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Aggregation of a mobile energy vehicle of the "Autotractor" with a technological module

Abstract. The relevance of the research was determined by necessity to increase the efficiency of machine and tractor units (MTUs) in both traction-powered and transport-technological operations, while ensuring operational safety. The objective of the research was to experimentally determine the effect of the mass of the technological module (TM) on the axle loads of a mobile energy vehicle (MEV) of the "Autotractor" during aggregation with a rear-mounted three-point hitch. The research addressed the issue of stability and load distribution in MTUs, particularly those with MEVs

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of the "Autotractor" based on high-mobility truck platforms. The MEV-115 "Autotractor", developed at the Institute of Mechanics and Automation of Agro-Industrial Production of the National Academy of Agrarian Sciences of Ukraine, was introduced. This vehicle featured several innovative design solutions, including a centralised tyre pressure control system, a hydraulic system, a frame-based TM mounting system, and a specially designed rear three-point hitch. The hitch structure enabled aggregation with TMs weighing up to 2 tonnes. Its compact design allowed for hassle-free mounting of the TM onto the vehicle frame without disassembling the hitch. Experimental research using strain gauge scales was carried out to verify theoretical calculations on the distribution of axle loads in the MEV depending on the weight and centre of mass of the TM. Critical TM parameters were established for safe operation: the distance from the TM's centre of mass to the rear axle (0-4 m) and the TM weight (6.39-18.7 kN). TM configurations ensuring balanced axle loads were also defined, eliminating parasitic power circulation between the axles of the MEV-115 "Autotractor". The minimum front axle load necessary to maintain steerability during transport operations was determined to be at least 20% of the total MTU weight. The results confirmed the validity of the theoretical models and demonstrated the effectiveness of the approach. The findings may be applied to enhance MEV design and optimise their use in agricultural production

Keywords: experimental research methods; measuring equipment; sensor calibration; tractor; mobile energy vehicle (MEV)

INTRODUCTION

The research into aggregation processes has been essential for ensuring the effective and safe operation of agricultural and industrial machinery. It enabled the optimisation of the interaction between mobile energy vehicles (MEVs) and technological modules (TMs), increasing the efficiency of operations and reducing energy consumption. The research allowed for a comprehensive assessment of critical parameters such as weight, centre of mass coordinates, structural stability, and the load on key MEV components. Determining these characteristics contributed to optimising load distribution, enhancing vehicle stability and reliability, reducing wear of main components, and thereby extending service life, minimising maintenance and repair costs, and improving the overall efficiency of the unit in varied operating conditions. Moreover, analysing the interaction between aggregated components facilitated improved structural designs, increased manoeuvrability, and adaptation of the machinery to different working environments – factors critical to the advancement of modern mobile technologies.

Previous scientific efforts had largely focused on developing tractor stability models, evaluating their static and dynamic properties, and proposing methodological frameworks for assessing stability. However, the stability parameters of MEVs of the "Autotractor" type, particularly during aggregation with TMs, remained insufficiently researched. The stability of motion and load distribution in MEV-based MTUs was of paramount importance. These processes underpinned safe movement during transport, transitions with attached implements, soil compaction concerns, and overall safety. For instance, research by G. Carabin *et al.* (2023) highlighted that over 100 fatal accidents involving tractor rollovers were recorded annually in Italy – posing not only a risk to human life but also causing significant financial losses due to equipment damage and operational downtime.

M. Bietresato & F. Mazzetto (2020) pointed out that international standards for evaluating the stability of agricultural machinery lacked sufficient detail. These standards typically focused only on the roll-over angle and failed to account for operational factors such as soil type, tyre pressure, and terrain slope. The authors introduced a new test platform capable of more accurately determining the centre of mass and assessing stability in various positions. However, that research did not address dynamic load effects during motion, necessitating further research. Researchers B. Franceschetti *et al.* (2021) emphasised the heightened rollover risk associated with articulated narrow-track tractors. They developed a kinematic model to simulate tractor behaviour virtually, enabling the determination of a minimum transverse stability angle (39.3° at a -35° pitch angle). While these results could assist in optimising tractor design for greater stability, they specifically concerned articulated-frame MEVs and thus required refinement for application to the "Autotractor"-type MEVs.

