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Original Study Article

Capabilities for increasing the technological level of high-power wheeled tractors

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ABSTRACT

BACKGROUND: Solving the problem of efficient use of the Russian-produced energy-saturated 4K4b wheeled tractors of high (235–350 kW) power, which are the basis for the formation of an innovative fleet of mobile energy facilities in the regions of the Siberian Federal District, in zonal tillage technologies with velocity ranges limited by the requirements of agricultural technology and resource saving, is a relevant task.

AIMS: Determination the conditions for the reasonable configuration of the 4K4b wheeled tractors for operational tillage technologies.

METHODS: The basis for solving the problems to achieve the aim is the conditions and methods of a multi-level system of technological adaptation of wheeled tractors.

RESULTS: Based on the results of simulation and experiment, it was determined that the most reasonable method for adapting tractors to tillage technologies in terms of minimum labor costs and the level of capabilities implementation is the formation of the operating mass of the basic configuration at the nominal mode, corresponding to the optimal values of the specific mass at $\phi^*_{KPH} = 0.40$ and $V_{H2} = 2.90$ m/s which are $m^*_{удн1} = 58.0$ kg/kW for single wheels and $m^*_{удн2} = 62.4$ kg/kW for dual wheels, with adjustable axle distribution. The scientific novelty of the study lies in building the model that helps to establish a reasonable traction range of a tractor of various configurations for operational tillage technologies with an interval of nominal operating velocities of 2.5–3.3 m/s, limited by the conditions of resource saving by the modes of maximum traction efficiency and acceptable slipping.

CONCLUSIONS: The practical value of the study lies in the possibility of using the developed recommendations for the reasonable configuration of tractors in tillage operations.

Keywords: *wheeled tractors; tillage technologies; adaptation methods; specific mass.*

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Оригинальное исследование

Потенциальные возможности повышения технологического уровня колесных тракторов высокой мощности

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АННОТАЦИЯ

Обоснование. Решение проблемы эффективного использования энергонасыщенных колесных 4к4б тракторов высокой мощности (235–350 кВт) российского производства, представляющих основу формирования инновационного парка мобильных энергетических средств регионов Сибирского федерального округа, в зональных технологиях почвообработки с ограниченными по требованиям агротехники и ресурсосбережения скоростными диапазонами, является актуальной задачей.

Цель работы — определение условий рациональной комплектации колесных 4к4б тракторов для операционных технологий почвообработки.

Материалы и методы. В основу решения поставленных задач для достижения заявленной цели положены условия и методы многоуровневой системы технологической адаптации колесных тракторов.

Результаты. По результатам моделирования и эксперимента определено, что наиболее рациональным по минимуму трудозатрат и уровню реализации потенциальных возможностей методом адаптации тракторов к технологиям почвообработки является формирование эксплуатационной массы базовой комплектации в номинальном режиме, соответствующей оптимальным значениям удельной массы при $\phi^*_{KPH} = 0,40$ и $V_{H2} = 2,90$ м/с на одинарных $m^*_{удн1} = 58,0$ кг/кВт и сдвоенных $m^*_{удн2} = 62,4$ кг/кВт колесах, с регулируемым распределением по осям. Научная новизна исследования заключается в построении модели, позволяющую установить рациональный тяговый диапазон трактора разной комплектации для операционных технологий почвообработки с интервалом номинальных рабочих скоростей 2,5–3,3 м/с, ограниченный по условиям ресурсосбережения режимами максимального тягового КПД и допустимого буксования.

Заключение. Практическая ценность исследования заключается в возможности использования разработанных рекомендаций по рациональной комплектации тракторов на операциях почвообработки.

Ключевые слова: *колесные тракторы; технологии почвообработки; методы адаптации; удельная масса.*

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BACKGROUND

The formation of an innovative tractor fleet in agriculture for a country's main crop producers involves transitioning to new and modernized existing models of energy-rich wheeled tractors, adapted to regional natural production conditions. Considering natural and production–economic factors [1], the basis for reequipping the tractor fleet in the Krasnoyarsk Territory and other regions of the Siberian Federal District for zonal grain cultivation technologies is served by the model ranges of wheeled 4k4b high-power (235–350 kW) Russian-made tractors K7–Kirovets by PTZ and Rostselmash with mechatronic control and navigation systems [2, 3].

