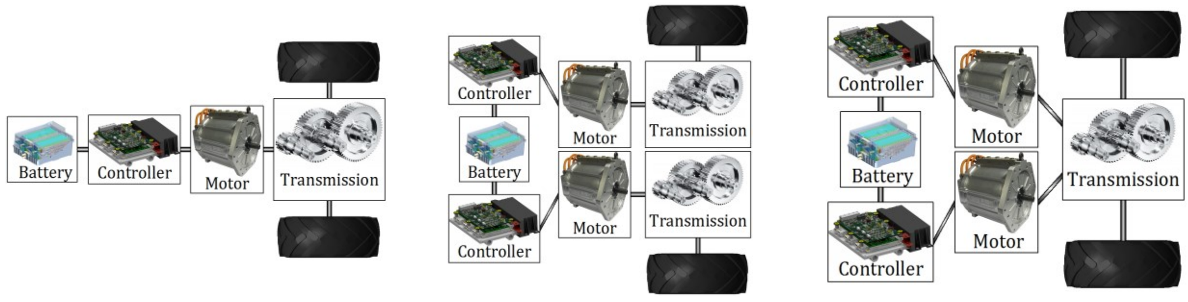
2. Research Status of Electric Tractor Designs

The introduction of an electric drive in vehicles of the automobile industry is more broadly outlined than for the tractor industry. With the ever-increasing development of the technology of the construction of accumulator batteries and electric motors, the probability of their use on agricultural tractors also increases. And although for the sustainable development of agriculture it is now more relevant to introduce a wide range of renewable or clean energy sources instead of the internal combustion engine [3], the use of purely electric low-power tractors is a promising direction.

An overview of the current state of electric power plants of tractors and agricultural machines is given in [4], where it is presented that the use of electric drives of machines leads to an increase in energy efficiency, and also ensures the universality of rural activities. The number of works in which the selection of electric motors to replace the internal combustion engine in low-power tractors takes place is increasing. Thus, in works [5], the possibility of operating low-power agricultural tractors operating with the use of a Brushed DC Motor (BDC) as the main source of energy is considered. The evaluation took place in view of the autonomy of the tractor under different power requirements and when compared with a conventional agricultural tractor in terms of operational energy consumption and energy efficiency. The study showed that such an implementation is viable in terms of cost and energy efficiency. The use of a Induction Motor (IM) instead of an internal combustion engine [6, 7] with approximately the same power increases the traction force by approximately 2 times.

A comparison of the involvement of a Induction Motor and a DC motor [8] showed that a low-power tractor with a DC motor developed a greater pulling force of a jerk, surpassing a low-power tractor with an Induction Motor by 22%. The introduction of a Brushless DC Motor (BLDC) [9, 10] allowed to increase the traction efficiency of the tractor by an average of 3% in agricultural work. According to [11], the permanent magnet synchronous motor (PMSM) is the best choice for use in the electric drive system of a tractor, because due to proper torque control, it meets the standards of an agricultural tractor [12, 13].

The vast majority of mini tractors have a classic 4x2 design with two driving wheels on the rear axle. There are several variations of the construction of the electric low-power tractor transmission (Figure 1). Thus, in works [14, 15] the replacement of the internal combustion engine with an electric drive is considered (Figure 1a). The advantages of such a scheme are that the selection of the electric motor is based on the characteristics of the internal combustion engine; easy adaptability to agricultural work; the presence of a rear PTO shaft. From the works [6, 16], the arrangement of electric motors on the drive axle of the tractor becomes known (Figure 1b). The advantages of such a scheme are: increased reliability and design simplicity due to a reduction in the number of mechanical components; adaptability of tractor operation, as it allows independent control of the speed and torque of each wheel; installation of less powerful electric motors. From the work [17, 18], a design that works as a two-flow transmission with two electric motors becomes known (Figure 1c). The advantages of such a scheme: a wide range of speed changes; quick reaction of engines by torque; reducing the size of the transmission unit, which leads to a decrease in weight and energy consumption; the presence of a rear PTO shaft. Each of the considered schemes has certain advantages, but the most popular remains from Figure 1a.



a b c

Figure 1: Possible schematic (a, b, c) solutions of the power plant of low-power tractors (4x2)