According to V. Rondelli *et al.* (2013), despite the mandatory use of rollover protective structures (ROPS), tractor instability incidents remained a significant concern. The authors investigated the impact of various factors—soil morphology, climatic conditions, and operator experience – on tractor stability. They utilised a real-time monitoring system to evaluate rollover risks and suggest corrective actions, although the research did not assess the long-term effectiveness of these interventions. G. Previati *et al.* (2014) explored tractor stability on slopes using mathematical models to determine tipping thresholds. Their analysis included tyre stiffness, asymmetric implement placement, and a comparison between traditional front axles and passive suspensions. While they found that suspension systems could improve stability, their research did not include dynamic parameters such as speed or varying loads, indicating the need for further investigation.

D. Pessina *et al.* (2022) researched the lateral stability limitations of narrow-track agricultural tractors and the influence of design features (wheels, tyre pressure, and accessories) on rollover resistance. Their research covered tractors of different constructions but did not include dynamic field conditions, calling for extended researches to better predict stability in real-world settings. In contrast, S.P. Pogorilyy *et al.* (2022; 2023) focused on justifying traction performance indicators for MEVs. However, their work considered the design and aggregation parameters of TMs only in general terms, without addressing the physical processes occurring during aggregation.

Taking into account the predominance of research dedicated to conventional tractor-layout MEVs, it became evident that researching the stability of "Autotractor"-type MEVs was crucial for both agricultural professionals and vehicle manufacturers. The aim of this research was to explore the impact of TM mass on axle loads in the "Autotractor" – type MEV in order to reduce operational costs by designing and implementing agricultural units based on this MEV configuration.

MATERIALS AND METHODS

The object of the research was the multifunctional MEV-115 "Autotractor", developed in 2023 at the Institute of Mechanics and Automation of Agro-Industrial Production of the National Academy of Agrarian Sciences of Ukraine (Pogorilyy *et al.*, 2022; 2023) (Fig. 1). The machine was equipped with a custom-designed three-point hitch. The mass of the MEV-115 "Autotractor" amounted to 3500 kg, with an internal combustion engine rated at 88.3 kW (115 hp), a wheel arrangement of 4x4, and a maximum speed of 90 km/h.

Figure 1. Mobile Energy Vehicle MEV-115 "Autotractor"
Source: compiled by the authors

A key feature of the MEV-115 "Autotractor" was the centralised tyre pressure control system, which allowed for pressure reduction during field operations (0.05-0.07 MPa) and an increase to the recommended value for road transport (0.27 MPa). This system also allowed for dynamic pressure adjustment during technological operations, depending on the weight of the TM. The MEV-115 "Autotractor" was designed as an alternative to tractors of traction class 1.4 (with a drawbar pull of 14 kN), which were primarily used for transport and technological operations whose efficiency was largely influenced by moving distance. Under such conditions, the MEV-115 "Autotractor" was required to aggregate with TMs (machines or implements) designed for class 1.4 tractors.

To examine the operation of the three-point hitch and to research the processes that occurred during aggregation with the TM, experimental research was carried out. The following criteria were established for the performance of the three-point hitch: time required to lift the TM from the lower to upper position, time to lower it, the distribution of loads on the MEV's axles, and the hydraulic pressure in the MEV's system during aggregation.

For the experimental researches, 20 kN-capacity strain gauge vehicle scales of the VAPO-15 type were used. These were manufactured by scientific-testing institutes of the former Soviet Union. Prior to conducting the research, the scales were calibrated using certified equipment, in particular the DOSM-3-3 dynamometer (Ukraine). The calibration was performed in 200 kg increments from 0 to 2000 kg. Data registration was carried out using an L-CARD-E14-440 AD/DA converter and LGraph2 software.

Through regression analysis, quantitative dependencies were established that supported engineering decisions regarding the MEV's design and operation. A force diagram (Fig. 2) representing the MEV-115-based MTU was used to derive the chain between the MEV's parameters and the aggregated TM mounted on the rear three-point hitch.