The defining parameter of the traction concept tractor is the nominal traction force $P_{kr\ n}$, under which a set of working machines and a composition of units for operational soil cultivation technologies of groups of different energy intensities are formed. The stability of this indicator, regardless of the energy saturation level and configuration, is fundamental in the existing and future systems for constructing the type and aggregation of tractors. With increasing energy saturation of the traction concept tractor, the condition for implementing $P_{kr\ n}$ and operational power N_{ve} shifts to the higher speed zone with a simultaneous increase in the speed range with incomplete use of engine power, in which traction performance is limited by adhesion.

The problem of effectively using energy-saturated tractors of various basic configurations on single (1w) and dual (2w) wheels in soil cultivation technologies with speed ranges limited by the requirements of agricultural technology and resource saving has acquired particular relevance and requires a solution, considering the possibility of implementing the recommendations developed by manufacturers under conditions of production operation.

STUDY AIMS AND OBJECTIVES

This work aimed to determine the conditions for the rational configuration of 4k4b wheeled tractors for operational soil cultivation technologies.

The study object is the process of forming the adapter parameters of wheeled tractors for operational tillage technologies.

Achieving this goal involves solving the following tasks:

1. Establish the conditions for implementing the potential capabilities of tractors in soil cultivation technologies;;
2. Make a comparative appraisal of the efficiency of the methods used for adapting tractors to operational tillage technologies; and
3. Develop recommendations for the rational configuration of tractors for soil cultivation operations.

MATERIALS AND METHODS

Solving the problems to achieve the set aim is based on the conditions and methods [4–6] of a multilevel system of the technological adaptation of wheeled tractors:

1. The speed range of modern and promising tillage units, rational in terms of agricultural requirements and resource saving, is in the range of $\left(V_{\min} - V_{\max}\right)^*$ = 2,0–3,9 m/s (7–14 km/h) with nominal operating speeds for established groups of operations $V^*_{H1} = 2{,}50$ m/s (9.0 km/h); $V^*_{H2} = 2{,}90$ m/s (10.5 km/h); and $V^*_{H3} = 3{,}33$ m/s (12.0 km/h).
2. The maximum traction efficiency zone on the potential traction characteristic of a 4k4 wheeled tractor under standard conditions, regardless of the configuration and level of energy saturation, is limited by the mode $\overline{\varphi}^*_{\text{кр}\min} = 0{,}36$ of maximum value $\overline{\eta}^*_{\text{т}\max} = 0{,}665$ (1w) to 0.715 (2w) at $P^*_{\text{кр}\min} = m_э \cdot g \cdot \varphi^*_{\text{кр}\min}$ and the maximum permissible slipping $\delta_{\text{пр}} = 0{,}16$ corresponding to the mode $\overline{\varphi}_{\text{кр}} = 0{,}47$ (1w) to 0.49 (2w) and $P_{\text{кр}\,\delta} = m_э \cdot g \cdot \varphi^*_{\text{кр}\,\delta}$ according to the adhesion conditions of the propulsion.
3. The nominal traction mode of the tractor $\varphi^*_{\text{кр н}} = 0{,}40$ at $\eta^*_{\text{тн}} \to \eta^*_{\text{тн}\max}$ determines the value of the main classification indicator $P^*_{\text{кр н}} = 3{,}92 \cdot m_э \cdot 10^{-3}$ (kN) and is the basis for optimizing the main adapter parameter for operating technologies, namely, specific weight $m_э = \dfrac{m_э}{N_{\text{вэ}}}$ in a rational traction range, limited to $\varphi^*_{\text{кр}\min}$ and $\varphi^*_{\text{кр}\max} = 0{,}45$ at $\delta_{\max} \le \delta_{\text{пр}}$ and $\eta_{\text{тд}} \le \eta_{\text{тн}}$.

The condition for the full implementation of the power $N_{\text{вэ}}$ of a tractor of any configuration in a rational traction range $(P_{\text{кр}\max} - P_{\text{кр}\min})^*$ and a range of nominal values $(V_{H\min} - V_{H\max})^*$ is the equality of the following ratios [7]:

$$N_{\text{вэ}} = \frac{P^*_{\text{кр}\max} \cdot V_{H\min}}{\eta_{\text{тд}}} = \frac{P^*_{\text{кр}\min} \cdot V_{H\max}}{\eta_{\text{т}\max}} = = \frac{P^*_{\text{крн}} \cdot V^*_H}{\eta_{\text{тн}}} = \frac{P_{\text{кр}1\max} \cdot V_{\min}}{\eta_{\text{т}\delta}} = \frac{P_{\text{кр}\delta} \cdot V_\delta}{\eta_{\text{т}\delta}}, \quad (1)$$

where $P_{\text{кр}\delta}$, $V_\delta = 2{,}0$ m/s, and $\eta_{\text{т}\delta}$ are indicators at $\delta_{\text{пр}}$; $V_{\min} = 2{,}20$ is the minimum operating speed for the operations of group 1 at $\delta_{\text{пр}}$, and $P_{\text{кр}1\max} = P_{\text{кр}\delta} \cdot \dfrac{V_\delta}{V_{\min}}$.

