LABORATORY EXPERIMENTAL STUDY OF THE TRACTION CHARACTERISTICS OF AN “AUTO-TRACTOR” BASED ON AN OFF-ROAD VEHICLE
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ЛАБОРАТОРНЕ ЕКСПЕРИМЕНТАЛЬНЕ ДОСЛІДЖЕННЯ ТЯГОВИХ ВЛАСТИВОСТЕЙ “АВТОТРАКТОРА” НА БАЗІ АВТОМОБІЛЯ ВИСОКОЇ ПРОХІДНОСТІ

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ABSTRACT

The relevance of the study stems from the need to substantiate the traction-adhesion and traction-speed characteristics of a new type of mobile power unit designed to perform transport and technological operations involving the aggregation of agricultural machinery coupled with tractors of traction classes 1.4–2. The aim of the work was to experimentally determine the influence of mass and transmission operating modes on the traction force, the drive wheel slip coefficient and the speed of the multifunctional mobile power unit “Avtotraktor”. Experimental studies of the machine’s traction characteristics on an asphalt concrete surface were conducted for two MEZ mass variants – without additional load and with installed ballast – using statistical methods for data analysis. Based on the research results, regression relationships were established between the slip coefficient and speed of movement as a function of traction force for various transmission operating modes. It was found that ballasting the “Avtotraktor” significantly reduces slip across the entire range of traction forces and enhances the efficiency of the machine’s traction potential. Rational ranges for the use of first and second gears have been determined depending on the magnitude of the tractive effort. It has been experimentally confirmed that, under ballast conditions and with the correct selection of transmission operating modes, the “Avtotraktor” meets the requirements for mobile power units of tractive classes 1.4–2. The results obtained can be used in the further improvement of the design of “Avtotraktor”-type mobile power units, as well as to justify their operating modes during transport and technological operations in agricultural production.

АНОТАЦІЯ

Актуальність дослідження зумовлена необхідністю обґрунтування тягово-зчіпних та тягово-швидкісних характеристик мобільних енергетичних засобів нового типу, призначених для виконання транспортно-технологічних операцій із агрегатуванням сільськогосподарських машин, які агрегатуються з тракторами тягового класу 1,4-2. Метою роботи було експериментальне визначення впливу маси та режимів роботи трансмісії на реалізацію тягового зусилля, коефіцієнт буксування ведучих коліс і швидкість руху багатофункціонального мобільного енергетичного засобу «Автотрактор». Проведено експериментальні дослідження тягових характеристик машини на асфальтобетонному покритті для двох варіантів маси МЕЗ – без довантаження та з установленим баластом – із застосуванням статистичних методів обробки результатів. За результатами досліджень побудовано регресійні залежності коефіцієнта буксування та швидкості руху від величини тягового зусилля для різних режимів роботи трансмісії. Встановлено, що довантаження «Автотрактор» забезпечує істотне зниження буксування у всьому діапазоні тягових зусиль та підвищує ефективність реалізації тягового потенціалу машини. Визначено раціональні діапазони використання першої та другої передач залежно від величини тягового зусилля. Експериментально підтверджено, що за умов баластування та правильного вибору режимів роботи трансмісії «Автотрактор» відповідає вимогам до мобільних енергетичних засобів тягових класів 1,4-2. Отримані результати можуть бути використані при подальшому вдосконаленні конструкції мобільних енергетичних засобів типу «Автотрактор», а також для обґрунтування режимів їх експлуатації під час виконання транспортно-технологічних операцій у сільськогосподарському виробництві.

INTRODUCTION

The study of tractive force and traction properties of wheeled vehicles is one of the key scientific and applied tasks in the field of agricultural and transport engineering. The magnitude of the realised tractive force directly determines the productivity of machine-tractor units, the energy efficiency of performing technological operations, the level of drive wheel slip, tyre wear and fuel consumption. These issues are of particular relevance for multi-purpose mobile power units that combine the functions of a tractor and a transport vehicle and operate across a wide range of loads and speeds.

The fundamental principles of the theory of traction force implementation in wheeled vehicles are based on studies of the interaction between the drive unit and the supporting surface, the influence of the vehicle's mass, load distribution between the axles, and transmission operating modes. *Vantsevich et al, (2016),* examined the optimisation of the mobility of all-wheel-drive vehicles on stochastic surfaces, demonstrating the significant influence of normal reactions at the wheels on the realisation of the machine's traction potential, which is relevant for both lorries and tractors.