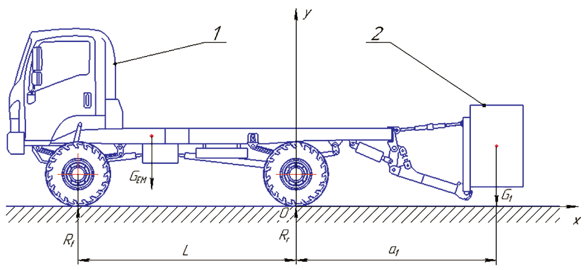

Figure 2. Force diagram of the machine-tractor unit
Note: 1 – MEV; 2 – rear TM; GEM – MEV weight, kN; G1 – TM weight, kg; Rf, Rr – load on the front and rear MEV axles respectively, kN; L – MEV wheelbase, m; a1 – distance from the rear axle to the TM's centre of mass, m
Source: compiled by the authors

Regression analysis was employed to determine the correlation between TM mass and axle loads on the MEV during aggregation with the rear three-point hitch. This analysis enabled the following: assessment of the influence of TM weight on load redistribution between axles; identification of critical loading values affecting the MEV's stability and steerability; development of a mathematical model to forecast axle loads for different TM masses; and optimisation of aggregation parameters to ensure efficient operation without overloading or adverse effects on the vehicle's handling.

RESULTS AND DISCUSSION

Based on the theoretical research (Pogorilyy *et al.*, 2023), the dependencies of the loads on the front and rear axles of the MEV on the mass of the technological module (TM) were determined:

$$P_r = 1.9091 \cdot m + 13.806, \quad (1)$$

where P_r – rear axle load, kN; m – cargo mass, kg.

$$P_f = -0.909 \cdot m + 20.194, \quad (2)$$

where P_f – front axle load, kN.

A graphical representation of the obtained results is presented in Figure 3.

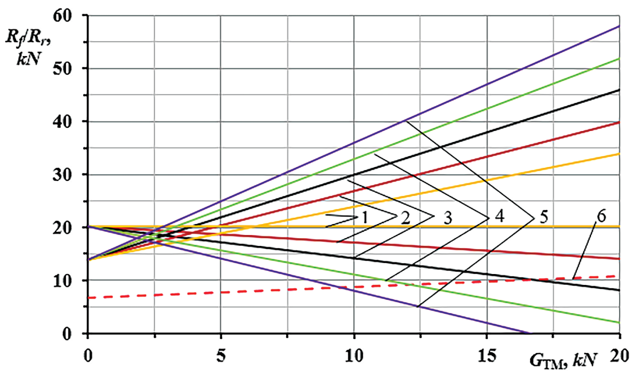

Figure 3. Dependence of axle loads on the mass of the TM

Note: 1, 2, 3, 4, 5 – loads on the front and rear axles according to the change in the coordinate of the center of mass of the TM from the axis of the rear wheels: 0; 1; 2; 3; 4 m; 6 – limit of controllability of the unit

Source: compiled by the authors

According to the results of theoretical calculations, the parameters of the technological module (TM) aggregated via the rear-mounted three-point hitch of the MEV-115 "Autotractor" were determined. Specifically, the distance from the TM's centre of mass to the centre of the rear axle ranged from 0 to 4 metres, while the TM weight varied from 67 to 9.5 kN. For instance, with a TM weight of 20 kN and a centre of mass located 3 m behind the rear axle, the load on the front axle of the MEV decreased from 20.2 to 2.01 kN, whereas the load on the rear axle increased from 13.8 to 52 kN. Under the condition of equal axle loading, the distance from the TM's centre of mass to the MEV's rear axle ranged from 0 to 4 metres, while the TM weight varied from 6.39 to 1.87 kN. The limiting factor for the TM weight was the minimum required load on the front axle of the MEV to ensure adequate steerability of the unit during transport operations, which had to be no less than 20% of the total weight of the machine-tractor unit (line 6 in Fig. 3). In this case, for a TM weight of 12 kN, the minimum required front axle load for the MEV was 9 kN.

To verify the theoretical data obtained, experimental research was conducted. A methodology was developed to carry out experimental investigations aimed at determining the influence of TM parameters on the characteristics of the MEV of the "Autotractor" type (Pogorilyy *et al.*, 2023). In light of the above, it became necessary to perform researches to validate the theoretical data by experimentally determining the effect of the TM mass on the axle loads of the MEV.

To assess the adequacy of the theoretical results obtained, experimental research was conducted. In accordance with the methodology developed by S.P. Pogorilyy *et al.* (2023), measurements of the loads on both the front and rear axles of the MEV were performed. The axle loads of the MEV were determined using strain gauge scales. Since the MEV combined with the TM was symmetrical in the longitudinal plane, it was sufficient to take readings and record measurements from one side of the MEV (Fig. 4).