In relation to unit power $N_{вэ} = 1,0$ kW and $P_{уд} = m_{уд} \cdot g \cdot \varphi_{кр} \cdot 10^{-3}$ Eq. (1) takes the form:

$$\left[\begin{array}{l} \dfrac{(m_{уд} \cdot \varphi_{кр})^*_{\max} \cdot V^*_{H\min}}{\eta_{тд}} = \\ = \dfrac{(m_{уд} \cdot \varphi_{кр})^*_{\min} \cdot V^*_{H\max}}{\eta_{т\max}} = \\ = \dfrac{(m_{уд} \cdot \varphi_{кр})^*_{H} \cdot V^*_{H}}{\eta^*_{тi}} = \\ = \dfrac{(m_{уд} \cdot \varphi_{кр})_{\delta} \cdot V_{\min}}{\eta_{т\delta}} = \\ = \dfrac{(m_{уд} \cdot \varphi_{кр})_{\delta} \cdot V_{\delta}}{\eta_{т\delta}} \end{array} \right] \cdot g \cdot 10^{-3} = 1,0. \quad (2)$$

With the established values of V_{Hi} and dependencies $\eta_{тi} = f(\varphi_{кр})$, the optimal levels of specific adapter parameters $m^*_{уд}$ (kg/kW) and $P^*_{уд}$ (kN/kW) for each group of operations are as follows:

$$\begin{cases} m^*_{удi} = \dfrac{\eta_{тi}}{g \cdot \varphi^*_{крi} \cdot V^*_{Hi} \cdot 10^{-3}}; \\ P^*_{удi} = m^*_{удi} \cdot g \cdot \varphi^*_{крi} \cdot 10^{-3} = \dfrac{\eta_{тi}}{V^*_{Hi}}. \end{cases} \quad (3)$$

Taking the nominal traction mode $\varphi^*_{кр\,н} = 0,40$ with $m^*_{уд\max} = m^*_{уд\,н} = \dfrac{\eta_{тн}}{g \cdot \varphi_{кр\,н} \cdot V_{H1} \cdot 10^{-3}}$ in the operations of group 1 as base one, the optimal ratios of specific parameters for different groups of operations and configurations are accordingly as follows:

$$\begin{cases} \lambda m^*_{удi} = m^*_{удi} m^*_{уд\,н} = \left(\dfrac{\lambda \eta_{тн}}{\lambda \varphi_{кр\,н} \cdot \lambda V_H} \right)_i \le 1,0; \\ \lambda P^*_{удi} = \dfrac{P^*_{удi}}{P^*_{уд\,н}} = \left(\dfrac{\lambda \eta_{тн}}{\lambda V_H} \right)_i \le 1,0; \\ \lambda m^*_{уд\,к} = m^*_{уд2к} m^*_{уд1к} = \left(\lambda \eta_{тн} \cdot \lambda \varphi_{кр\,н} \right)_к > 1,0. \end{cases} \quad (4)$$

Exceeding the actual value of the specific weight $m^{ф}_{удi}$ of optimal $m^*_{удi}$ shifts the traction mode $\varphi^*_{крi}$, corresponding to V^*_{Hi}, to the zone $\varphi^{ф}_{крi} < \varphi^*_{крi}$ and vice versa, at $m^{ф}_{удi} < m^*_{удi} \cdot \varphi^*_{крi} > \varphi^*_{крi}$.

