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METHODOLOGY FOR DETERMINING THE INDICATORS OF TRACTION-SPEED PROPERTIES OF A GROUND WHEELED ROBOT WITH AN ELECTROMECHANICAL TRANSMISSION

Modern trends in the development of armaments and combat tactics are characterized by the active implementation of ground wheeled robotic systems. The choice of the type of power plant and the design of the transmission for such systems is determined by their functional purpose and mass-dimensional parameters. Robots of small mass are generally equipped with electric drives that ensure high maneuverability and low observability, whereas heavier platforms require more powerful power units – primarily internal combustion engines with electromechanical transmissions, which improve their traction characteristics, autonomy, and passability.

The purpose of the article is to develop a method for determining the traction characteristics of a ground wheeled robot with an electromechanical transmission and to establish the main indicators of its traction-speed performance. The proposed approach can be used both at the design stage and for the preliminary assessment of the efficiency of machines proposed for adoption into service.

Keywords: *ground wheeled robot, electromechanical transmission, traction-speed performance, method.*

Statement of the problem. One of the directions in the development of armaments and their employment tactics in modern warfare is the use of ground wheeled robots – remotely operated or partially autonomous platforms capable of performing combat and/or logistical tasks without the direct presence of a human operator. The combat experience of the Defence Forces of Ukraine demonstrates that ground wheeled robots have effectively become an integral element of contemporary warfare. Their large-scale deployment is transforming battlefield tactics, making combat more technologically advanced and safer for personnel. At the same time, a number of problems remain: a limited operational range due to the relatively short endurance of autonomous power sources, restricted mobility on terrain with complex relief or challenging physical and mechanical surface properties, and insufficient resilience of communication systems under conditions of electronic warfare, among others.

The results of the conducted analysis of ground robot designs show that the type of power plant and transmission configuration largely depend on the intended purpose, weight, and dimensional characteristics of the robot. Robots of relatively small size and mass are typically equipped with electric drives powered by chemical current sources, which provide adequate mobility and good stealth characteristics. However, along with these advantages, the electric drive also has certain disadvantages, such as a limited operational range that, under certain climatic and operational conditions, may even lead to the non-combat loss of the robot. Another relatively negative factor may be the need for powerful charging devices within the operational area, which can be difficult to provide under heavy enemy fire.

Robots with larger dimensions and mass possess better tactical and technical characteristics but require more powerful power units. In such cases, power plants with internal combustion engines and electromechanical transmissions are most commonly used. In modern terminology, such a power plant is referred to as a hybrid system. This configuration increases the traction characteristics of the machine and expands its operational radius, autonomous endurance, and passability – factors of particular importance for ground robots intended for logistical missions and for heavy combat robots.

In the most suitable configuration for a ground wheeled robot, the electromechanical transmission consists of an electric generator driven by an internal combustion engine, electric hub motors, and an energy storage device. In a simpler and more affordable configuration, the transmission may be implemented without an energy storage unit. In addition to the previously mentioned advantages, the electromechanical transmission also allows the potential energy of vehicle acceleration to be used for electrodynamic braking with recuperation of braking energy.

The evaluation of the traction-speed performance of a ground wheeled robot with an electromechanical transmission requires an appropriate methodology. Such a methodology may be used both at the design stage of the robot and for assessing the traction-speed performance indicators of machines that developers propose – on their own initiative – for adoption into service.

Analysis of recent research and publications. The main sources of information relevant to the research topic at present include online publications, scientific articles in open-access sources, and available patent-information materials.

The Doctrine of the Commander-in-Chief of the Armed Forces of Ukraine [1] defines the general role of unmanned systems and complexes – including ground platforms – in enhancing the combat potential of the Defence Forces of Ukraine, ensuring technological superiority, and creating a powerful asymmetric instrument for countering the adversary. It also requires the implementation of a systematic approach to the employment of unmanned systems at the strategic, operational, and tactical levels in order to achieve maximum effect and inflict losses on the enemy.

In the monograph [2], among other issues, attention is focused on the use of robotic ground platforms for solving logistical tasks, particularly for the delivery of ammunition and equipment, as well as for providing logistical support to troops during combat operations without exposing personnel to risk. It is reasonable to assume that, for effective performance of these tasks, ground wheeled robots must have relatively high average movement speed, operational range, passability, and payload capacity, and therefore a comparatively large mass. The analysis of information provided in online publications [3–6] shows that electromechanical transmissions are used in the design of ground logistical and multifunctional wheeled robots with a gross weight ranging from 1.5 to 15 tonnes, both those already adopted for service and prospective models.