Analyzing the above, it is necessary to pay attention to the fact that each modernization of a wheeled tractor requires a study of changes in its traction indicators [19]. The need for increased tractive power today creates big problems, because the complex influence of the soil environment during its cultivation forms varied resistance. In the case when the tractor is not adapted to changes in resistance during tillage operations, excessive skidding of the drive wheels occurs [20]. The conclusion from work [21] is that according to the characteristics of electric tractors, it is relevant to study the weight distribution of an electric tractor and optimize the load distribution on the axles to improve its traction characteristics. In [22], the technology of automatic battery ballast for electric tractors is proposed, which ensures effective adaptation of tire grip to changes in the soil environment. The disadvantage of this technology can be considered that the authors do not take into account the physical properties of the tires of the wheeled tractor, which can directly affect the traction indicators. Therefore, the study of multi-criteria optimization [23] of traction indicators of an electric tractor when performing traction work is promising.

3. Materials and Methods

3.1. Mathematical Model

The calculation scheme of the model is shown in Figure 2. The studied model evaluates the traction performance of a wheeled tractor and is based on the calculation of a system of differential equations:

$$\begin{aligned} & m\cdot\ddot{X}+P_{kr}=2\left(P_{o1}+P_{o2}\right); \\ & m\cdot\left(\ddot{Z}+g\right)+P_{krz}=2\left(G_{k1}+G_{k2}\right); \\ & \frac{J_o\cdot\ddot{\varphi}_o}{2}+G_{k1}\left(X_{o1}-X\right)+ \\ & +G_{k2}\left(X_{o2}-X\right)=0.5P_{krz}\left(X_{o3}-X\right)- \\ & -P_{o1}\left(Z_{o1}-Z\right)+P_{o2}\left(Z_{o2}-Z\right)+0.5P_{kr}\left(Z_{o3}-Z\right), \end{aligned} \tag{1}$$

where X, Z, φ_o are generalized coordinates; P_{o1}, P_{o2} are forces pushing the tractor body forward; G_{k1}, G_{k2} are radial loads on tires; P_{kr}, P_{krz} are horizontal and vertical components of traction force on the hook; x_{o1}, x_{o2}, x_{o3}, z_{o1}, z_{o2}, z_{o3} are horizontal and vertical coordinates of the points of the tractor frame in the selected frame of reference.

To implement the system of differential equations (1), it is necessary to establish relationships between the coordinates of the points of tractor frame and generalized coordinates [24]

$$\begin{aligned} & X_{oi}=X-\rho\cdot\cos\left(\varphi_o+\lambda_{oi}\right); \\ & Z_{oi}=Z+\rho\cdot\sin\left(\varphi_o+\lambda_{oi}\right), \end{aligned} \tag{2}$$

where ρ_{oi}, λ_{oi} are radii-vectors and angles of points of the tractor frame in the polar coordinate system with the center at point O.

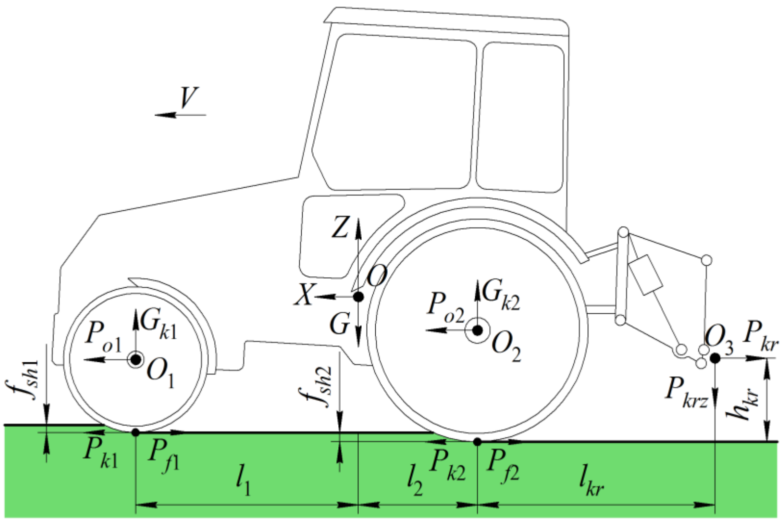


Figure 2: Calculation scheme of the tractor

Thus, the radial deflection of tires is determined as follows:

$$f_{sh}=\frac{D}{2}+Z_G-Z_o, \tag{3}$$

where D is the outer diameter of the tire; Z_G is the vertical coordinates of the ground level, which in the general case are random functions of the traveled path.