Kim et al., (2021), examined the influence of soil moisture on the traction performance of tractors. The study analyses traction performance, the traction coefficient and wheel slip depending on soil conditions, which is important for assessing the efficiency of tractors under various operating conditions. *Roşca et al., (2022),* examined a mathematical model for predicting the traction characteristics of a wheeled tractor based on tyre-soil interaction, which allows for the assessment of the traction coefficient and power transmission efficiency. *Luo et al., (2023),* propose a method for controlling the slip coefficient during soil cultivation, demonstrating modern approaches to maintaining optimal traction force. *Osinenko (2015)* focused on optimising the control of a tractor's tractive effort, taking into account soil characteristics, which is important for improving the tractor's efficiency. *Baek et al., (2025),* investigated the relationship between the slip coefficient and traction performance in modern electric tractors, which broadens our understanding of the mechanisms of traction force transmission. *Shafaei et al., (2021),* investigated the relationship between wheel slip in agricultural tractors and the efficiency of traction force application during soil cultivation operations. The authors experimentally determined the range of optimal wheel slip at which the maximum efficiency of the drive system is achieved. *Battiato et al., (2013),* developed and verified a model for predicting the traction performance of mechanical all-wheel-drive tractors. The work takes into account axle loads, tyre pressure, soil type and driving modes. The model allows the determination of traction force and slip without conducting full-scale field tests. *Roşca et al., (2022),* presents an improved model of tyre-soil interaction for assessing the traction force and wheel slip of wheeled tractors. Particular attention is paid to the influence of tyre deformation on the tractor's traction force. *Janulevičius and Damanauskas, (2022),* investigated the effect of tyre pressure on the amount of wheel slip and the traction efficiency of tractors under various operating conditions. A mathematical model for predicting wheel slip as a function of load and tyre pressure is proposed. *Zhang et al., (2016),* discusses an algorithm for integrated control of tractive effort and slip coefficient in high-power tractors. An optimal slip range has been established, which ensures maximum tractive efficiency and reduced energy losses. *Bondarenko et al., (2022),* reviewed and analysed methods for the experimental determination of tractors' traction properties, including measurements of traction force, slip and load distribution across the axles.

Recent studies further demonstrate that tire inflation pressure, wheel load and ballast are key manageable parameters for controlling drawbar performance and slip. *Battiato and Diserens (2017)* validated a model that simulates drawbar pull, traction coefficient and efficiency as functions of slip, wheel load, tyre size and pressure. *Janulevičius and Damanauskas, (2022),* included tyre inflation pressure in slippage prediction. *Alkhalifa et al., (2024),* confirmed the combined influence of vertical load and pressure on tyre-soil interaction; and *Franceschetti et al. (2025)* specifically evaluated ballast and tyre pressure in tractor traction trials on a concrete track. Modern measurement and simulation tools, including machine vision for slip-ratio measurement and software for tractor performance analysis, also support the need for verified experimental data sets (*Zhu et al., 2022; Barbosa et al., 2025*).

The possibilities of using the "Autotractor" for potato harvesting are also considered, for example, by mounting a rotary potato harvester on it, the design of which is described in *Bulgakov et al., (2021)*. However, in this case, as in all others, additional research is needed on the dynamics and manoeuvrability of such an "Autotractor," now as a machine-tractor unit. Using the methods outlined by *Bulgakov et al., (2019),* and *Ivanovs et al., (2020)*, it is possible to conduct such research and determine its optimal parameters.

However, these studies do not provide a dedicated empirical assessment of drawbar pull, wheel slip and travel speed for a multifunctional 4x4 mobile power unit based on an off-road vehicle chassis and intended to substitute tractors of traction classes 1.4–2 under transport and technological operating conditions.

The novelty of the present study lies in the laboratory experimental determination of the traction-adhesion and traction-speed characteristics of the “Avtotractor” prototype for two mass configurations, with and without additional ballast, and for two transmission modes, followed by regression modeling and statistical verification of model adequacy.

Therefore, the objectives of the research were: (i) to determine the effect of additional ballast on the realised tractive force and slip coefficient; (ii) to establish regression dependencies between tractive force, slip coefficient and travel speed; (iii) to identify rational ranges of first- and second-gear operation; and (iv) to evaluate whether the prototype provides a drawbar-pull range corresponding to traction classes 1.4–2 under controlled laboratory conditions.

