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# A STUDY OF THE INTERACTION BETWEEN SOIL AND THE PNEUMATIC WHEELS OF AGRICULTURAL GANTRY SYSTEMS

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**ABSTRACT.** At the stage at which agricultural gantry systems are being designed, developed, and studied, the question of a rational choice of tyres for such systems is relevant, as tyres are the most important part of an agricultural gantry system and have a significant effect on most of its operating properties. The methods that can be used for choosing tyres for traditional mobile-powered equipment are already well established by scientific experience, but the movement of agricultural gantry systems in permanent artificial tracks creates somewhat different conditions and demands for a pneumatic tyre when compared to a traditional tractor moving along agricultural soil. This is why the development of methods that will assist in finding rational parameters for the pneumatic tyres of agricultural gantry systems that are moving along compacted soil in permanent artificial tracks is an urgent and relevant task. The purpose of the study is to optimise the parameters for the tyres of agricultural gantry systems in terms of their being able to travel on compacted soil in permanent artificial tracks. Theoretical studies and the synthesis of the parameters for a pneumatic wheel to work with an agricultural gantry system took place by modelling on a PC the performance conditions of such a vehicle. The basis for the study methods was formed by the fundamentals of tractor theory and theoretical mechanics, using the software program Mathcad. The traction factor of an agricultural gantry system's pneumatic wheel was used as the performance criterion for the effectiveness of the work being done by the wheel. The physical object of study was an agricultural system that has been developed by us. As a result of the study, it was determined that the solving of the task that has been set out - using an analysis of partial derivates of the function of the efficiency of an agricultural gantry system's wheel – makes it possible to quickly and effectively determine the rational optimum points for its pneumatic tyre's parameters. It was determined that, for the agricultural gantry system at hand, and in view of the maximum efficiency of its pneumatic wheel, the wheel's tyre width[4] must be within the range of 0.20–0.30 m and its diameter must be within the range of 0.90–1.25 m. With those ranges, it is recommended that the tyre's inflation pressure be increased from 100 kPa to 160 kPa because the partial derivates of the function of the efficiency at those parameters would decrease to near zero. It has been proven that the choice of tyre type for agricultural gantry systems should be based first on the choice of its width and then its load-bearing capacity – its diameter. The proposed methods for finding rational parameters for pneumatic wheels make it possible to determine the tyre parameters for all kinds of agricultural gantry systems which will be required to travel on compacted soil in permanent artificial tracks. For the agricultural gantry system that has been developed by us, using tyres of the 9.5R32 type provides the highest levels of efficiency, *i.e.* at a factor of 0.86.

## Introduction

The quick global development of wheeled agricultural systems (Blackwell *et al*., 2004; Gil-Sierra *et al*., 2007; Tullberg *et al*., 2007; Onal, 2012; Bindi *et al*., 2013; Chamen, 2015; Bulgakov *et al*., 2018a) clearly indicates a wide range of applications when it comes to using agricultural gantry systems (Webb *et al*., 2004; Pedersen, 2011; Bochtis *et al*., 2010; Pedersen *et al*., 2013, 2016; Bulgokov *et al*., 2017, 2019a) as a single powered module travelling along compacted trails that are formed by permanent artificial tracks. The latter's natural meaning is determined by the results shown in solving the fundamental contradiction in the system of "chassis-soil", *i.e*. that in order to achieve high traction performance the chassis has to be in contact with a dry, compacted soil surface but, in order to grow normally, crop plants need optimum moisture levels and uncompacted soil. In practice, these requirements can be met simultaneously only when setting clear borders between the travelling areas for powered equipment (the field's technological zone) and the growth areas for plants (the field's agricultural zone).

The movement of agricultural gantry systems along permanent artificial tracks creates somewhat different conditions and demands for a pneumatic tyre when compared to a traditional tractor that has agricultural soil beneath its wheels. This means that one of the requirements for the parameters of artificial tracks (Nadykto, Uleksin, 2008) is their sufficient compaction, ensuring the improvement of traction and operating performance for agricultural gantry systems that have to move along such tracks. As a result, any established normative limitations on the effect on the soil of chassis systems can be ignored with the area of artificial tracks. On the other hand, it has been established (Bulgakov *et al*., 2018b) that the wheel width of agricultural systems must be as small as possible. This reduces the amount of the field that is lost to the technological zone.