The degree of implementation of the potential capabilities of a tractor of any configuration in soil cultivation technologies with established values of $m^*_{уд\,н}$, $m^*_{удi}$ and $m^{ф}_{удi}$ is characterized by the complex indicator $K_{Э}$ [5], which represents the product of partial efficiency criteria for productivity $K_W = \lambda \cdot \eta_{тд}$, operating weight $K_m = \left(2 - \lambda \cdot m_{уд}\right)$, and fuel consumption $K_E = \left(2 - \dfrac{1}{\lambda \eta^2_{т}}\right)$:

$$K_{Э} = K_W \cdot K_m \cdot K_E \ge K^*_{Э\min}. \quad (5)$$

From the condition $K_{Э\max} = 1,0$, at $\lambda \eta_{т} > 1,0$ and $\lambda m_{уд} \le 1,0$ the restrictions $K_W = K_m = K_E = 1,0$ are accepted.

To comparatively assess the technological level of a tractor on dual and single wheels, Eq. (5) has the form:

$$\lambda K_{ЭК} = \frac{K_{Э2К}}{K_{Э1К}} = \left(\lambda K_W \cdot \lambda K_m \cdot \lambda K_E\right)_К. \quad (6)$$

The basic configuration of 4k4b wheeled tractors is characterized by furnishment with single (1w) or dual (2w) wheels. Installing dual wheels is a rather simple and effective way to solve the problem of implementing the power of energy-saturated tractors by substantially increasing and regulating the operating weight while increasing the carrying capacity and reducing the specific pressure on the soil. In relation to the model ranges of Kirovets and RSM tractors [2–5], the increase in $m_{Э\max}$ due to a set of 800/65R32 and 710/70R38 tires weighing $m_{2К} = 2200$ kg reaches 13%–14% while reducing the specific pressure by 43% and rolling losses by up to 27% with an unsubstantial (1.5%–2.0%) decrease in the abscissa of the center of mass.

RESULTS AND DISCUSSION

According to the simulation results, for each group of operations, the nominal values of the specific parameters $m^*_{уд\,н}$ and $P^*_{уд\,н}$ for $\varphi^*_{кр\,н} = 0,40$ and permissible intervals for their change within the limits of the rational traction range $\varphi^*_{кр\min} < \varphi^*_{кр\,н} < \varphi^*_{кр\max}$ were established using Eq. (4) and the experimental dependencies $\eta_{т} = f(\varphi_{кр})$ of the specified tractors of different configurations [5].

The dependencies obtained enabled giving a comparative assessment of the efficiency and feasibility of the most used methods for implementing the potential capabilities of these tractors (Table 2) in operational soil cultivation technologies.

Option 1 characterizes a tractor with a constant specific weight for single 67.3* kg/kW and dual 72.4* kg/kW wheels at $\varphi^*_{кр\,н} = 0,40$ and rated speed $V^*_{H1} = 2,50$ m/s in group 1 operations, corresponding to $m^*_{Э} = 255 \cdot P_{кр\,н}$ (kN) and $A^*_{ц} = 0,57$ (1w)/0.56 (2w). The specified configuration ensures the tractor functioning in the traction range $(\varphi^*_{кр\,\delta} - \varphi^*_{кр\min})$ with a range of operating speeds of 2.0–2.8 m/s, corresponding to the operations of groups 1–2 of high-speed ($V_{\min 1} = 2,2$ m/s) and special ($V_{\delta} = 2,0$ m/s) units at $K_{Э} = 0,887 - 1,00$. In the

Table 1. Specific parameters-adapters of the 4K4b wheeled tractors of various configurations to tillage technologies
Таблица 1. Удельные параметры-адаптеры колёсных 4к4б тракторов разной комплектации к технологиям почвообработки

Traction mode (force)	Configuration	$\bar{\varphi}_{кр}$	$\bar{\eta}_{т}$	$\bar{m}^{*}_{уд}$, kg/kW				
					V_{H2}=2,90 m/s	V_{H3}=3,33 m/s	V_{min}=2,20 m/s	V_{δ}=2,0 m/s
$\varphi^{*}_{кр\,min}$	1 w	0,360	0,665	75,3	64,9	56,5	85,5	94,1
	2 w	0,360	0,715	81,0	69,8	60,8	92,1	101,3
$\varphi^{*}_{кр\,н}$	1 w	0,400	0,660	67,3	58,0	50,5	76,5	84,1
	2 w	0,400	0,710	72,4	62,4	54,3	82,3	90,5
$\varphi^{*}_{кр\,max}$	1 w	0,450	0,640	58,0	50,2	43,5	66,4	73,1
	2 w	0,450	0,690	62,3	53,7	46,8	71,4	78,5
$\varphi_{кр\,\delta}$	1 w	0,470	0,633	54,9	47,3	41,2	62,4	68,6
	2 w	0,490	0,683	56,8	49,0	42,7	64,3	70,7