MATERIALS AND METHODS

The subject of the study is the multifunctional mobile power unit “Avtotractor”, developed in 2023 at the Institute of Mechanics and Automation of Agro-Industrial Production of the National Academy of Agrarian Sciences of Ukraine *(Pohorilyy et. al., 2022; Pohorilyy et. al., 2023)* (Fig. 1). The design of the machine involves the use of an original attachment, specially designed to suit its layout and functional purpose. The machine’s operating weight is 3500 kg, the rated power of the internal combustion engine is 88.3 kW (115 hp), the wheel configuration is 4×4, and the maximum transport speed is up to 90 km·h^{-1}.

Fig. 1 – “Avtotraktor” mobile power unit

A design feature of the “Avtotraktor” is the presence of a centralised tyre pressure regulation system, which allows the pressure to be reduced to 0.05–0.07 MPa during field agricultural operations and increased to the recommended level of 0.27 MPa during transport journeys. Furthermore, the system allows tyre pressure to be adjusted quickly and directly during the course of agricultural operations, depending on the load weight and the type of crop.

The “Avtotractor” has been developed as a functional alternative to tractors of traction class 1.4 with a nominal drawbar pull of 14 kN, which are primarily used for transport and agricultural operations, the efficiency of which is largely determined by the length of journeys. Under such conditions, the must ensure reliable coupling with agricultural machinery and implements designed to work with tractors of the corresponding traction class.

To verify the drawbar pull of the “Avtotractor”, traction tests were conducted on an asphalt concrete surface (Fig. 2).

Fig. 2 – Traction tests of the “Avtotractor” on an asphalt concrete surface

The following instruments and equipment were used during the traction tests:

- a load cell for measuring traction force (Fig. 3, a);
- a sensor for measuring wheel revolutions (Fig. 3, b);
- odometer wheel (Fig. 3, c);
- SOSpr-26-2-000 stopwatch;
- stationary vehicle scales;
- 50 m tape measure;
- ballast (a concrete block weighing 1470 kg was used as ballast) (Fig. 3, d, e).

Signal recording from the sensors was carried out using an E14-440 analogue-to-digital converter (ADC) and a personal computer (Fig. 4, a), as well as an Arduino Uno microcontroller board (Fig, 4. b).

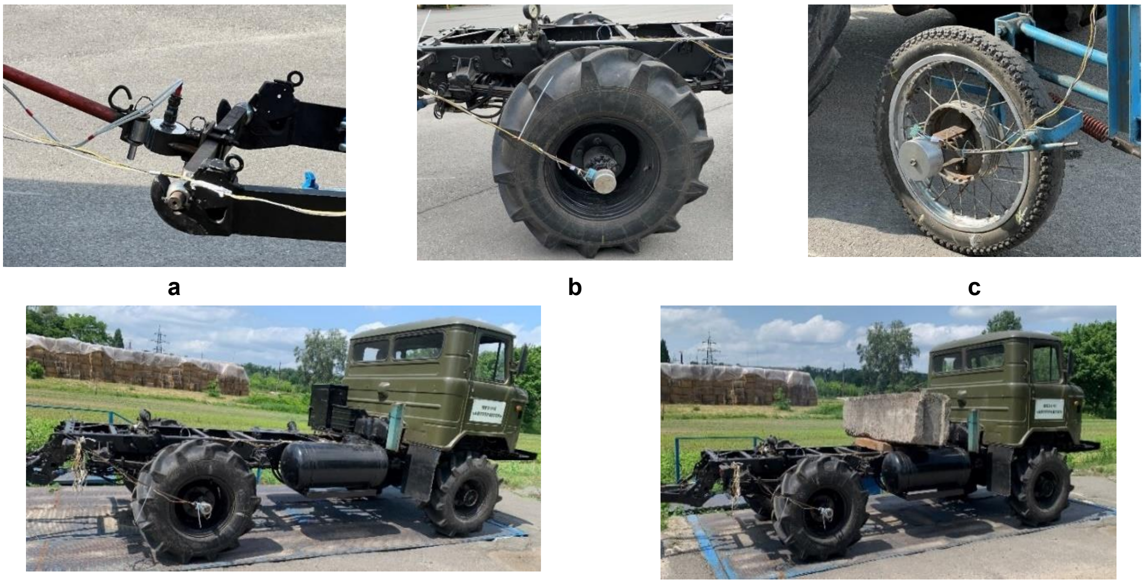
a b c
d e

Fig. 3 – Instruments and equipment used in the research:
a – strain gauge for measuring traction force; b – sensor for measuring wheel revolutions;
c – odometer wheel; d – MEZ without ballast; e – MEZ with ballast