To determine the forces P_{oi} pushing the tractor frames forward, it is necessary to know the tangential traction forces P_{ki} and rolling resistance forces P_{fi}, on each wheel:

$$P_{oi}=P_{ki}-P_{fi}\,. \tag{4}$$

The force of rolling resistance P_{fi} is determined, including, by the amount of soil compaction h_{gi} or the depth of the rut after the N-th wheel pass:

$$P_{fi} = \sum_{i=1}^{N} \left(\begin{array}{c} \dfrac{0,81 \cdot k_0 \cdot k_N \cdot b_{ki}}{100\sqrt{a_k \cdot b_k}} \times \\ \times \left(\sqrt[3]{\dfrac{G_{ki}^2}{\left(\dfrac{k_0 k_N}{100\sqrt{a_k b_k}}\right)^2 b_{ki}^2 D_i \left(1+\dfrac{f_{шi}}{h_g}\right)}} \right) \end{array} \right)^2, \quad (5)$$

where k_0, k_N are the coefficient of volumetric soil shrinkage and the coefficient that takes into account the change in the physical and mechanical properties of the soil, which for the first four passes N can be determined with the reliability of $R^2 = 0.999$; a_{ki}, b_{ki} are length and width of the spot of contact of the i-th tire with the ground; h_g – deformations of the soil under each wheel of the tractor.

Determination of radial loads on tractor wheels is as follows

$$G_{k1,2} = G\frac{l_{2,1}}{2L} - \left(P_{k1,2} - G \cdot f \cdot \frac{l_{2,1}}{L}\right) \cdot \frac{h_{kr}}{2L}, \quad (6)$$

where L is the longitudinal base of the tractor; l_1 and l_2 are the distance from the center of gravity to the axes of the front and rear axles; f is the coefficient of rolling resistance of the wheels; h_{kr} is the height of the point of action of the traction force on the hook from the support surface.

The only unknown quantity is the skidding of the tractor wheels, which is determined by the known dependence of the actual and theoretical speeds. Summarizing the above and taking into account the change in slip coefficients, it becomes possible to determine the tangential traction force of the front wheel P_{k1} and the rear driving wheel P_{k2}.

$$P_{k1} = \left(C_c \cdot F_k + G \cdot \text{tg}\varphi_c\right); \quad (7)$$

$$P_{k2} = \left(\begin{array}{c} \left(C_c \cdot F_k + G \cdot \text{tg}\varphi_c\right) \times \\ \times \left\{ 1 - \dfrac{k_c\left(1-\delta_2\right)}{a_k \cdot \delta_2} \left[1 - e^{-\frac{a_k \cdot \delta_2}{k_c\left(1-\delta_2\right)}} \right] \right\} \end{array} \right), \quad (8)$$

where C_c is the shear stress in the soil; φ_c is the angle of internal friction in the soil; k_c is the coefficient of deformation in the soil.

Radial deflection of tires, in addition to determination by formula (3), can be determined by physical properties of tires:

$$f_{sh} = \frac{c_2 \cdot G_k}{2\left(p_{sh} + p_0\right)} + \sqrt{\left(\frac{c_2 \cdot G_k}{2\left(p_{sh} + p_0\right)}\right)^2 + c_1 \cdot G_k}, \quad (9)$$

where c_1, c_2 are constant coefficients; G_k is tire load; p_0 is a constant coefficient that characterizes the pressure that depends on the stiffness of the frame at zero internal pressure.

Based on the numerical calculation, the main traction indicators are determined: speed (V), wheel slip (δ_2) and tractor efficiency (η) without taking into account the operation of the power plant.

3.2. DLG-PowerMix Test Cycles

The procedure of the DLG-PowerMix traction test cycles consists of 12 stages of tests of the agricultural tractor in field operations under varied external loads [25]: plowing and cultivation, traction-drive cycles with power take-off through the power take-off shaft (PTO): milling with a rotary tiller and hay hoeing, as well as traction-drive cycles with power take-off through the PTO and the hydraulic system of the tractor: manure spreading and hay baling (Table 1).