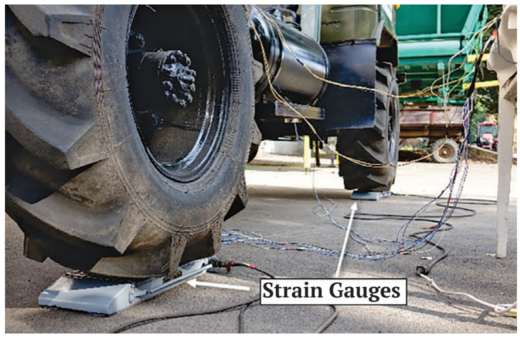

Figure 4. Placement of strain gauges on the MEV-115 "Autotractor"

Source: compiled by the authors

The tank and additional ballast were used as the technological module (TM), allowing the TM mass to be varied from 500 kg to 1500 kg (Fig. 5). The experimental researches were conducted in the following sequence: first, the TM was lifted from the supporting surface, during which, at the moment of rest, the TM mass exerted no load on the MEV axles. The TM was then raised to its upper position until the safety valve of the hydraulic system was activated at a pressure of 13.5 MPa, with the internal combustion engine of the MEV-115 "Autotractor" at 3000 rpm. Subsequently, the TM was lowered from the upper position until the load was removed from the rear axle due to the mass of the TM.

Figure 5. General view of MEV-115 with TM during the experiment

Source: compiled by the authors

The strain gauge scales registered the loads that arose during the experiments, and the signal from them was transmitted to an analogue-to-digital converter and recorded on a personal computer using the LGraph2 software (Fig. 6). The data sampling frequency was 10 kHz. During the 12 experimental trials conducted, the variable parameter was the TM mass, which ranged from 0 to 1500 kg with an increment of 500 kg. Each measurement was repeated three times.

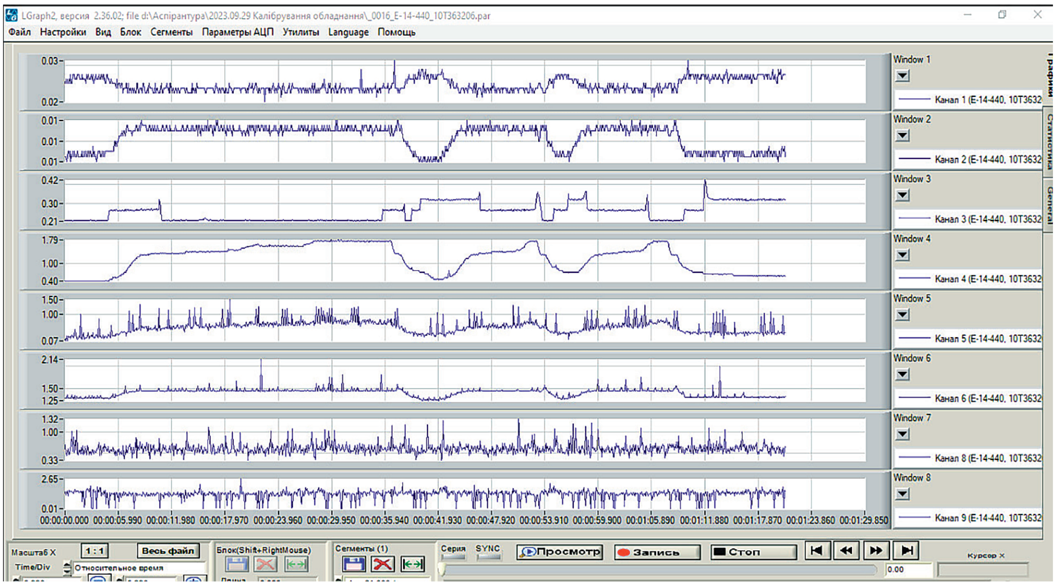

Figure 6. LGraph2 program window during experiment
Source: compiled by the authors

The data obtained were converted from voltage (V) values into load (kN), with each strain gauge scale having its own calibration characteristic determined during the tare procedure. The subsequent processing of the experimental data involved calculating the average value for each trial, the variance, and the standard deviation. All collected data conformed to a normal distribution. Based on the results of the experimental data processing, regression equations were obtained that described the chain between the TM mass and the axle loads of the MEV:

$$P_r = 0.0194 \cdot m + 12.837, \tag{3}$$

where P_r – rear axle load, kN; m – cargo mass, kg.