Tyres are the most important part of an agricultural gantry system. When interacting with the compacted ground surface of permanent artificial tracks, they have a significant effect on most of the agricultural gantry system's operating properties: its travel safety levels, traction and speed, travel performance over a rough surface, load-bearing capacity, stability, controllability, riding comfort, riding smoothness, and fuel economy levels (Bulgakov *et al*., 2019b). Therefore, at the design, development, and study stage for any agricultural gantry system, the question of a rational choice of tyres is relevant for such systems.

The methods used for choosing tyres for traditional powered mobile equipment have been well established through scientific experience (Guskov, 1996; Bulgakov *et al*., 2016). In light of being able to achieve the best levels of traction performance for powered equipment, the optimal tyre dimensions and tyre pressure must ensure the highest levels of performance by the pneumatic wheel at the specified load.

Those questions that relate to studying the traction properties of wheeled machinery are discussed in Panchenko, Kyurchev, 2008; Adamchuk *et al*., 2016, 2018). It must be noted that, for machinery as a whole, the established way of assessing traction properties and dynamic qualities is to use the efficiency factor and dynamic factor of the means of traction in question (Bulgakov *et al*., 2017). On the other hand, each wheel of an agricultural gantry system functions in individual conditions in terms of its vertical load, torque, and travelling conditions.

The traction properties of agricultural gantry systems depend upon a number of parameters. These include its structural parameters on the one hand and the physical and mechanical properties of the surface of any permanent artificial tracks on the other.

The classic theory regarding wheeled equipment states (Kutkov, 2014) that an increase in tyre size (the outer diameter and width) increases the powered equipment's traction properties upon an identical vertical load on the tyre. As the force countering the machine's rolling diminishes while the soil is in the process of being compacted as it is compressed by the moving equipment, the traction effect of power increases because the tyre's area that is in contact with the ground becomes greater. Moreover, its travel performance also improves (the chassis' specific pressure on the soil decreases and the ground clearance increases). Simultaneously, an increase of the tyre's dimensions (with the same vertical load upon it) leads to its higher levels of cost and the weight on the powered equipment. Rationally-chosen tyres, in terms of their diameter, width, and internal pressure, making it possible to achieve the highest levels of efficiency for the wheel in question.

The aim of this study was to optimise the parameters for the tyres on the chassis of an agricultural gantry system when travelling along the compacted ground surface of permanent artificial tracks.

## Material and Methods

Theoretical studies regarding the pneumatic wheel of an agricultural gantry system, and the synthesis of the parameters involved, took place by modelling on a PC the conditions of its performance. The basis for the study methods were the fundamentals involved in tractor theory and theoretical mechanics (Popp, Schiehler, 2010; Rajamani, 2012), using the Mathcad software program.

The physical object of the study was an agricultural system that had been developed by us (Fig. 1). Its chassis consists of a frame to which wheels with pneumatic tyres of the 9.5R32 size are attached via four semi-axles.

The traction factor $\eta_k$ of the agricultural gantry system's pneumatic wheel was used as the performance criterion for the effectiveness of the work being done by the wheel, being calculated from a known relation (Kutkov, 2014):

$$\eta_k = (1-\delta)\cdot[1-\frac{F_r}{F_k}], \quad (1)$$

where:

$\delta$ – the spin factor of the wheels;

$F_r$ – the rolling resistance of the pneumatic wheel;

$F_k$ – the contact traction force created by the pneumatic wheel.

**Figure 1.** The agricultural gantry system used for experimental studies on the work of its pneumatic wheels.

According to the task that had been set out, *i.e.* to select the optimal parameters for pneumatic tyres on the wheels of agricultural gantry systems under conditions of a constant vertical load upon them ($G_N$ = const), a compromise solution has to be found by solving the following equation:

$$\frac{\partial \eta_k}{\partial (D_0, b_0, p_w)} \to 0, \qquad (2)$$

where:
$D_0$ – static diameter of the tyre;
$b_0$ – width of the tyre;
$p_w$ – internal pressure of the tyre.

Seeking an extreme of the tyre's parameters by way of solving the partial derivates Eq. 2 of its efficiency upon a constant load upon the tyre enables to determine the tyre's minimum width, $b_0$, its optimal diameter, $D_0$, and the internal pressure, $p_w$, upon which the value of $\eta_k$ is the highest.

## Results and Discussion

So that the theoretical studies could be carried out, the wheeled chassis of the agricultural gantry system is taken to be mobile along a horizontal, compacted, and deformable surface which is made up of permanent artificial tracks and is represented by an equivalent diagram indicating the forces affecting it (Fig. 2).