The article [7] justifies the use of a hybrid power plant with an electromechanical transmission in heavy class combat ground robots and concludes that the application of hybrid power plants is a global trend in the development of medium and heavy ground robotic systems, providing enhanced combat capabilities and low observability in the immediate contact zone with the enemy. The article [8] provides a sufficiently comprehensive justification of the design of a ground wheeled robot with a hybrid transmission. However, the proposed configuration uses a hydrostatic transmission which, although having layout and traction properties comparable to those of an electromechanical transmission, provides lower movement speeds.

Information necessary for this study regarding the general requirements for the design of transmissions of ground vehicles, structural solutions for meeting these requirements, and typical transmission designs is presented in works [9, 10]. The article [11] provides an overview of modern transmissions for multi-axle vehicles. In the monograph [12], the features of vehicles with hybrid power plants are analyzed, electric systems and components of hybrid vehicles are considered, general information about electromechanical transmissions is presented, and a mathematical model of a hybrid vehicle is described. Conceptual principles for forming a hybrid drive for a high-mobility vehicle and methodological recommendations for determining its basic parameters are presented in articles [13, 14].

The work [15] outlines the main indicators of traction-speed performance of a vehicle, formulates the content and sequence of their calculation, and determines the influence of design and operational factors on traction-speed characteristics. In article [16], a graph-analytical method and analytic-stochastic methods for evaluating the tractive dynamics of military vehicles are proposed, based on comparing the tractive force developed by the vehicle at the driving wheels with the resistance forces arising during motion. Certain provisions of the methodology proposed in [17] for calculating the parameters of an electric vehicle – which logically combines electrical and mechanical parameters – may be used to determine the basic parameters of the electrical part of the electromechanical transmission of a ground wheeled robot.

Overall, the analysis of research and publications provides sufficient information necessary to determine the scope and appropriate research methods.

The purpose of the article is to develop a methodology for the traction calculation of a ground wheeled robot with an electromechanical transmission and to determine the main indicators of its traction-speed performance.

Summary of the main material. The study is performed for an all-wheel-drive ground robot intended for logistical tasks, moving in a straight line along the X-axis of a fixed coordinate system XOZ. The motion occurs under the action of forces and moments generated by the power source and the surrounding environment (Figure 1).