Table 1. DLG-PowerMix cycles for field operations [26]

<table>
<tr><th>Type of work</th><th>Cycle</th><th>Load, %</th><th>Rotate PTO, min^{-1}</th><th>Conditions of conduct</th></tr>
<tr><td rowspan="4">Traction</td><td>Plowing Z1P</td><td>100</td><td>–</td><td rowspan="4">Reduction of the average speed of no more than 2.5 km/h (except for the Z1P cycle, if the tractor cannot develop a higher tractive power).</td></tr>
<tr><td>Plowing Z2P</td><td>60</td><td>–</td></tr>
<tr><td>Cultivation Z1G</td><td>100</td><td>–</td></tr>
<tr><td>Cultivation Z2G</td><td>60</td><td>–</td></tr>
<tr><td rowspan="6">Traction-drive</td><td>Rotary harrow Z3K</td><td>100</td><td rowspan="8">540</td><td rowspan="8">Reduction of the average speed by no more than 2.5 km/h and the average rotation frequency of the PTO shank by no more than 7.5%.</td></tr>
<tr><td>Rotary harrow Z4K</td><td>70</td></tr>
<tr><td>Rotary harrow Z5K</td><td>40</td></tr>
<tr><td>Mower Z3M</td><td>100</td></tr>
<tr><td>Mower Z4M</td><td>70</td></tr>
<tr><td>Mower Z5M</td><td>40</td></tr>
<tr><td rowspan="2">Traction-drive, hydraulic</td><td>Manure spreading Z6MS</td><td>100</td></tr>
<tr><td>Hay baling Z7PR</td><td>100</td></tr>
</table>

Thus, the basic components for determining the influence of tractor weight distribution on its traction indicators are presented.

According to the table 1, the tractor receives the greatest loads during traction operations: plowing (Z1P), cultivation (Z1G), rotary harrow (Z3K), mower (Z3M), manure spreading (Z6MS) and hay baling (Z7PR).

3.3. Multi-criteria Optimization of Indicators

The essence of the method is that the own criteria $f(x)$, $i = 1, n$ in any way are combined into one integral criterion $F(x) = \Phi(f_1(x), f_2(x),..., f_n(x))$, and then is the maximum or minimum of this objective function [23]. If the combination of own criteria is built based on the object relationship of own criteria and the generalized criterion, then the optimal solution of the optimization problem will be correct. In the process of comparing the values of optimality criteria, they must be reduced to one dimension, or to a dimensionless form. The transformation to a scale with values in the range from 0 to 1 is chosen as the normalized one.

The work considers the multi-criteria optimization of traction indicators according to the priority of the highest productivity, and then the largest values of the speed of movement and the efficiency of the tractor are selected as partial criteria, which must correspond to the maximum values of the partial criteria K_1 and K_2.

$$K_1(G_k, p_{sh}) = \frac{V^*(G_k, p_{sh})}{V_{\max}}; \quad (10)$$

$$K_2(G_k, p_{sh}) = \frac{\eta^*(G_k, p_{sh})}{\eta_{\max}}, \quad (11)$$

where V^*, η^* are the current values of speed and efficiency of the tractor; $V_{\max}$, $\eta_{\max}$ are the maximum values of speed and efficiency of the tractor.

The general optimality criterion is as follows:

$$K_\Sigma = \sum_{i=1}^{n}(Z_i \cdot K_i) + \sum_{j=1}^{m}(Z_j \cdot P_j), \quad (12)$$

where Z_i, Z_j are weighting factors; P_j is a penalty function that reduces the value of the generalized criterion when the varied parameter exceeds the permissible values.

Penalty functions include the change in permissible load at the minimum and maximum permissible pressure in the tire

$$P_{Q_r}(Q_r) = \begin{cases} 1 - \dfrac{Q_r^*}{Q_{r\max}}, & if\ Q_r^* > Q_{r\max}; \\ 0, & if\ \ Q_{r\min} \le Q_r^* \le Q_{r\max}; \\ 1 - \dfrac{Q_r^*}{Q_{r\min}}, & if\ Q_r^* < Q_{r\min}, \end{cases} \quad (13)$$

where Q_r^* is the current values of the load on the bus; $Q_{r\max}$, $Q_{r\min}$ are maximum and minimum permissible load on the tire.

Also, include the change of rear drive wheel slippage in the penalty functions:

$$P_{\delta_2}(\delta_2) = \begin{cases} 1 - \dfrac{\delta_2^*(G_k, p_{sh})}{\delta_{\max}}, & if\ \delta_2^* > \delta_{\max}; \\ 0, & if\ \ 0 \le \delta_2^* \le \delta_{\max}, \end{cases} \quad (14)$$

where δ_2^*, $\delta_{\max}$ are the current and maximum rear wheel slip values.