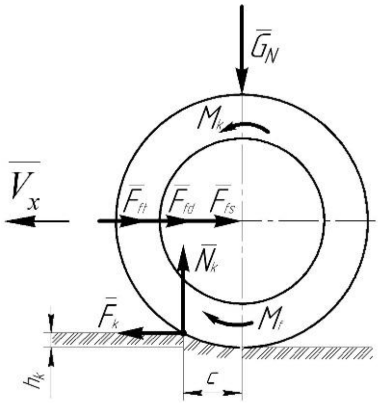


**Figure 2.** Equivalent diagram of the agricultural gantry system's pneumatic wheeled chassis

In a situation which involves uniform rolling of the agricultural gantry system's elastic tyre on a horizontal deformable surface and on permanent artificial tracks, the energy transferred to the wheel does three types of work that, all together, make up the total energy of rolling resistance on the wheel: further vertical compaction of the soil; elastic deformation of the soil causing internal friction in the tyre; friction of the tyre's tread against the ground's surface at the point of contact.

In that respect, the equation for the balance of the forces of the wheel's rolling resistance can be described as follows:

$$\mathrm{F_r} = F_{fs} + F_{fd} + F_{ft}, \qquad (3)$$

where:
$F_{fs}$, $F_{fd}$, $F_{ft}$ – the forces of the wheel's rolling resistance, caused by the soil's vertical compaction, the tyre's internal friction, and the tyre tread's friction against the soil, respectively.

Viewing the indicated forces according to the methodology used (Guskov, 2007) makes it possible to determine the gross dependence Eq. 3 via parameters that define it as follows:

$$F_r = k_0 \cdot b_0 \cdot h_k^2 + k_r \cdot G_N \left(\frac{h_r}{D_0}\right)^{\frac{1}{3}} + \frac{2\mu_p \cdot G_N \cdot k_s \cdot h_r}{3D_0} \qquad (4)$$

where:
$k_0$ – the soil's compaction factor by volume, N·m$^{3-1}$;
$h_k$ – the track's depth, m;
$k_r$ – a dimensionless factor which is dependant upon the tyre's material, the structure of its body, and other circumstances;
$h_r$ – the tyre's normal deformation (sag), m;
$\mu_p$ – the tyre tread's factor of friction against the ground's surface (soil);
$k_s$ – the cinematic factor, taking into account the tyre's shape and the rotating plane's angle to the ground's surface (the soil);
$G_N$ – load upon the tyre.

To be able to determine the value of $h_r$ in terms of the tyre's normal deformation (sag), the following equation is used (Guskov, 1996):

$$h_r = \frac{G_N}{\pi \cdot p_w (D_0 \cdot b_0)^{\frac{1}{2}}}. \qquad (5)$$

To find the value of $h_k$ *i.e.* the depth of the track formed by further deformation of the soil by the surface of the agricultural gantry system's wheel is determined from the following empirical equation (Nadykto, Uleksin, 2008):

$$h_k = \frac{0.01 \cdot p_w - 0.0002 \cdot H}{\rho \cdot g} + 4.655 \frac{G_N \cdot \rho \cdot g}{p_w^2}, \qquad (6)$$

where:
$\rho$ – the soil's density, kg·m$^{3-1}$;
$g$ – the gravitational acceleration, m·s$^{2-1}$;
$H$ – the soil's harness, Pa.

The maximum contact traction force $F_k$ that is generated by the agricultural gantry system's pneumatic wheel can be determined from the condition of its sufficient traction on the soil. Based on that condition, the contact traction force $F_k$ depends upon the traction factor $\psi$ and on the load $G_N$ being applied to it (Kutkov, 2014):

$$F_k = \psi \cdot G_N, \tag{7}$$

where:

$\psi$ – the factor of traction for the pneumatic wheel on the ground's surface where permanent artificial tracks are being used.