Dependence of front axle load:

$$P_f = -0.0094 \cdot m + 21.263, \tag{4}$$

where P_f – load on the front axle, kN.

The regression equations had a coefficient of determination (approximation probability) of 0.99. Based on regression equations (3-4), graphical dependencies were constructed to illustrate the changes in front and rear axle loads depending on the variation in the mass of the three-point hitch (Fig. 8). The obtained regression equations (3-4) made it possible to research the influence of the three-point hitch mass on the axle loads of the mobile energy vehicle (MEV), allowing the determination of the required hitch mass to be aggregated with the MEV in order to achieve equal loads on the wheels. Under such conditions, the circulation of "parasitic" power between the axles did not occur. As shown in Figure 7, when the three-point hitch mass increased from 0 to 1500 kg, the rear axle load rose from 1200 to 4500 kg, while the front axle load decreased from 2100 to 600 kg. This corresponded to the requirements of DSTU 2189-93 (1994), which specified the need to ensure the controllability of the mobile technical aggregate (MTA) on public roads. The calculations confirmed compliance with the requirement $R_f = 0.2 \cdot G_r$ (G_r – was the total weight of the MTA (Pogorilyy *et al.*, 2023; Loveikin *et al.*, 2024).

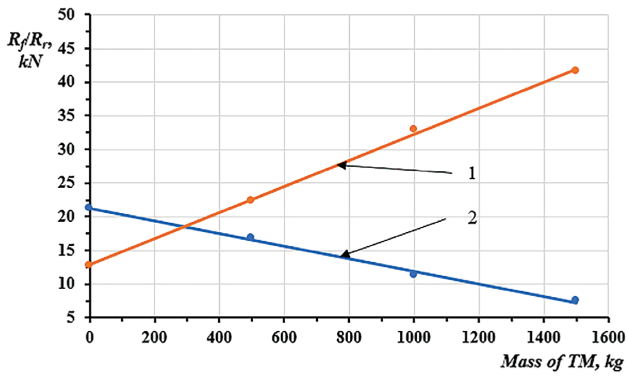

Figure 7. Experimental dependence of axle loads on the mass of the technological module
Note: 1 – rear axle load; 2 – front axle load
Source: compiled by the authors

To verify the adequacy of the theoretical results with respect to the experimental data, a method was used that involved constructing confidence intervals for the experimental data, as proposed by L.V. Viktorova *et al.* (2017) (Fig. 8).

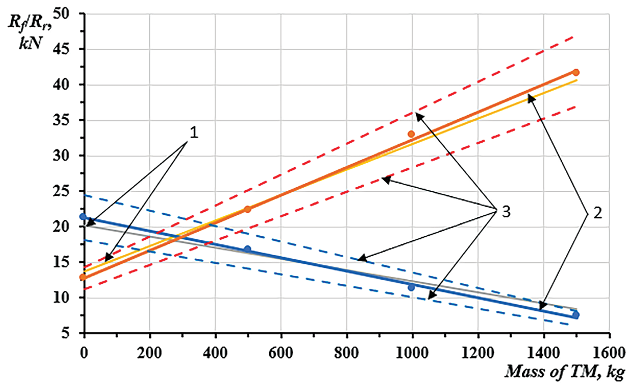

Figure 8. Verification of the adequacy of the experimental research

Note: 1 – theoretical dependence of front and rear axle loads; 2 – experimental dependencies of front and rear axle loads; 3 – confidence intervals

Source: compiled by the authors

The location of the theoretical dependence within the calculated confidence intervals of the experimental data indicated their adequacy with respect to the experimental results. As seen in Figure 9, the nature of both the experimental and theoretical dependencies was similar, and the condition ($R_f = R_r$) was observed under comparable three-point hitch parameters. The theoretical data fell within the confidence intervals, confirming their adequacy with a confidence probability of 95%.