a b

Fig. 4 – Equipment for recording traction tests

The number of experimental repetitions and the number of measurements in each were determined in accordance with the established ratio during all series of experiments *(Kalambet, 2015)*:

$$a_{sn} = \frac{a}{\sqrt{2(n-1)}} \tag{1}$$

Generalised form of the ratio:

$$a_{sn} = \frac{a}{\sqrt{2(N \cdot n-1)}} \tag{2}$$

where a_{sn} – root mean square error in determining the tensile force, kN; a – mean square error of the tensile force measurement, based on the results of previous experimental studies, kN; N – number of repetitions of the experiments at a single point in the plan; n – number of measurements in a single replicate.

To ensure the accuracy of the experiment, it was assumed that a_{sn} should not exceed 5% of a, i.e.

$$a_{sn} \le 0.05 \cdot a \tag{3}$$

Substituting expression (3) into equation (2), the following expression is obtained:

$$\frac{a}{\sqrt{2(N \cdot n - 1)}} \le 0.05 \cdot a \tag{4}$$

After simplification, the following relationship is obtained $N \cdot n$ = 201.

This indicates that, to achieve the required experimental accuracy, it is sufficient to perform the tests with two replicates (N = 2), each containing at least 100 measurements (n = 100) (*Birt and Burchu, 2014; Goncharuk, 2014; Koryagin, 2014; Mokin, 2014*).

In practice, the experiments were conducted using three replicates, with 100 measurements performed in each replicate.

The experiments were carried out at the Institute of Mechanics and Automation of Agro-Industrial Production of the National Academy of Agrarian Sciences of Ukraine. The experimental conditions are presented in Table 1.

Table 1

The experimental conditions

Parameter	Unit of measurement	Value
1. Tyre pressure:		
front	MPa	0.15±0.01
rear	MPa	0.15±0.01
2. Air temperature	°C	25±0.5
3. Barometric pressure	kPa	96±1
4. Wind speed	$\mathrm{m \cdot s^{-1}}$	3.3±0.5
5. Relative humidity	%	55±2
6. Engine oil temperature	°C	70±1
7. Engine coolant temperature	°C	85±1

Thanks to the use of an Arduino Uno microcontroller, an ADC and a personal computer with the appropriate software, all sensor signals were recorded in digital format and imported into Microsoft Excel.

RESULTS

The data obtained from the tests on the asphalt concrete pavement were processed using statistical methods, specifically the calculation of the mean value for each experiment, the variance and the standard deviation. All results obtained satisfy the conditions of a normal distribution.

Based on the processed data, the following regression equations were derived, which describe the relationship between the slip coefficient and tractive effort of the “Avtotractor” with a mass of 3410 kg (Fig.5):

$$y = 0.0098x^5 - 0.04985x^4 + 0.948287x^3 - 8.35815x^2 + 34.7746x - 50.7934 \tag{5}$$

where y – slip coefficient, %; x – tractive effort, kN.

When the mass of the MEZ is increased to 4880 kg, the equation takes the following form:

$$y = 0.0127x^2 + 0.0123x + 0.2905, \tag{6}$$

where y – slip coefficient, %; x – tractive force, kN.

The adequacy of the regression models was assessed using the coefficient of determination (R^2), the overall regression p-value, RMSE and MAE; the results are summarised in Table 2.

Fig. 5 shows the dependence of the slip coefficient of the drive wheels of the “Avtotractor” on the value of the tractive force for two variants of the machine’s mass: 3410 kg (without ballast) and 4880 kg (with ballast of 1470 kg installed) Fig.3, d, e.

The curve corresponding to a mass of 3410 kg is characterised by a gradual increase in slip as the tractive force increases. In the range up to 5-6 kN, the slip coefficient does not exceed 3-5%, indicating sufficient wheel grip on the supporting surface. A further increase in load to the level of 6-14 kN is accompanied by an increase in wheel slip to 5-12%. From a tractive force exceeding 14 kN, a sharp increase in the wheel slip coefficient is observed, indicating an approach to the limit of effective traction.