After substituting Eqs. 4–7 into Eq. 1 and carrying out a number of mathematical transformations, we achieve an equation that relates to the pneumatic wheel's efficiency $\eta_k$ to its parameters and the soil's properties:

$$\eta_\mathrm{k} = (1-\delta)\cdot\left[1 - k_0\cdot b_0\left(\frac{0.01\cdot p_w - 0.0002\cdot H}{\rho\cdot g} + 4.655\frac{G_N\cdot\rho\cdot g}{p_w^2}\right)^2\cdot(\psi\cdot G_N)^{-1} - \frac{k_r\cdot G_N^{\frac{1}{3}}}{\psi(\pi\cdot p_w)^{\frac{1}{3}}\cdot D_0^{\frac{1}{2}}\cdot b_0^{\frac{1}{6}}} - \right.$$
$$\left. - \frac{\mu_p\cdot k_s\cdot G_N}{3\psi\cdot\pi\cdot p_w\cdot b_0^{\frac{1}{2}}\cdot D_0^{\frac{3}{2}}}\right]. \tag{8}$$

Partial derivative equations (8) for all three of the tyre parameters being studied upon a constant load are as follows:

$$\frac{\partial\eta_\mathrm{k}}{\partial D_0} = \frac{(1-\delta)}{2}\cdot\left(\frac{\mathrm{A'}_5}{p_w^{\frac{1}{3}}\cdot D_0^{\frac{3}{2}}\cdot b_0^{\frac{1}{6}}} + \frac{3\mathrm{A'}_6}{p_w\cdot D_0^{\frac{5}{2}}\cdot b_0^{\frac{1}{2}}}\right), \tag{9}$$

$$\frac{\partial\eta_k}{\partial b_0} = (1-\delta)\cdot\left[-\mathrm{A'}_1\left(\mathrm{A'}_2\cdot p_w - \mathrm{A'}_3 + \frac{\mathrm{A'}_4}{p_w^2}\right)^2 + \frac{\mathrm{A'}_5}{3p_w^{\frac{1}{3}}\cdot D_0^{\frac{1}{2}}\cdot b_0^{\frac{7}{3}}} + \frac{\mathrm{A'}_6}{p_w\cdot D_0^{\frac{3}{2}}\cdot b_0^{\frac{3}{2}}}\right], \tag{10}$$

$$\frac{\partial\eta_k}{\partial p_\mathrm{w}} = (1-\delta)\cdot\left(-2\mathrm{A'}_1\cdot\mathrm{A'}_2^2\cdot p_w + \frac{2\mathrm{A'}_1\cdot\mathrm{A'}_2\cdot\mathrm{A'}_4 + \mathrm{A'}_1\cdot\mathrm{A'}_4^2}{p_w^2} + \frac{\mathrm{A'}_5}{3D_0^{\frac{1}{2}}\cdot b_0^{\frac{1}{3}}\cdot p_w^{\frac{4}{3}}} + \frac{\mathrm{A'}_6}{D_0^{\frac{3}{2}}\cdot b_0^{\frac{1}{2}}\cdot p_w^2}\right), \tag{11}$$

where

$$\mathrm{A'}_1 = \frac{k_0}{\psi\cdot G_\mathrm{N}};\ A'_2 = \frac{0.01}{\rho\cdot g};\ A'_3 = \frac{0.0002H}{\rho\cdot g};\ A'_4 = 4.655\cdot G_N\cdot\rho\cdot g;\ A'_5 = \frac{k_r\cdot G_N^{\frac{1}{3}}}{\psi(\pi)^{\frac{1}{3}}};\ A'_6 = \frac{\mu_p\cdot k_s\cdot G_N}{3\cdot\psi\cdot\pi}.$$

A further solution for the compromise task Eq. 2 for this agricultural gantry system indicated that, in searching for the extremes of the first area of equations Eqs. 9–11 for the parameters $D_0$, $b_0$ and $p_w$, the latter will reach towards infinity (Fig. 3).

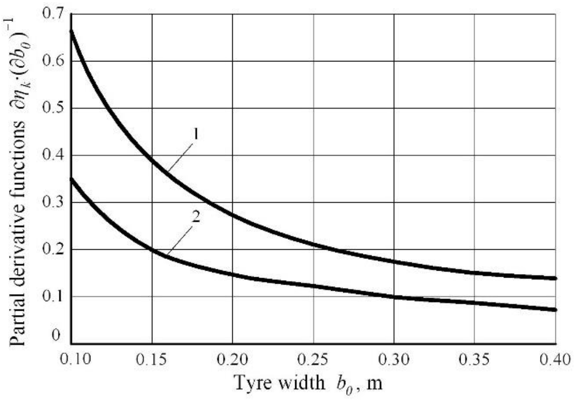


**Figure 3.** The dependence of the partial derivates of the function $\frac{\partial\eta_\mathrm{k}}{\partial b_0}$ in terms of the efficiency of the agricultural gantry system's wheel on its width $b_0$ while $G_N$ = const: 1) $D_0$ = 0.6 m, $p_w$ = 100 kPa; 2) $D_0$ = 1.2 m, $p_w$ = 160 kPa