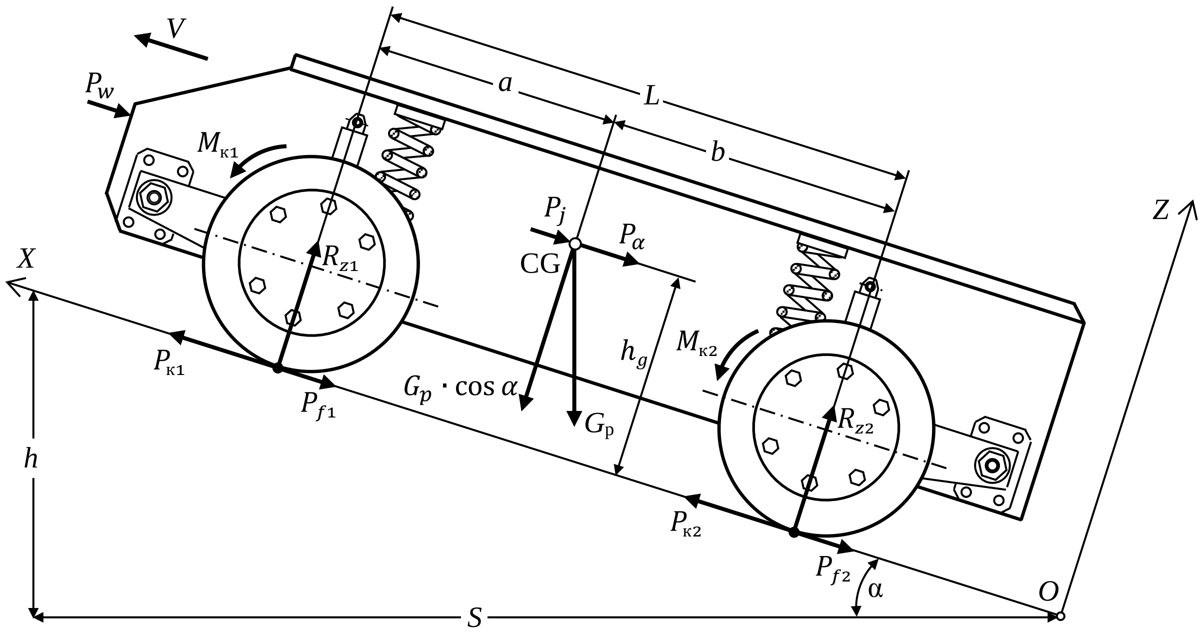

Figure 1 – Forces and moments acting on the wheeled robot during motion

In this figure, the following are indicated: $P_{к1}$, $P_{к2}$ – traction forces on the driving wheels; P_{f1}, P_{f2} – rolling resistance forces; P_α – grade resistance force; P_j – acceleration resistance force; P_w – aerodynamic drag force; R_{z1}, R_{z2} – vertical reactions of the supporting surface; G_p – total weight of the robot; $M_{к1}$, $M_{к2}$ – torques on the driving wheels; L – wheelbase of the robot; CG – center of gravity.

The power source is installed on the platform and includes an internal combustion engine (ICE) and an electric generator. The generator's energy is supplied to the traction electric motors and converted into mechanical energy, which is transmitted to the driving wheels through mechanical gear reducers. When electric hub motors are used, the mechanical reducer is integrated into their design.

To enhance survivability and reduce the unsprung mass of a military-purpose wheeled robot, the traction electric motors and reducers may be placed inside a protected hull. In this case, torque is transmitted to the driving wheels via a propeller shaft.

The research methodology includes a number of sequential stages aimed at determining the main parameters of the power unit of the ground wheeled robot and calculating the values of its traction-speed performance indicators.

Determination of the ICE Power. The maximum power of the internal combustion engine (ICE) is determined from the condition of ensuring the specified maximum vehicle speed V_{max} during steady-state motion on a horizontal road ($P_j = 0$, $P_\alpha = 0$). In this case, the power balance equation has the form:

$$N_{wh} + N_f + N_w = 0\,, \qquad (1)$$

where N_{wh} is the power delivered to the driving wheels;

N_f is the power required to overcome rolling resistance;

N_w is the power required to overcome aerodynamic drag.

The power delivered to the driving wheels is determined by the expression:

$$N_{wh} = N_{ICE} \cdot (1 - k_{ad}) \cdot \eta_e \cdot \eta_{mech}, \qquad (2)$$

where N_{ICE} is the ICE power;

k_{ad} is the power utilization factor accounting for the drive of auxiliary ICE equipment and operation of the robot's control systems;

η_e is the efficiency of the electrical part of the transmission;

η_{mech} is the efficiency of the mechanical part of the transmission (hub motor reducer).

After performing the necessary transformations and substituting the known expressions for P_f and P_w [15], we obtain:

$$N_{\text{ICE.max}} = \frac{V_{\max} \cdot (m_{\text{rob}} \cdot g \cdot \psi_v + F_{\text{rob}} \cdot k_w \cdot V_{\max}^2)}{\eta_{\text{e}} \cdot \eta_{\text{mech}} \cdot (1 - k_{\text{ad}})}, \quad (3)$$

where m_{rob} is the total mass of the robot, kg;

g is the acceleration due to gravity, m/s²;

ψ_v is the rolling resistance coefficient at maximum speed;

F_{rob} is the frontal area (midsection area) of the robot, m²;

k_w is the aerodynamic drag coefficient, N·s²/m⁴.

On a horizontal road, $\psi_v = f$, where f is the rolling resistance coefficient, a reference value for the given type and condition of the road surface. When moving uphill, $\psi_v = f + i$, where f is the longitudinal road grade.

Determination of the Parameters of the Traction Electric Motor. The power of the traction electric motor required to ensure the robot's motion at the speed $V_{\max}$ is determined by the following expression:

$$N_{\text{el.max}} = \frac{N_{\text{ICE.max}} \cdot \eta_{\text{e}} \cdot (1 - k_{\text{ad}})}{l_{\text{el}}}, \quad (4)$$

where l_{el} is the number of traction electric motors in the robot's transmission (for a transmission with hub motors l_{el} is equal to the number of driving wheels).