At maximum loads (20-21 kN), wheel slip reaches approximately 80%, which effectively corresponds to a regime of intense wheel slip accompanied by increased fuel consumption and severe tread wear.

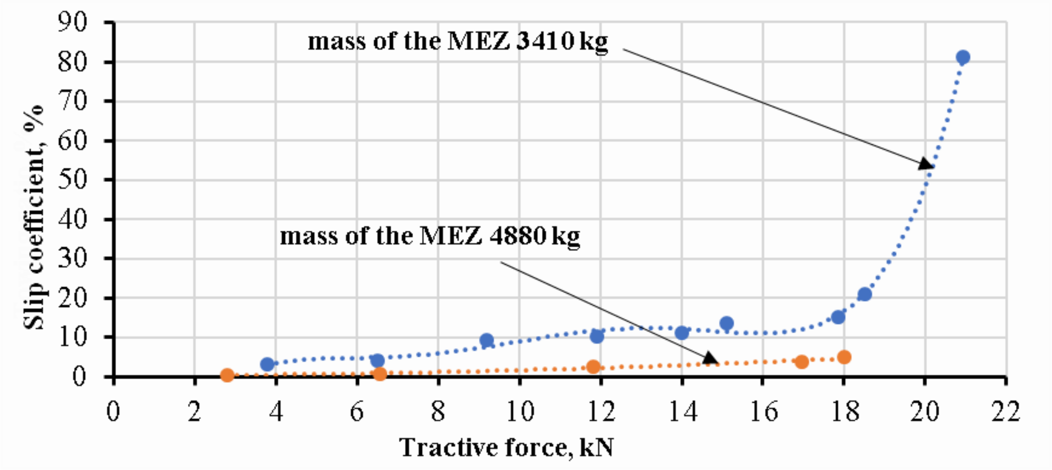

Fig. 5 – Dependence of the slip coefficient on the tractive force of the "Avtotractor"

For the additionally loaded version, where the MEZ mass is 4880 kg, the nature of the slip coefficient change with traction force differs significantly. Over the entire traction force range, slip remained insignificant: up to 1% in the light load zone (up to 6-7 kN) and no more than 3-5% when traction force increased to 14 kN. Maximum slip values at loads up to 17-18 kN did not exceed 6-8%, indicating significantly better traction of the drive wheels with the surface when the machine is operating in a ballasted state.

A comparison of the two experimental curves shows that adding ballast to the MEZ ensures a significant reduction in wheel slip across the entire range of tractive effort. Increasing the load on the driving axles made it possible to reduce the intensity of wheel slip and ensure the application of tractive effort without a sharp deterioration in traction properties. In the unballasted state, the vehicle reaches the maximum slip level as early as 14-15 kN, whereas in the ballasted variant no such trend is observed, and slip remains controlled and does not exceed the permissible limits (up to 15% for wheeled vehicles).

Based on the processed data, regression equations were derived to describe the relationship between speed and tractive effort of the "Avtotractor" in first gear (Fig. 6):

$$y = -0.000837x^3 + 0.0206x^2 + 0.1432x + 2.1048 \tag{7}$$

where y is the speed, m·s^{-1}; x – tractive force, kN.

In second gear, the equation takes the following form:

$$y = -0.00235x^3 + 0.00766x^2 - 0.00668x + 3.7861 \tag{8}$$

Table 2

Statistical indicators of the regression models

Equation	Dependent variable	n	R²	p-value	RMSE	MAE
(5)	Slip coefficient, %; m = 3410 kg	9	0.998	0.00039	1.11%	0.86%
(6)	Slip coefficient, %; m = 4880 kg	5	0.969	0.031	0.30%	0.27%
(7)	Speed, m·s^{-1}; first gear	10	0.951	0.00025	0.10 m·s^{-1}	0.08 m·s^{-1}
(8)	Speed, m·s^{-1}; second gear	6	0.968	0.048	0.11 m·s^{-1}	0.08 m·s^{-1}

Note: the p-value corresponds to the overall F-test of regression significance;
RMSE and MAE are expressed in the units of the dependent variable.

Fig. 6 shows the experimental relationships between the speed of the MEZ and the tractive force for two transmission operating modes: in first and second gears.