Table 2. Indicators of the technological level of the 4K4b wheeled tractors of various configurations
Таблица 2. Показатели технологического уровня колёсных 4к4б тракторов разной комплектации

Configuration (operating weight	Parameters	Parameter values (1w/2w)				
		V_{H1}=2,50 m/s	V_{H2}=2,90 m/s	V_{H3}=3,33 m/s	V_{min}=2,20 m/s	V_{δ}=2,0 м/с
Constant $m_{Э\,max} = m^{*}_{ЭН1} = 255 P_{кр\,н}$, kg	$m^{*}_{уд\,н}$, kg/kW	67,3/72,4	67,3/72,4	67,3/72,4	67,3/72,4	67,3/72,4
	$\bar{\varphi}_{кр\,н}$	0,400	0,347	0,296	0,444	0,470/0,485
	$\bar{\eta}_{тн}$	0,660/0,710	0,665/0,715	0,650/0,700	0,645/0,693	0,633/0,684
	$P_{уд}$, kN/kW	0,265/0,284	0,229/0,245	0,195/0,210	0,293/0,315	0,310/0,344
	$A^{*}_{ц}$	0,59/0,58	0,59/0,58	0,59/0,58	0,59/0,58	0,59/0,58
	$\bar{K}_{W}$	1,0	1,0	0,985	0,977	0,960
	$\bar{K}_{E}$	1,0	1,0	0,970	0,953	0,920
	$\bar{K}_{m}$	1,0	0,840	0,667	1,0	1,0
	$\bar{K}_{Э}$	1,0	0,840	0,637	0,931	0,887
	$\lambda\bar{K}_{ЭК}$	1,128	1,128	1,130	1,127	1,109
Adjustable with removable ballast $m_{Э\,max} = m^{*}_{ЭН1}$ $m^{*}_{ЭН1} = \frac{m^{*}_{ЭН1}}{\lambda V_{H1}} = 255 P_{кр\,н\,i}$	$m^{*}_{уд}$, kg/kW	67,3/72,4	58,0/62,4	50,5/54,3	67,3/72,4	67,3/72,3
	$\bar{\varphi}_{кр\,н}$	0,40	0,40	0,40	0,444	0,470/0,485
	$\bar{\eta}_{тн}$	0,660/0,710	0,660/0,710	0,660/0,710	0,645/0,693	0,633/0,684
	$P_{уд}$, kN/kW	0,265/0,284	0,228/0,245	0,198/0,213	0,293/0,315	0,310/0,344
	$m^{*}_{Буд}$	16,8/18,1	7,5/8,1	0/0	16,8/18,1	16,8/18,1
	$A^{*}_{ц}$	0,61/0,60	0,57/0,56	0,57/0,56	0,61/0,60	0,61/0,60
	$\bar{K}_{Э}$	1,0	1,0	1,0	0,931	0,882
	$\lambda\bar{K}_{ЭК}$	1,128	1,128	1,130	1,127	1,110

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Table 2. Ending

Таблица 2. Окончание

Configuration (operating weight)	Parameters	Parameter values (1w/2w)				
		V_{H1}=2,50 m/s	V_{H2}=2,90 m/s	V_{H3}=3,33 m/s	V_{min}=2,20 m/s	V_δ=2,0 m/s
Constant with adjustable axle distribution of removable ballast $m^*_{Буд}(0,07-0,08)\overline{m}^*_{уд}$	$m^*_{уд\,н}$, kg/kW	58,0/62,4	58,0/62,4	58,0/62,4	$62,4^*$/$64,3^*$	$68,6^*$/$70,7^*$
	$\overline{\varphi}_{кр\,н}$	0,450	0,400	0,350	0,470/0,485	0,470/0,490
	$\overline{\eta}_{тн}$	0,645/0,693	0,660/0,710	0,665/0,715	0,633/0,683	0,633/0,683
	$P_{уд}$, kN/kW	0,256/0,275	0,228/0,245	0,199/0,214	0,288/0,311	0,316/0,342
	$A^*_ц$	0,61/0,60	0,57/0,56	0,57/0,56	0,61/0,60	0,61/0,60
	$\overline{K}_W$	0,977	1,0	1,0	0,961	0,961
	$\overline{K}_E$	0,952	1,0	1,0	0,917	0,917
	$\overline{K}_m$	1,0	1,0	0,852	1,0	1,0
	$\overline{K}_Э$	0,930	1,0	0,852	0,881	0,881
	$\lambda\overline{K}_{ЭК}$	1,128	1,128	1,130	1,110	1,110