When designing a wheeled robot, based on the calculation results it is necessary to select a traction electric motor from the available model range and determine its reference characteristics: nominal power $N_{\text{el.nox}}$, kW; maximum motor torque $\text{M}_{\text{el.max}}$, N·m; maximum motor shaft speed $n_{\text{el.max}}$, rpm. Next, it is necessary to determine the nominal ω_1 and maximum ω_2 angular speeds of the motor shaft using the formulas:

$$\omega_1 = \frac{N_{\text{el.nom}} \cdot 10^3}{\text{M}_{\text{el.max}}}; \quad \omega_2 = \frac{2\pi \cdot n_{\text{el.max}}}{60}. \quad (5)$$

To construct the traction and dynamic characteristics of the wheeled robot, it is necessary to know the relationship describing the variation of the motor torque within the range of angular speeds $0 \le \omega \le \omega_2$, where ω is the current angular speed. For traction electric motors, this characteristic is described by the following expression:

$$\text{M}_{\text{el.}}(\omega) = \begin{cases} \text{M}_{\text{el.max}} \text{ if } 0 \le \omega \le \omega_1 \\ \text{M}_{\text{el.max}} \cdot \dfrac{\omega_1}{\omega} \text{ if } \omega_1 \le \omega \le \omega_2 \\ 0 \text{ if } \omega > \omega_2 \end{cases}. \quad (6)$$

The power of the electric motor in the range $0 \le \omega \le \omega_2$ is determined by the expression:

$$N_{\text{el}}(\omega) = M_{\text{el}}(\omega) \cdot \omega. \quad (7)$$

Thus, in the range of angular speeds $0 \ldots \omega_1$, the torque of the electric motor remains at its maximum value, while the power increases linearly from zero to $N_{\text{el.nom}}$. In the range of angular speeds $\omega_1 \ldots \omega_2$, the torque decreases according to a hyperbolic law, while the power remains constant at the level of $N_{\text{el.nom}}$.

Determination of the Gear Ratio of the Mechanical Reducer and the Torque on the Driving Wheels. The gear ratio of the mechanical reducer of the hub motor is determined from the condition of ensuring the specified maximum vehicle speed at the maximum angular speed ω_2 of the motor shaft:

$$u_{\text{mg}} = (\omega_2 \cdot r_{\text{wh}})/V_{\max}, \quad (8)$$

where r_{wh} is the wheel radius, m.

The total torque on the driving wheels is determined by the expression:

$$M_{\text{wh}}(\omega) = M_{\text{el}}(\omega) \cdot l_{\text{el}} \cdot u_{\text{mg}} \cdot \eta_{\text{m}}. \quad (9)$$

Calculation and Construction of the Traction Characteristic of the Wheeled Robot. The traction characteristic represents the graphical dependence of the traction force on the driving wheels $P_{\text{к}}$ on the vehicle speed V.

The characteristic $P_{\text{wh}} = f(V)$ is calculated for steady-state motion of the robot, that is, under the condition $dV/dt = 0$.

For a wheeled robot with an electromechanical transmission, the value of P_{wh} is determined by the expression:

$$P_{\text{wh}}(\omega) = \frac{M_{\text{wh}}(\omega)}{r_{\text{wh}}} = \frac{\left(M_{\text{el}}(\omega) \cdot l_{\text{el}} \cdot u_{\text{mg}} \cdot \eta_{\text{m}}\right)}{r_{\text{wh}}}. \quad (10)$$

The robot's speed, in m/s, is determined by the following expression:

$$V(\omega) = \frac{(\omega \cdot r_{\text{wh}})}{u_{\text{mg}}}. \quad (11)$$

Figure 2 shows the traction characteristic of a robot with an electromechanical transmission, calculated using formulas (3)–(11) for a logistics robot with a gross mass of 1.7 t and a maximum speed of 30 km/h.