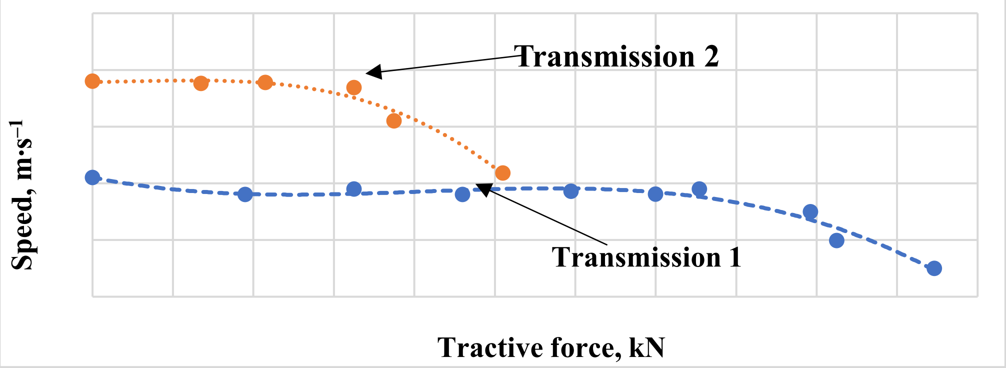

Fig. 6 – Dependence of travel speed on the tractive force of the "Avtotractor"

The curve corresponding to the machine's operation in first gear (Fig. 6) is stable and relatively gentle. In the low traction force range (0-4 kN), the travel speed is approximately 1.9-2.1 m·s^{-1}, which corresponds to the transmission's rated operating mode. A further increase in load to 12-14 kN is accompanied by a slight fluctuation in travel speed within the range of 1.8-1.9 m·s^{-1}. From loads exceeding 15-16 kN, there is a gradual decrease in speed. At loads of 18-20 kN, the speed decreases to 1.0-1.2 m·s^{-1}, and at the maximum applied tractive force (around 21 kN) it is approximately 0.5 m·s^{-1}, indicating operation in a mode close to the limit, with a significant increase in wheel slip and a loss of tractive efficiency.

The curve corresponding to operation in second gear (Fig. 6) shows higher speed values across the entire load range. In the low traction force range (0-4 kN), the machine achieves a speed of 3.7-4.0 m·s^{-1}, which is characteristic of the transmission operating in a higher gear. As the tractive force increases to 6-8 kN, the speed gradually decreases to 3.2–3.6 m·s^{-1}, which is associated with increased load on the transmission and increased wheel slip. A further increase in the traction load to 10-11 kN leads to a significant reduction in speed – down to 2.2-2.4 m·s^{-1}, which corresponds to the limit values for the traction force in this gear. Operating in second gear provides a higher transport speed, but the permissible range of tractive forces is limited: after 10-11 kN, the speed drops sharply, indicating that it is impossible to effectively apply a greater tractive force.

Thus, the obtained dependencies confirm that the rational choice of gear should be determined by the magnitude of the required tractive force: for high loads, first gear is advisable, whilst second gear provides a higher speed, but only under conditions of low tractive load.

The obtained dependencies confirm the advisability of using ballasting to improve the traction characteristics of the MEZ, especially when performing work requiring the development of significant tractive forces.

DISCUSSION

The obtained results are consistent with published data indicating that ballast, vertical wheel load and tyre inflation pressure strongly influence drawbar performance and slip. In the unballasted configuration, the "Avtotractor" approached the traction limit when the tractive force exceeded 14–15 kN, whereas the ballasted configuration kept slip below 6–8% up to 17–18 kN. This behaviour agrees with the findings of Battiato and *Diserens (2017), Kumar et al. (2018), Janulevičius and Damanauskas (2022)* and *Franceschetti et al. (2025)*, who showed that the correct combination of wheel load, ballast and tyre pressure can improve the realisation of tractive effort and reduce non-productive slip losses.

At the same time, the laboratory asphalt-concrete surface used in the present work represents a controlled high-adhesion condition and should not be interpreted as a direct substitute for all field soils. The influence of soil texture, moisture content, cone index, implement type and tyre pressure settings can change both the slip level and the permissible drawbar pull; these factors were emphasised in recent tyre-soil interaction and tractor performance studies (*Alkhalifa et al., 2024; Barbosa et al., 2025*). Therefore, further research should include field validation on soils of different mechanical composition and moisture, testing of the centralised tyre pressure regulation system, and assessment of fuel consumption and drawbar power during aggregation with real agricultural implements.