Thus, the generalized criterion has the following form:

$$K_\Sigma(G_k, p_{sh}) = \left(\begin{array}{c} Z_1 \cdot \left(\dfrac{V^*(G_k, p_{sh})}{V_{\max}} \right) + \\ + Z_2 \cdot \left(\dfrac{\eta^*(G_k, p_{sh})}{\eta_{\max}} \right) + \\ + Z_{Q_r} \cdot P_{Q_r}(Q_r) + \\ + Z_{\delta_2} \cdot P_{\delta_2}(\delta_2) \end{array} \right). \quad (15)$$

Analyzing equation (15), it can be seen that the generalized criteria and value Q_r the value of the weighting coefficients is quite significantly affected, which is primarily due to the fact that the penalty functions P_j and partial criteria K_i varies in different ranges: $0 < K_1(G_k, p_{sh}) \le 1$; $0 < K_2(G_k, p_{sh}) \le 1$; $0 < P_{Qr}(Q_r) < -\infty$; $0 < P_{\delta 2}(\delta_2) \le -\infty$. When choosing the values of the weighting factors for partial criteria, it is necessary to be guided by the fact that the sum of the weighting factors should be equal to 1. When choosing the value of the weight factor for the penalty function, it is necessary to take into account that when the penalty function reaches a value that exceeds the limits of the load range, the tractor becomes inoperable.

4. Results

At the first stage, the influence of weight distribution and tire pressure on tractor traction performance was investigated during the simulation of PowerMix test cycles. Figure 3 shows the dependence of the average integral indicators of speed, slipping of the rear wheels and efficiency of the tractor on the change in weight distribution and pressure in the front tires. Figure 4 shows the dependence of the average integral indicators of speed, slipping of the rear wheels and the efficiency of the tractor on the change in weight distribution and pressure in the rear tires. Figure 5 shows the change of the generalized criterion according to the indicators of the maximum value of speed and the efficiency of the tractor, as well as the minimum value of slipping of the rear wheels.