Figure 2 – Traction characteristic

Calculation and construction of the dynamic characteristic of the robot. The dynamic characteristic represents the graphical dependence of the dynamic factor D on the vehicle speed $D = f(V)$. The dynamic factor is a dimensionless quantity that characterizes the potential capability of the wheeled robot to overcome the total road resistance and its ability to accelerate under given road conditions. The dynamic factor is determined by the expression:

$$D(\omega) = \frac{M_{\text{el}}(\omega) \cdot l_{\text{el}} \cdot u_{\text{mg}} \cdot \eta_{\text{m}} - F_{\text{rob}} \cdot k_w \cdot [V(\omega)]^2}{m_{\text{rob}} \cdot g}. \quad (12)$$

Figure 3 shows the dynamic characteristic of the wheeled robot with the above-mentioned mass and maximum speed parameters. Using the dynamic characteristic, it is possible to determine the following indicators of the traction-speed performance of the wheeled robot: the maximum speed V_ψ of the robot under given road conditions characterized by the rolling resistance coefficient ψ (see Figure 3);

The dynamic factor D_v at the maximum kinematic speed of the robot; the maximum dynamic factor $D_{\max}$ and the corresponding minimum steady speed of motion; the maximum longitudinal road grade $i_{\max}$ that the robot can overcome on a road with a given rolling resistance coefficient f; as well as several other indicators.

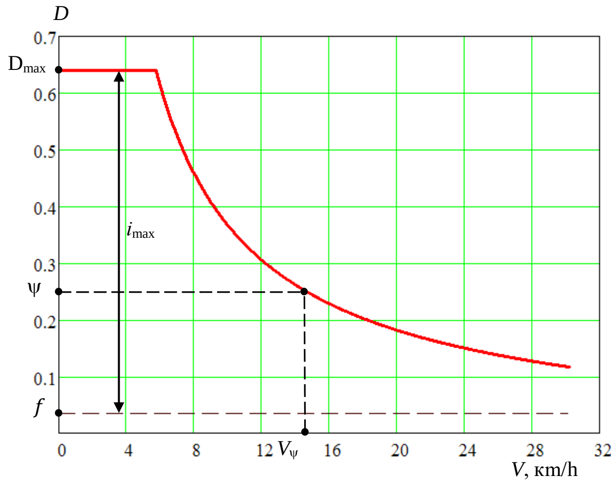

Figure 3 – Dynamic characteristic

For the given example, the maximum longitudinal grade on an unpaved road is $i_{\max} = D_{\max} - f = 0.64 - 0.035 = 0.605$.

Accordingly, the maximum ascent angle that the robot can overcome on an unpaved road is $\alpha_{\max} = \text{arctg}\,(0.605) = 31^{\circ}$.

Determination of the Robot Acceleration Characteristics. The acceleration that a wheeled robot can develop during motion is determined by the following expression [15]

$$j = \frac{D - \psi}{\delta} \cdot g\,, \quad (13)$$

where δ is the coefficient accounting for the inertia of rotating masses, which indicates how many times the energy required to accelerate the wheeled robot exceeds the energy required to accelerate its translationally moving masses. In the general case, for a wheeled robot with an electromechanical transmission, is determined by the expression:

$$\delta = 1 + \frac{\left(J_{\text{arm}} \cdot u_{\text{mg}} \cdot \eta_{\text{m}} + J_{\text{mg}}\right) \cdot l_{\text{el}} + J_{\text{wh}}}{r_{\text{wh}}^2 m_{\text{rob}}}, \quad (14)$$

where J_{arm} is the moment of inertia of the motor armature;

J_{mg} is the moment of inertia of the rotating masses of the reducer referred to the driving wheel;

J_{wh} is the moment of inertia of the wheels.

If accurate data on the moments of inertia J_{arm}, J_{mg} and J_{wh} are not available, an approximate value may be taken as $\delta = (1.005\ldots1.008)\,G_{\text{p}}/G$, G is the actual weight of the wheeled robot.

The acceleration time and distance of the wheeled robot are calculated using the following expressions:

$$t_{ac}(\omega) = V(\omega)/j(\omega);$$
$$S_{ac}(\omega) = j(\omega) \cdot [t_{ac}(\omega)]^2. \quad (15)$$

The graphs of the acceleration time and acceleration distance of the wheeled robot are shown in Figure 4.