operations of groups 2 and 3, because of the shift of the traction mode to the zone, $\varphi_{кр\min} < \varphi^*_{кр\min}$ $\overline{K}_Э = 0,840-0,637$, which is irrational because of the excess of $m^*_{уд}$ up to 33%. The configuration with dual wheels in all traction and speed modes, except $\varphi_{кр\delta}$, ensures an increase in the technological level of the tractor to $\lambda\overline{K}_{ЭК} = 1,128$. This category includes the K-730 and K-735 tractors of the K-7 series with single wheels in the standard configuration [8].

Option 2 represents a tractor with a wide range of specific weight regulations due to removable ballast from $m^*_{уд\min} = m^*_{уд3} = 50,5$ (1w) to 54.3 (2w) kg/kW at $m_{уд} = 0$ up to $m^*_{уд\max} = m^*_{уд1} = 67,3$ (1w) to 72.4 (2w) kg/kW with full ballast $m^*_{Буд\max} = m^*_{уд3} = 16,8(1к)-18,1(2к)$ kg/kW for the use of different groups in soil cultivation operations in the zone $\varphi^*_{кр\,н} = 0,40$ with $\overline{K}_Э = 1,0$ and stability of the indicator $\lambda\overline{K}_{ЭК}$. For operation as part of mounted units at V=2,0-3,0 m/s, the abscissa of the center of mass is changed to $A^*_ц = 0,61/0,60$ by moving a part of the ballast weights, considering their location while maintaining the value $m^*_{уд1}$. Meanwhile, a $N_{вэ} \geq 200$ kW tractor with full ballast, regardless of its configuration, grades into a higher traction class. This option is the most optimal for implementing the potential capabilities of the tractor in soil cultivation technologies but requires additional costs and qualifications of the operator to adapt it to operating conditions. This category is represented by RSM series 2 and 3 tractors on dual wheels in the basic configuration with a maximum mass of removable ballast $m_{Б\max} = (0,20-0,25\cdot m^*_Э)$.

The doubling of wheels with a full weight $m_{2К} = 2200$ [2–3] provides in all variants an increase in the nominal traction force by 8.63 kN, which is decisive for the transition of the tractor to the adjacent higher (up to 6) traction class. The tractor transition from traction class 6 to traction class 8 when doubling the wheels is possible by installing additional ballast weighing at least 2400 kg.

For option 3, we considered a tractor of any basic configuration with a constant value and adjustable distribution along the axes of the specific mass $\overline{m}^*_{уд} = 58,0$ (1w) to 62.4 (2w) kg/kW due to displaceable removable ballast $m^*_{Буд} = (0,075-0,085)\overline{m}^*_{уд}$ at a nominal traction speed mode corresponding to $\varphi^*_{кр\,н} = 0,40$ и $V_{Н2} = 2,90$ m/s. The established values of $\overline{m}^*_{уд}$ oensure the tractor functioning in operations of all groups in the traction range $(\varphi_{кр\min} - \varphi_{кр\max})^*$ at $\overline{K}_Э = 0,852-1,00$. The abscissa of the center of mass is increased to $A^*_ц = 0,61/0,60$ in the group 1 operations by moving a part of the rear ballast to the zone of the front one. To implement potential opportunities in the $(V_\delta - V_{\min}) = 2,0-2,2$ m/s interval at $\overline{K}_Э > R_{Э\min}$, the HAWI (hydraulic adhesion weight increaser) from the condition $\overline{m}^{*}_{\text{ГСВуд}} = (0{,}107 - 0{,}110)\cdot \overline{m}^{*}_{\text{уд}}$. is used. This option for adapting the tractor to production conditions has considerable advantages over those discussed above regarding the technological level and implementation costs. In a somewhat simplified form, it is used when setting up the K-739, K-740, and K-742 tractors to perform specific operations on dual wheels.