The nature of the function of the created dependency (see Fig. 3) provides for two characteristic zones of intensive dynamics from its argument. As a rule, such graphs have points of rational optimum. By using the methodology (Nadykto, Velichko, 2014) of searching for the optimum of this type graph, it was determined that the zone of the tyre's rational width $b_0$ is in the range of 0.20–0.30 m. With that result having been determined, it is recommended that the tyre's internal pressure $p_w$ be increased from 100 kPa to 160 kPa because the partial derivate of the function $\frac{\partial\eta_\mathrm{k}}{\partial b_0}$ would then decrease to near zero. On the basis of this analysis, it can be concluded that when the stated conditions of use can be met for the agricultural gantry system, the width of its tyres must be at least 0.20 m to maximise the highest possible levels of efficiency for the tyres.

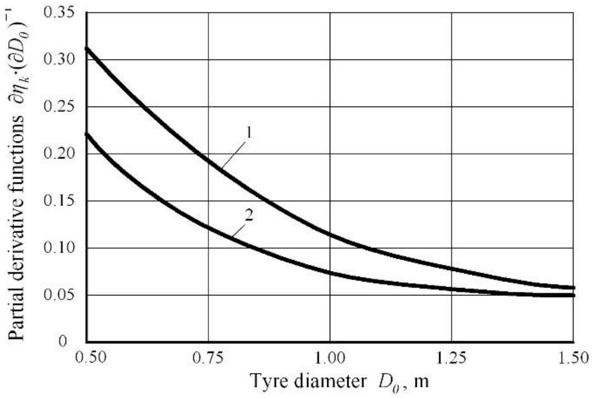


**Figure 4.** The dependence of the partial derivates of the function $\frac{\partial\eta_\mathrm{k}}{\partial D_0}$ of the efficiency of the agricultural gantry system's wheels on its tyre diameter $D_0$ at $G_N$ = const: 1) $b_0$ = 0.20 m, $p_w$ = 100 kPa; 2) $b_0$ = 0.30 m, $p_w$ = 160 kPa.

For the indicated values of the zones of rational optimum for the parameter $b_0$, a graphical dependency of the partial derivative of $\frac{\partial \eta_k}{\partial D_0}$ on $D_0$ was plotted (see Fig. 4). The nature of that dependency is similar to that for Fig. 3. Its analysis indicated that the zone of rational optimum for $D_0$ falls within the range of 0.90–1.25 m. With this as with the previous area, it is also recommended that the tyre's internal pressure $p_w$ be increased from 100 kPa to 160 kPa because of the partial derivates of the function $\frac{\partial \eta_k}{\partial D_0}$ would then decrease to near zero. Therefore, under the stated conditions of use for the agricultural gantry system, the diameter of its tyres must be at least 1.20 m, which will maximise the levels of efficiency of the tyres.

The results yielded when searching for rational parameters for the wheel tyres of an agricultural gantry system have been confirmed by the results shown in plotting the dependencies of the efficiency of its wheels (Fig. 5).

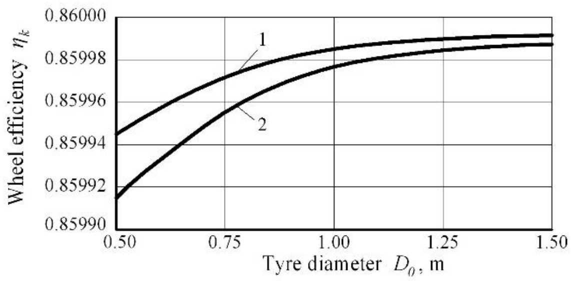


**Figure 5.** The dependence of the efficiency $\eta_k$ of the agricultural gantry system's wheel on its diameter $D_0$: 1) $b_0$ = 0.30 m; 2) $b_0$ = 0.20 m

The analysis of the dependence graph in Fig. 5 supplies the conclusion that, under the conditions of there being an identical load $G_N$ = const on the agricultural gantry system's wheel, its efficiency $\eta_k$ increases with an increase in the wheel's diameter $D_0$ and width $b_0$. The nature of such a dependency provides from its argument two characteristic zones of intensive dynamics. The search for the rational optimum of $D_0$ indicated that the outer diameter of the agricultural gantry system's tyre must be 1.245 m. The value yielded is taken as a base value for further calculations.