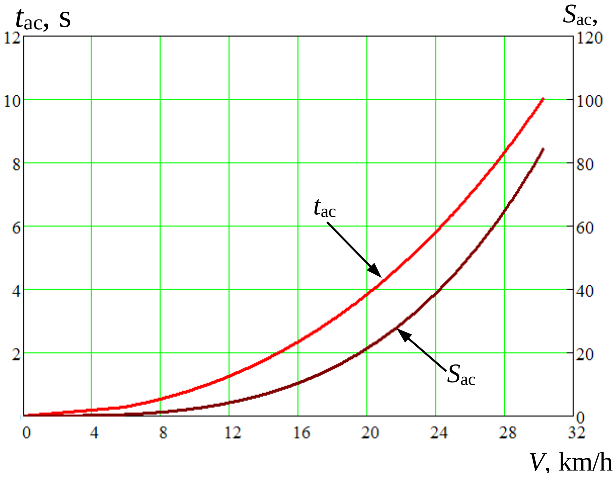

Figure 4 – Acceleration time and distance curves of the wheeled robot

The graphs make it possible to determine the speed of the wheeled robot at any moment in time or at any point along the acceleration distance under the specified operating conditions, as well as to solve the inverse problem. In the presented example, the acceleration time of the loaded wheeled robot to the maximum speed of 30 km/h is 10 s, and the distance covered by the robot during acceleration to 30 km/h is 85 m.

The graphs shown in Figures 1, 2, 3 are constructed under the assumption that the wheeled robot moves on a dry, horizontal unpaved road. If the formula-based framework of the developed methodology is implemented in a modern mathematical software environment such as Mathcad, it becomes possible to perform studies of the traction-speed characteristics of the wheeled robot with high efficiency for different values of its mass and dimensions, power unit and transmission parameters, and various operating conditions.

Conclusions

1. Compared to an all-electric transmission, an electromechanical transmission provides a greater operational range for a ground wheeled robot, eliminates dependence on the availability of electrical charging devices in combat conditions, and enables the use of robots with greater mass and, accordingly, greater combat capabilities.

2. The developed methodology makes it possible to rapidly and with sufficient accuracy determine the characteristics of the power unit and electromechanical transmission of a ground wheeled robot, as well as the values of its traction-speed performance indicators. The methodology can be used both at the design stage of a wheeled robot and for evaluating the traction-speed characteristics of machines that developers propose, on their own initiative, for adoption into service.

Further research will focus on analyzing the ride smoothness characteristics of the ground wheeled robot.

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МЕТОДИКА ВИЗНАЧЕННЯ ПОКАЗНИКІВ ТЯГОВО-ШВИДКІСНИХ ВЛАСТИВОСТЕЙ НАЗЕМНОГО КОЛІСНОГО РОБОТА З ЕЛЕКТРОМЕХАНІЧНОЮ ТРАНСМІСІЄЮ

Одним із напрямів розвитку озброєння і тактики його застосування у сучасній війні є використання наземних колісних роботів на полі бою. Результати аналізу конструкцій наземних роботів показують, що тип енергетичної установки і структура трансмісії суттєво залежать від призначення, масогабаритних характеристик робота. Роботи з невеликими розмірами і масою оснащуються електроприводом, що забезпечує їм достатні ходові якості та відповідні маскувальні властивості. Роботи з більшими розмірами і масою мають кращі тактико-технічні характеристики, але потребують потужніших енергетичних установок. У цьому випадку найчастіше застосовують енергетичні установки з двигуном внутрішнього згоряння та електромеханічною трансмісією. За таких умов підвищуються тягові характеристики машини, збільшуються бойовий радіус, тривалість автономної роботи та прохідність.

У статті сформульовано методику розрахунку тягових характеристик наземного колісного робота з електромеханічною трансмісією та визначено основні показники його тягово-швидкісних властивостей. Методика охоплює низку таких послідовних етапів: визначення необхідної потужності двигуна внутрішнього згоряння; визначення параметрів тягового електродвигуна; визначення передатного числа механічної коробки передач; розрахунок і побудова тягової та динамічної характеристик; визначення прискорювальних характеристик робота. Запропонована методика дає змогу швидко і з достатньою точністю визначати характеристики енергетичної установки й електромеханічної трансмісії наземного колісного робота, а також значення його тягово-швидкісних властивостей. Наведений підхід можна використовувати як на етапі проєктування колісного робота, так і під час оцінювання тягово-швидкісних властивостей машин, що пропонуються розробниками до прийняття на озброєння на ініціативній основі.

Ключові слова: *наземний колісний робот, електромеханічна трансмісія, тягово-швидкісні властивості, методика.*

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