The presented simulation results show that the potential opportunities for increasing the technological level of high-power wheeled tractors at the achieved speed intervals cannot be used to perform tillage and sowing operations according to agrotechnical requirements and energy costs without regulating the operating weight by installing a ballast and dual wheels. Performing these operations considerably increases the labor intensity of tractor operation and requires a higher professional level of machine operators and the use of additional technical means for preparatory work on adjusting parameters, namely, adapters before the start of the technological process. Considering the estimated efficiency indicators of the main methods and the level of ballasting, the adaptation should be based on the last option using dual wheels with an adjustable installation of removable ballast $\overline{m}^{*}_{\text{Буд}} = (0{,}07 - 0{,}09)\overline{m}^{*}_{\text{уд}}$ as the basic configuration of the tractor.

CONCLUSIONS

1. The rational traction range of the 4k4b tractor of various configurations for operational tillage technologies with a range of nominal operating speeds of 2.5–3.3 m/s, according to resource-saving conditions, is limited within the maximum traction efficiency zone by modes $\varphi^{*}_{\text{кр min}}(\eta_{\text{т max}}) - \varphi^{*}_{\text{кр max}}(\delta_{\text{д}}) = 0{,}36 - 0{,}45$ with an acceptable reduction in the complex indicator of manufacturability $\overline{K}_{\text{Э min}} \geq 0{,}880$.
2. The most effective method for adapting a tractor to tillage technologies in terms of minimum labor costs and the implementation level of potential capabilities is to form the operating weight of the basic configuration at $\varphi^{*}_{\text{кр н}} = 0{,}40$ and $V_{\text{Н2}} = 2{,}90$ m/s with an adjustable distribution along the axes of the mass of removable ballast included in it, corresponding to the optimal value of the specific adapter parameter at $m^{*}_{\text{уд н1}} = 58{,}0$ kg/kW for single wheels and $m^{*}_{\text{уд н2}} = 62{,}4$ kg/kW for dual wheels with $m^{*}_{\text{Буд}} = (0{,}075 - 0{,}080)m^{*}_{\text{уд н}}$ and providing $\overline{K}_{\text{Э}} = 0{,}852 - 1{,}00$.
3. Considering the development trends and limited speed intervals of operating technologies for soil cultivation, the basic configuration of wheeled 4k4b tractors should be based on the specific gravity $m^{*}_{\text{уд н2}} = 62 - 63$ kg/kW on dual wheels, including removable ballast of $m^{*}_{\text{Буд}} = 5{,}0 - 5{,}5$ kg/kW with adjustable distribution along the axes and the use of $V_{\min} \leq 2{,}0 - 2{,}2$ m/s with attachments for an HAWI based on $m^{*}_{\text{ГСВуд}} = 0{,}107 - 0{,}110 m^{*}_{\text{уд н2}}$.

ADDITIONAL INFORMATION

Authors' contribution. N.I. Selivanov, A.V. Kuznetsov, N.V. Kuzmin — search for publications, writing the text of the manuscript; V.G. Shram, Yu.F. Kaiser — editing the text of the manuscript; N.I. Selivanov — expert opinion, approval of the final version. All authors made a substantial contribution to the conception of the work, acquisition, analysis, interpretation of data for the work, drafting and revising the work, final approval of the version to be published and agree to be accountable for all aspects of the work.

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Вклад авторов. Н.И. Селиванов, А.В. Кузнецов, Н.В. Кузьмин — поиск публикаций по теме статьи, написание текста рукописи; В.Г. Шрам, Ю.Ф. Кайзер — редактирование текста рукописи, создание изображений; Н.И. Селиванов — экспертная оценка, утверждение финальной версии. Авторы подтверждают соответствие своего авторства международным критериям *ICMJE* (все авторы внесли существенный вклад в разработку концепции, проведение исследования и подготовку статьи, прочли и одобрили финальную версию перед публикацией).

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REFERENCES

1. Selivanov NI, Kuznetsov AV, Kuzmin NV. Standard sizes of wheeled tractors and the composition of tillage units for the East Siberian agrozone. *Vestnik AGAU.* 2022;3(209):94–101. (in Russ). doi: 10.53083/1996-4277-2022-209-3-94-101

2. Tractors "Kirovets" K-744R, K-744R1, K-744R2, K-744R3. Operating instructions 744R-0000010 IE.2. Tractors "Kirovets" K-744R, K-744R1, K-744R2, K-744R3. Operating Instructions 744P-0000010. IE. CJSC "Petersburg Tractor Plant" Saint Petersburg. (in Russ). Accessed: 21.03.2023. Available from: https://zinref.ru/000_uchebniki/05300_traktora/004_00_00_Kirovec_k_744_r_rukovodstvo/000.htm

3. Operating instruction3.s Operating Instructions Versatile 435, 485, 535 -89002113. Buhler Versatile Inc. Winnipeg, Manitoba, Canada, 2009. (in Russ). Accessed: 21.03.2023. Available from: https://hostozavr.com/files/traktora/rukovodstvo-po-jekspluatacii-traktorov-versatile-435-485-535.pdf.