CONCLUSIONS

1. Experimental studies of the traction performance of the “Avtotractor” on an asphalt concrete surface have shown that the results obtained are statistically significant ($R^2 = 0.951–0.998$; $p \leq 0.048$) and conform to the conditions of a normal distribution, confirming the accuracy of the measurements taken and the subsequent mathematical processing of the data.

2. A clear relationship has been established between the slip coefficient and the magnitude of the tractive force, the nature of which changes significantly depending on the vehicle’s mass. For an unballasted “Avtotractor” with a mass of 3410 kg, a sharp increase in slip is observed when the tractive force exceeds 14-15 kN, indicating that the limit of wheel-surface adhesion has been reached, accompanied by a reduction in tractive efficiency.

3. Increasing the load on the “Avtotraktor” to a mass of 4880 kg provides a significant improvement in the machine’s traction and grip properties across the entire range of loads studied. At the same time, the slip coefficient remains within acceptable limits (up to 6-8%) even at a tractive effort of 17-18 kN, indicating the realisation of tractive potential in the ballasted state.

4. The regression models constructed for the speed of the “Avtotractor” as a function of tractive effort for first and second gears confirm the influence of the transmission operating mode on the machine’s tractive performance.

5. Operation in second gear is characterised by a higher speed, but the effective realisation of tractive effort in this mode is limited to values of 10-11 kN, after which a sharp drop in speed is observed, indicating that it is not advisable to use a higher gear under significant tractive loads.

6. A summary of the experimental results indicates that, through the rational selection of transmission operating modes and the use of ballasting, the experimental “Avtotractor” prototype ensures stable traction force delivery within a range characteristic of traction classes 1.4-2.

REFERENCES

[1] Alkhalifa N., Tekeste M.Z., Jjagwe P., Way T.R. (2024). Effects of vertical load and inflation pressure on tire-soil interaction on artificial soil. *Journal of Terramechanics*, 112, pp. 19–34. DOI: 10.1016/j.jterra.2023.11.002

[2] Baek S.Y., Jeon H., Park C.G., Kim Y.J. (2025). Slip and tractive efficiency of an electric tractor with a 4WID E-axle system, *Scientific Reports*, 15, DOI: 10.1038/s41598-025-08572-4

[3] Barbosa I.A., Coelho A.L.F., Queiroz D.M., Furtado Junior M.R., Villibor G.P. (2025). Development of software for performance analysis of wheeled tractors. *Journal of Terramechanics*, 119, Article 101054. DOI: 10.1016/j.jterra.2025.101054

[4] Battiato A., Diserens E. (2013). Traction performance simulation for mechanical front wheel drive tractors: towards a practical computer tool. *Journal of Agricultural Engineering*, DOI: 10.4081/jae.2013.309

[5] Battiato A., Diserens E. (2017). Tractor traction performance simulation on differently textured soils and validation: a basic study to make traction and energy requirements accessible to the practice. *Soil and Tillage Research*, 166, pp. 18–32. DOI: 10.1016/j.still.2016.09.005

[6] Birt, G. O., Burchu, Yu. G. (2014). Methodology and Organization of Scientific Research. *Textbook. Kyiv. Center for Educational Literature*. 142 pp.

[7] Bondarenko V.M., Kravchenko O.V. (2022). Analysis of Methods and Means for Evaluating Tractor Traction Properties. *Automobile Transport*, DOI: 10.20998/2078-6840.2022.2.12

[8] Bulgakov, V., Bonchik, V., Holovach, I., Fedosiy, I., Volskiy, V., Ihnatiev, Y., Olt, J. (2021). Justification of parameters for novel rotary potato harvesting machine. *Agronomy Research*, 19 (Special Issue 2), pp. 984–1007.

[9] Bulgakov, V., Ivanovs, S., Adamchuk, V., Antoshchenkov, R. (2019). Investigations of the Dynamics of a Four-Element Machine-and-Tractor Aggregate. *Acta Technologica Agriculturae*, 22(4), pp. 146–151.

[10] Franceschetti B., Filannino L., Piovaccari G., Rondelli V. (2025). Influence of ballast and tyre inflation pressure on traction performance of agricultural tractors evaluated in trials on concrete track. *AgriEngineering*, 7(4), Article 109. DOI: 10.3390/agriengineering7040109

[11] Goncharuk, T. V. (2014). Fundamentals of Scientific Research. *Textbook*. Ternopil. TNEU, 272 p.