The research results of other authors working in this field demonstrated the following. In the research by H. Yang *et al.* (2020), the issue of tractor rollover on slopes was considered, particularly at an incline angle of approximately 15°. The authors developed a mathematical model of tractor rollover, which accounted for the kinematics of motion, forces acting on the wheels, and the influence of lateral acceleration. The model was tested using the CarSim/Matlab Simulink environment to analyse the tractor's dynamic behaviour. The research also assessed the effectiveness of an active stability control system designed to reduce the risk of rollover on slopes. The main conclusion was that as lateral acceleration increased, the load on the left wheel decreased, and when it reached zero, the tractor lost stability and overturned.

Researchers V. Vantsevich *et al.* (2016) proposed a method for optimising the mobility of a hybrid 4×4 wheeled vehicle by investigating axle loads and power distribution control. A mobility index and Lagrange multiplier were used to determine the optimal power distribution. A control algorithm was developed that adjusted the power split to maintain the optimal trajectory.

The findings reported by I. Ahmadi (2011) showed that tractor stability on slopes depended not only on rollover risk but also, to a large extent, on the risk of lateral slippage. The author proposed a dynamic model of tractor lateral rollover that took into account external positional disturbances, enabling a quantitative assessment of the influence of ground inclination, travel speed, and machine design features on overall stability. It was established that slippage was a more critical factor in the loss of tractor stability than rollover, particularly under conditions of increased slope angles and when moving at speeds exceeding 5 m/s. Specifically, when the slope angle increased beyond 15°, the risk of lateral slippage rose non-linearly, significantly reducing safety levels. Furthermore, the model accounted for the effects of tyre type, tractor centre of mass, and suspension stiffness, which were essential for evaluating the machine's dynamic performance.

In the work of G. Golub *et al.* (2023), a mathematical model was presented for determining soil reactions and, accordingly, the pressure exerted by tractor drive systems on the soil, depending on the tractor's structural parameters. The model's adequacy was assessed, and an example was provided for calculating the weight distribution across the tractor axles. A. Keller *et al.* (2023) developed an algorithmic framework for the multi-criteria optimisation of the functional properties of mobile power units (MPUs) in agriculture. The key quality criteria identified included: soil pressure, productivity, fuel and energy efficiency, maintenance costs, and overall energy efficiency. The work of E. Sangenis *et al.* (2025) resulted in the development of a software suite for the multi-criteria optimisation of active vehicle safety. The universal MOVI software was used as the optimisation module. In the research by H. Silleli *et al.* (2008), a prototype of an anchoring mechanism was presented, designed to increase the operator's safety zone on narrow-track wheeled agricultural tractors. The researchers developed the device's design, described its working principle, and conducted initial experimental tests. The results demonstrated that the proposed mechanism could effectively reduce the risk of injury to the driver in the event of a rollover, without compromising the tractor's controllability or stability during operation.

The article by B. Franceschetti *et al.* (2014) examined the effectiveness of a mathematical model of tractor rollover dynamics by comparing its results with real-world tests on lateral stability. The authors carried out numerical simulations and experimental testing to verify the model's accuracy under slope-working conditions. The results showed a high level of agreement between the simulations and practical data, confirming the usefulness of such a model for predicting rollover risk and improving safety in agricultural applications.

V. Bulgakov *et al.* (2021; 2024) investigated methods to improve the efficiency of using modular tractor constructions. It was determined that such constructions were limited by increased travel speed due to vertical oscillations caused by ground unevenness. Experiments showed that throttling the hydraulic system of the energy module's rear suspension could reduce the amplitude of vertical oscillations by 15-20%, lower peak frame loads by 10-12%, and decrease fuel consumption by 3-5%. This contributed to improved ride smoothness and increased operational efficiency of the aggregates.

The results of research into the processes occurring in MEVs and MTAs during field movement, operation on slopes, and aggregation with three-point hitches played a significant role and were essential for improving existing MEVs and MTAs and for developing new designs.

CONCLUSIONS

The obtained results of the research on the process of aggregating the three-point hitch (TM) with the mobile energy vehicle (MEV) made it possible to theoretically investigate the aggregation process and justify the parameters for safe performance of technological operations during transport movements of the MTA based on the MEV-115 "Autotraktor". The theoretically established chain between the parameters of the TM and the MEV during aggregation using the rear three-point hitch allowed the determination of axle loads of the MEV for given TM parameters. In cases of uneven load distribution between the front and rear axles, a difference in tyre deflection occurred, which altered their rolling radii. As the MEV-115 "Autotraktor" was not equipped with an inter-axle differential, it was important to ensure an even load distribution between the axles ($R_f = R_r$). This made it possible to avoid the appearance of parasitic power, reduced fuel consumption, minimised soil compaction, and increased the traction efficiency coefficient of the MEV.