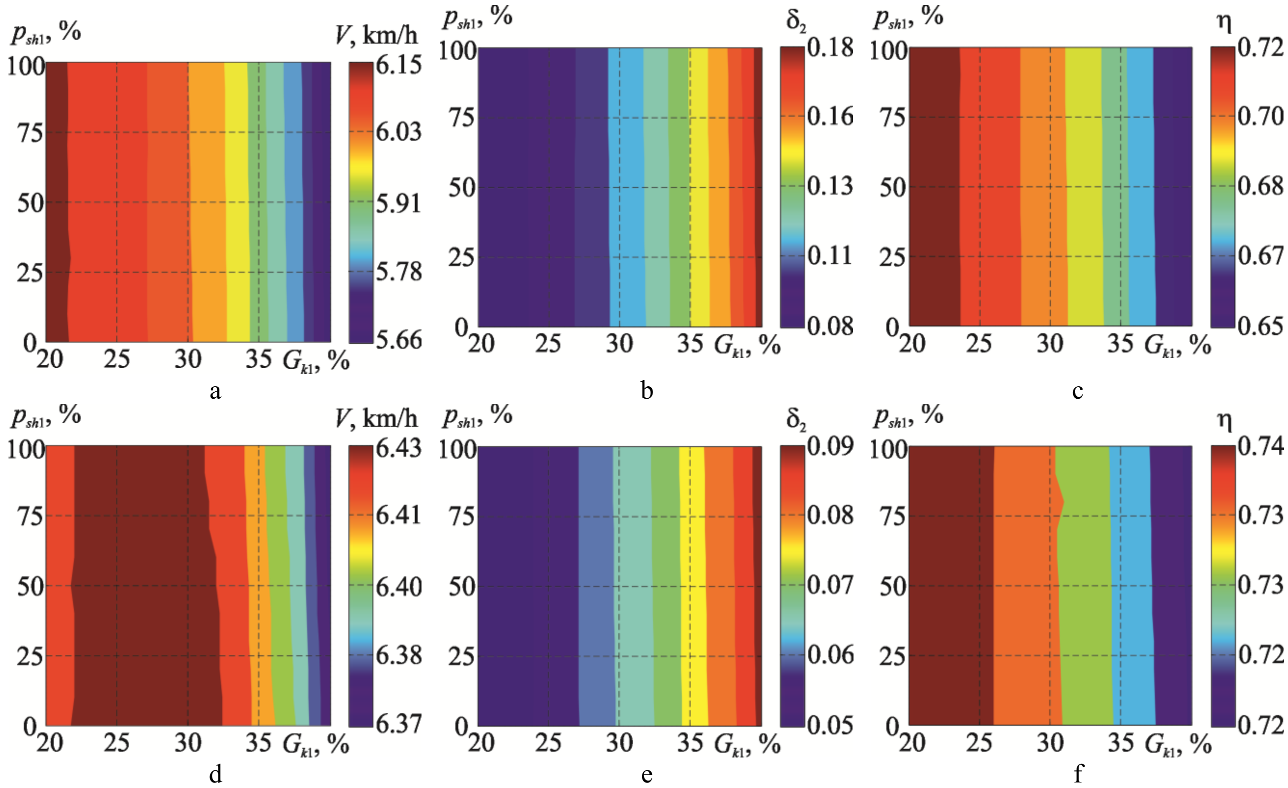


Figure 3: Dependence of low-power tractor indicators speed (a, d), rear wheel slipping (b, e), efficiency (c, f) on the distribution of the total weight on the front axle G_{k1} and the pressure in the front tires p_{sh1} when simulating the field operation of plow aggregation Z1P (a, b, c) and Z2P (d, e, f)