[12] Ivanovs, S., Bulgakov, V., Nadykto, V., Ihnatiev, Ye., Smolinskyi, S., Kiernicki, Z. (2020). Experimental study of the movement controllability of a machine-and-tractor aggregate of the modular type. *INMATEH – Agricultural Engineering*, Vol. 61(2), pp. 9–16. 10.35633/inmateh-61-01.

[13] Janulevičius A., Damanauskas V. (2022). Prediction of tractor drive tire slippage under different inflation pressures. Journal of Terramechanics, 101, pp. 23–31. DOI: 10.1016/j.jterra.2022.03.001

[14] Kalambet, S. V. (2015). Methodology of Scientific Research. Textbook. Dnipropetrovsk: *Makovetsky Publishing House*, 191 p.

[15] Kim W.-S., Kim Y.-J., Park S.-U., Choi C.-H. (2021). Influence of soil moisture content on the traction performance of a 78-kW agricultural tractor during plow tillage, *Soil and Tillage Research*, 207, DOI: 10.1016/j.still.2020.104851.

[16] Koryagin, M. V. (2014). Fundamentals of Scientific Research. *Textbook.* Kyiv. Alerta. 622 p.

[17] Kumar S., Pandey K.P., Kumar R., Kumar A. (2018). Effect of ballasting on performance characteristics of bias and radial ply tyres with zero sinkage. *Measurement*, 121, pp. 218–224. DOI: 10.1016/j.measurement.2018.02.043

[18] Luo C., Wen C., Meng Z., Liu H., Li G., Fu W. (2023), Research on the Slip Rate Control of a Power Shift Tractor Based on Wheel Speed and Tillage Depth Adjustment, *Agronomy*, 13. DOI: 10.3390/agronomy13020281.

[19] Mokin, B.I. (2014). Methodology and Organization of Scientific Research. *Textbook*. Vinnytsia. VNTU. 180 p.

[20] Osinenko P.V. (2015). A method of optimal traction control for farm tractors with soil-condition estimation, *Biosystems Engineering*, 133, DOI: 10.1016/j.biosystemseng.2014.1627.

[21] Pohorilyy, S.P., Prysyazhnyy, V.G., & Mirnyi, V. Y. (2023). Justification of the parameters of technological modules for mobile energy vehicles “Autotractor”. *Mechanics and Automatics of Agroindustrial Production*, 1(115), 135 – 142. https://doi.org/10.37204/2786-7765-2023-1-14.

[22] Pohorilyy, S.P., Prysyazhnyy, V.G., Tretyak, V.M., Panasyuk, V.I., Mirnyi, V.Y., & Barabash, R.I. (2022). Perspectives of using mobile energy vehicle of traction class 1.4; 2 in agricultural production. *Mechanization and Electrification of Agriculture*, 15(114), 108-114. https://doi.org/10.37204/0131-2189-2022-15-13.

[23] Roşca R., Cârlescu P., Ţenu I., Vlahidis V., Perşu C. (2022). The Improvement of a Traction Model for Agricultural Tire-Soil Interaction, *Agriculture*, 12. DOI: 10.3390/agriculture12122035.

[24] Shafaei S.M., Loghavi M., Kamgar S. (2021). Fundamental realization of longitudinal slip efficiency of tractor wheels in a tillage practice. *Soil and Tillage Research*, 205, Article 104765. DOI: 10.1016/j.still.2020.104765

[25] Tiwari V.K., Pandey K.P., Pranav P.K. (2010). A review on traction prediction equations. *Journal of Terramechanics*, 47(3), pp. 191–199. DOI: 10.1016/j.jterra.2009.10.002

[26] Vantsevich, V., Paldan, J., & Farley, B. (2016). Mobility optimization and control of a 4x4 HE-vehicle in curvilinear motion on stochastic terrain. *In ASME 2016 international design engineering technical conferences (article number V003T01A005).* https://doi.org/10.1115/DETC2016-59207

[27] Zhang X., Wang J., Li Y. (2016). Integrated control method of traction and slip ratio for rear-driving high-power tractors. *Transactions of the Chinese Society of Agricultural Engineering*, DOI: 10.11975/j.issn.1002-6819.2016.12.007

[28] Zhu S., Wang L., Zhu Z., Mao E., Chen Y., Liu Y., Du X. (2022). Measuring method of slip ratio for tractor driving wheels based on machine vision. Agriculture, 12(2), Article 292. DOI: 10.3390/agriculture12020292