Pursuant to the requirements of the agricultural track system and for the task that has been set out for the study, it is recommended that the pneumatic tyre $b_0$ be as narrow as possible. In order to be able to satisfy that requirement, the following dependency shall be analysed where it relates to the efficiency $\eta_k$ of the agricultural gantry system's wheel in relation to its width $b_0$ (Fig. 6).

The nature of the dependency shown in Fig. 6 also provides for two zones in which the graph has a point of rational optimum. The search for that point indicated that it is located where the tyre width $b_0$ equals 0.250 m.

Based on the values yielded in terms of rational parameters for tyres for the agricultural gantry system's wheels, tyres of a size of 9.5R32 were selected, with $D_0$ = 1.245 m and $b_0$ = 0.241 m because, amongst the possible tyre alternatives with parameters that come close to those values, the tyre selected had the smallest profile width while simultaneously also having the highest wheel efficiency $\eta_k$.

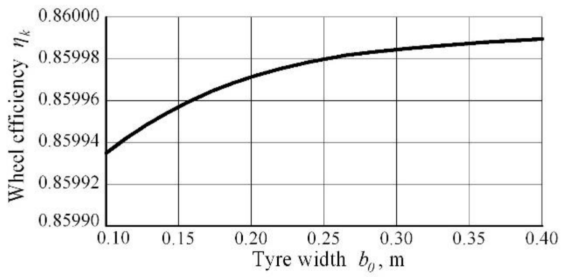


**Figure 6.** The dependency of the efficiency $\eta_k$ of the agricultural gantry system's wheel on its tyre width $b_0$ at $D_0$ = 1.245 m.

The proposed methods for finding rational parameters for pneumatic wheels make it possible to determine the tyre parameters for all kinds of agricultural gantry systems when they are required to travel on compacted soil in permanent artificial tracks.

## Conclusions

1. When adapting the parameters for the tyres of agricultural gantry system wheels which are required to travel on compacted soil in permanent artificial tracks, a compromise solution has to be found where, on the one hand, the profile width of the tyres of an agricultural gantry system must be as small as possible but, on the other hand, the wheel must still operate at its maximum levels of efficiency. In solving the task that has been set out, the use of the analysis of partial derivates of the function of the efficiency of an agricultural gantry system's wheel makes it possible, quickly and effectively, to determine the points of rational optimums for its pneumatic tyre's parameters.
2. The search for rational parameters in relation to the pneumatic wheels of the agricultural gantry system that has been developed by us indicated that the range of rational optimum tyre widths is between 0.20–0.30 m, and the range of optimum tyre diameters is between 0.90–1.25 m. With that in mind, it is recommended that the inflation pressure of the tyres be increased from 100 kPa to 160 kPa because the partial derivates of the function of the efficiency at those parameters would decrease to near zero.
3. The studies that have been conducted indicate that, under the conditions of there being an identical load on the agricultural gantry system's tyre, the efficiency of its wheels increases with an increase of the tyre's diameter and width. From their argument, the nature of these dependencies provides for two characteristic zones of intensive dynamics. The search for the rational optimums of the indicated parameters showed that the outer diameter of the agricultural gantry system's tyre must be 1.245 m and its width must be 0.250 m. It has been proven that the choice of tyre

type for agricultural gantry systems should be first based on the choice of width and then on load-bearing capacity – its diameter.

4. The fact has already been identified that there are tyre parameters for every agricultural gantry system. With that in mind, the operating weight of such a system imposes a certain load on its wheels, which enables its pneumatic wheels to work at their maximum levels of efficiency. For an agricultural gantry system with the described structure, and based on the yielded values for rational tyre parameters, tyres that are of the 9.5R32 size were chosen where they also had the highest efficiency levels, *i.e*. 0.86.

5. The proposed methods of choosing tyre types for pneumatic wheels make it possible to determine the tyre parameters for all kinds of agricultural gantry systems for travelling on compacted soil in permanent artificial tracks.

**Conflict of interest**

The authors declare that there is no conflict of interest regarding the publication of this paper.

**Author contributions**

VB – study conception and design, critical revision and approval of the final manuscript;
JO – drafting of the manuscript, critical revision and approval of the final manuscript;
VK – analysis and interpretation of data;
MC, MS, SK – acquisition of data.

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