Based on these chains, a graph showing the dependence of front and rear axle loads on TM weight was constructed. Theoretical calculations made it possible to determine the parameters of the TM aggregated via the rear three-point hitch of the MEV-115 "Autotraktor". In particular, it was established that the distance from the centre of mass of the TM to the rear axle varied from 0 to 4 m, and the TM weight ranged from 6.7 to 95 kN. For instance, with a TM weight of 20 kN and a 3 m distance between its centre of mass and the rear axle, the front axle load decreased from 20.2 to 2.01 kN, while the rear axle load increased from 13.8 to 52 kN.

Under conditions of uniform axle loading, the distance from the TM's centre of mass to the rear axle ranged from 0 to 4 m, and the TM weight ranged from 6.39 to 1.87 kN. The limiting factor for the TM weight was the minimum required front axle load of the MEV, needed to ensure controllability of the aggregate during transport movements, which had to be at least 20% of the total weight of the MTA. Under such conditions, with a TM weight of 12 kN, the minimum required front axle load of the MEV was 9 kN.

Future research will focus on other TM installation zones on the "Autotraktor" – type MEV, including the front, inter-axle, and frame-mounted zones. The results of these researches will enable the analysis of TM parameters in these zones and the justification of their application.

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CONFLICT OF INTEREST

None.

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Агрегатування мобільного енергетичного засобу типу «Автотрактор» із технологічним модулем

Анотація. Актуальність дослідження обумовлена необхідністю підвищення ефективності машинно-тракторного агрегату (МТА) як на тягово-привідних операціях, так і на транспортно-технологічних з обов'язковим забезпеченням безпеки під час експлуатації. Метою роботи було встановлення, експериментальним шляхом, впливу маси ТМ на навантаження на осі мобільного енергетичного засобу (МЕЗ) типу «Автотрактор» під час агрегатування на задньому навісному пристрої. Розглянуто проблему стійкості та розподілу навантажень у МТА, зокрема МЕЗ типу «Автотрактор» на базі вантажних автомобілів підвищеної прохідності. Представлено розроблений в Інституті механіки та автоматики агропромислового виробництва Національної академії аграрних наук України багатофункціональний мобільний енергетичний засіб МЕЗ 115 «Автотрактор», що мав унікальні конструкційні рішення, зокрема централізовану систему контролю тиску повітря в шинах, гідравлічну систему, систему агрегатування ТМ на раму та спеціально розроблену та виготовлену задню навісну систему. Конструкція навісної системи МЕЗ типу «Автотрактор» забезпечувала агрегатування ТМ масою до 2 т. Компактне розміщення навісної системи на машині дозволяло безперешкодне агрегатування ТМ на рамі без демонтажу навісної системи. Проведено експериментальні дослідження за допомогою тензометричних ваг для перевірки теоретичних розрахунків розподілу навантажень на осі МЕЗ типу «Автотрактор» залежно від ваги та координати центру мас ТМ. Визначено критичні параметри ваги ТМ, які забезпечують безпечну експлуатацію МТА: відстань від центру мас ТМ до осі задніх коліс (0-4 м) та вага ТМ (6,39-18,7 кН). Встановлено параметри ТМ, які забезпечують рівномірне навантаження на осі, що у свою чергу унеможливлює виникнення паразитної потужності між осями МЕЗ 115 типу «Автотрактор». Встановлено мінімально необхідне навантаження на передню вісь для забезпечення керованості МТА при переїздах, яке повинно становити не менше 20 % загальної ваги МТА. Результати дослідження підтверджують достовірність теоретичних моделей та показали ефективність описаної теорії. Отримані дані можуть бути використані для вдосконалення конструкцій МЕЗ та оптимізації параметрів у сільськогосподарському виробництві

Ключові слова: методи проведення експериментальних досліджень, вимірювальна техніка, калібрування датчиків, автотрактор, мобільний енергетичний засіб (МЕЗ)