4. GOST 27021-86 Traktory selskokhozyaystvennye i lesokhozyaystvennye. Tyagovye klassy. Moscow: IPK Izdatelstvo standartov; 1986. (in Russ). Accessed: 21.03.2023. Available from: https://docs.cntd.ru/document/1200009845

5. Zaprudsky VN, Makeeva YuN. Evaluation of the effectiveness of the use of wheeled tractors of high power on the main tillage. *Vestnik KrasGAU.* 2016;5:117–122. (in Russ). Accessed: 21.03.2023. Available from: http://www.kgau.ru/vestnik/2016_5/content/18.pdf

6. Selivanov NI, Zaprudsky VN, Makeeva YuN, et al. Rational traction range for the use of wheeled tractors. In: *Proceedings of the international scientific and practical conference dedicated to the 70th anniversary of Krasnoyarsk State Agrarian University. Part 2. Science: experience, problems, development prospects.* Krasnoyarsk: KrasGAU; 2022:115–119. (in Russ).

7. Libtsis SE. Potential possibilities of using the power of energy-saturated tractors. *Tractors and agricultural machinery.* 1986;9:8–16. (in Russ).

8. Glushkov RV, Krylov AV, Kuznetsova PA. Method for determining the energy consumption of a prototype cultivator. In: *Resource-saving technologies in the agro-industrial complex of Russia. Proceedings of the III International Scientific Conference.* Krasnoyarsk; 2022:319–323. (in Russ).

СПИСОК ЛИТЕРАТУРЫ

1. Селиванов Н.И., Кузнецов А.В., Кузьмин Н.В. Типоразмеры колесных тракторов и состав почвообрабатывающих агрегатов для Восточно-Сибирской агрозоны // Вестник АГАУ. 2022. № 3 (209). С. 94–101. doi: 10.53083/1996-4277-2022-209-3-94-101

2. Тракторы «Кировец» К-744Р, К-744Р1, К-744Р2, К-744Р3. Инструкция по эксплуатации 744Р-0000010. ИЭ. ЗАО «Петербургский тракторный завод». Санкт-Петербург. [дата обращения: 21.03.2023] Режим доступа: https://zinref.ru/000_uchebniki/05300_traktora/004_00_00_Kirovec_k_744_r_rukovodstvo/000.htm.

3. Инструкция по эксплуатации Versatile 435, 485, 535 -89002113. Buhler Versatile Inc. Виннипег, Манитоба, Канада, 2009. [дата обращения: 21.03.2023] Режим доступа: https://hostozavr.com/files/traktora/rukovodstvo-po-jekspluatacii-traktorov-versatile-435-485-535.pdf.

4. ГОСТ 27021-86 Тракторы сельскохозяйственные и лесохозяйственные. Тяговые классы. М: ИПК Издательство стандартов, 1986. [дата обращения: 21.03.2023] Режим доступа: https://docs.cntd.ru/document/1200009845

5. Запрудский В.Н., Макеева Ю.Н. Оценка эффективности использования колесных тракторов высокой мощности на основной обработке почвы // Вестник КрасГАУ. 2016. № 5. С. 117–122. [дата обращения: 21.03.2023] Режим доступа: http://www.kgau.ru/vestnik/2016_5/content/18.pdf

6. Селиванов Н.И., Запрудский В.Н., Макеева Ю.Н., и др. Рациональный тяговый диапазон использования колесных тракторов // Материалы международной научно-практической конференции, посвященной 70-летию ФГБОУ ВО Красноярский ГАУ. Часть 2. Наука: опыт, проблемы, перспективы развития. Красноярск: КрасГАУ, 2022. С. 115–119.

7. Либцис С.Е. Потенциальные возможности использования мощности энергонасыщенных тракторов // Тракторы и сельхозмашины. 1986. № 9. С. 8–16.

8. Глушков Р.В., Крылов А.В., Кузнецова П.А. Методика определения энергозатрат опытного образца культиватора // Ресурсосберегающие технологии в агропромышленном комплексе России. Материалы III Международной научной конференции. Красноярск, 2022. С. 319–323.

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