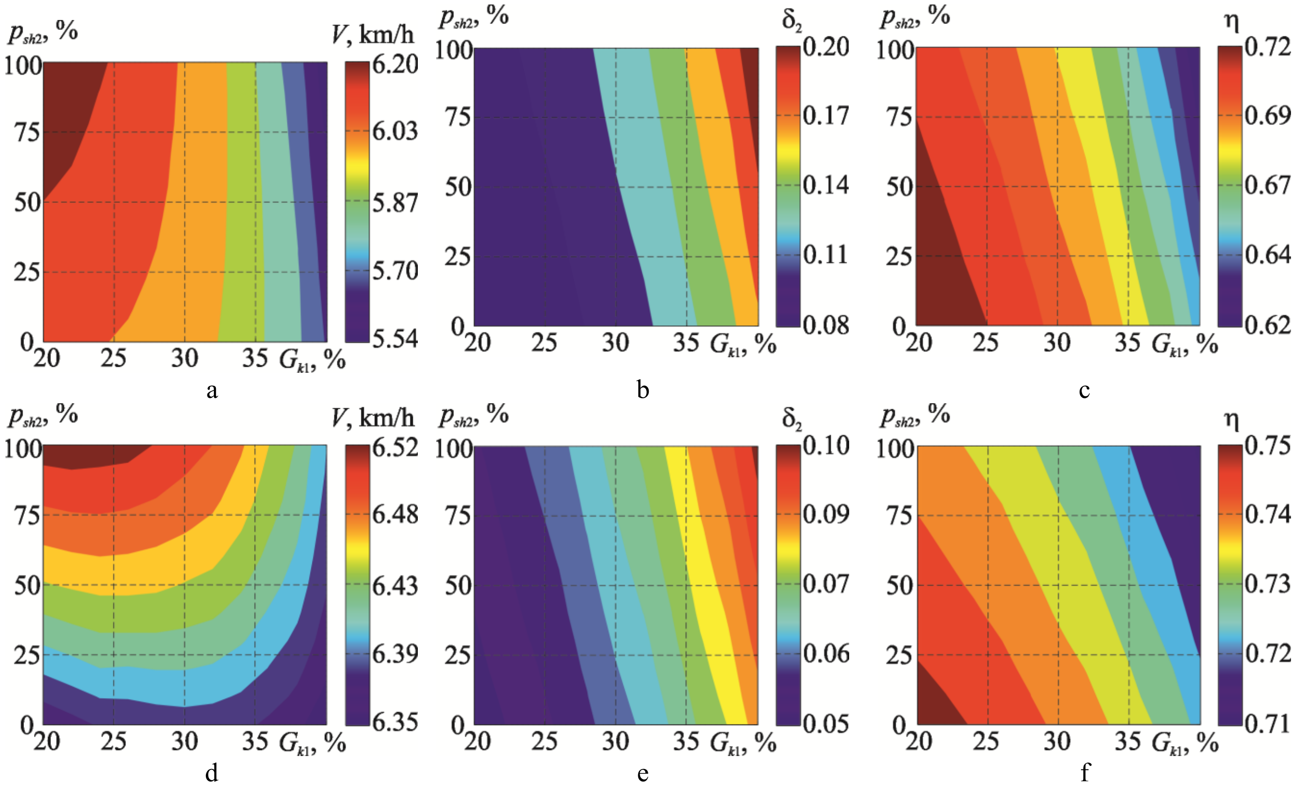


Figure 4: Dependence of low-power tractor indicators speed (a, d), rear wheel slipping (b, e), efficiency (c, f) on the distribution of the total weight on the front axle G_{k1} and the pressure in the front tires p_{sh2} when simulating the field operation of plow aggregation Z1P (a, b, c) and Z2P (d, e, f)

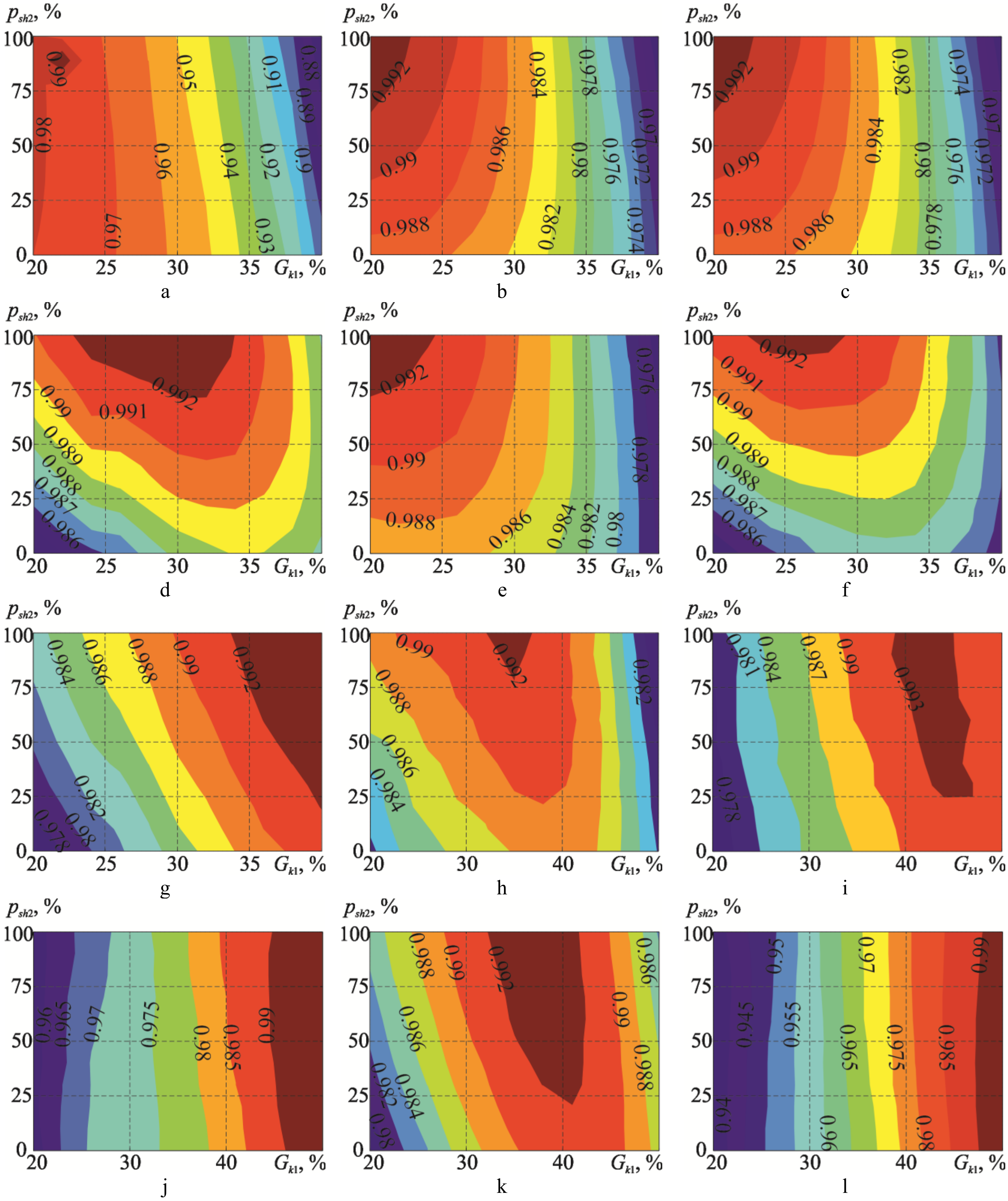


Figure 5: Change of the generalized criterion according to the indicators of optimality from the distribution of the total weight on the front axle G_{k1} and the pressure in the rear tires p_{sh2} when simulating the PowerMix test cycles: Z1P (a); Z2P (b); Z1G (c); Z2G (d); Z3K (e); Z4K (f); Z5K (g); Z3M (h); Z4M (i); Z5M (j); Z6MS (k); Z7PR (l)

5. Discussion

As can be seen from Figure 4, in contrast to the results from Figure 3, the value of the function changes in the vertical (change from the weight distribution) and in the horizontal planes (change from the pressure in the rear tires). The obtained results from Figure 3 show that the pressure in the front tires practically does not affect the main traction indicators of low-power tractor according to the 4x2 layout. The effect of pressure when performing traction work from Z1P plowing is about 1% at 100% load, which allows you to neglect this indicator. As for the influence of weight distribution, this indicator has a great influence on the speed of movement, skidding of the rear driving wheels and the efficiency of the tractor, which is shown in Figure 3, 4. From Figure 4, it is noticeable that the achievement of both the maximum value for speed (V) and tractor efficiency (η), and the minimum value for slipping of the rear driving wheels (δ_2) is achieved at different values of weight distribution and pressure in the rear tires, which emphasizes the feasibility of introducing a generalizing criterion of optimality. As mentioned above, the values of the weighting coefficients for the partial criteria were selected in such a way as to balance the indicators. However, in the future, it is possible to investigate the influence of structural features on traction indicators in the course of achieving the tasks of agricultural environmental sustainability with the priority of slipping, tractor efficiency and evaluation of soil compaction. Figure 3 – 5, the change in tire pressure is shown as a percentage, which represents the change from the minimum allowable value to the maximum allowable pressure value regulated by the tire manufacturer

Analyzing the results obtained from Figure 5, we note that the maximum value of the generalized optimality criterion when performing a certain type of work is achieved when:

- traction work Z1P, Z2P → upon reaching G_{k1} = 21% and G_{k2} = 79% with pressure p_{sh2} = 90%;
- traction work Z1G, Z2G → upon reaching G_{k1} = 25% and G_{k2} = 75% with pressure p_{sh2} = 80÷100%;
- traction-drive work Z3K, Z4K, Z5K → upon reaching G_{k1} = 29% and G_{k2} = 71% with pressure p_{sh2} = 50÷100%;
- traction-drive work Z3M, Z4M, Z5M → upon reaching G_{k1} = 43% and G_{k2} = 57% with pressure p_{sh2} = 50÷100%;
- traction-drive work, hydraulic Z6MS → upon reaching G_{k1} = 38% and G_{k2} = 62% with pressure p_{sh2} = 24÷100%;
- traction-drive work, hydraulic Z7PR → upon reaching G_{k1} = 50% and G_{k2} = 50% with pressure p_{sh2} = 0÷100%.

As can be seen from the obtained results of optimal weight distribution when performing one or another job, the data differ. Depending on the time of execution of a specific traction work, the overall weight distribution may not be calculated in the optimal zone, the adjustment is then made based on the adjustment of the pressure in the rear tires. Assuming that traction work is performed for the same amount of time, the overall optimal weight distribution is G_{k1} = 34% and G_{k2} = 66%.

The shortcoming of this study is that it does not take into account the dependence of the battery discharge of the electric tractor when performing traction work. In the future, this indicator will be taken into account when selecting an electric motor for low-power tractor with a 4x2 construction scheme.

6. Conclusions

An approach to determining the optimal values of weight distribution on the axle of a wheeled tractor and tire pressure according to traction criteria based on simulation of DLG-PowerMix test cycles is presented. The relationship between weight distribution on the axle of low-power tractor and the pressure in the tires of the rear driving wheels during the variation of traction indicators during the execution of technological works on soil cultivation was established. The obtained result should be useful in the design or modernization of electric low-power tractor, which have gained great popularity.

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