DEVELOPMENT OF A MODEL FOR CALCULATING THE SLIP COEFFICIENTS OF A MECHANICAL WHEELED VEHICLE WITH TWO STEERING AXLES

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Resume

The purpose of the study is to perform appropriate calculations of the values of the total slip coefficients alternately on the sides of a vehicle, depending on the angles of rotation of its axles, using the single slip coefficients of its individual wheels directly when turning. The basis of the methodological approach in this study is a combination of system analysis of the principles of calculating the slip coefficients of a mechanical wheeled vehicle with an analytical investigation of problematic aspects of developing a model for calculating the slip coefficients of a vehicle with two steering axles. The results obtained indicate the presence of a persistent relationship between the slipping coefficients of a mechanical wheeled vehicle and the rotation angles of its two steering axles, including a number of other parameters that are important from the standpoint of traffic safety.

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1 Introduction

Mobile and manoeuvrable mechanical wheeled mechanisms are widely used in various branches of modern industry for the qualitative solution of issues of the cargo transportation and mechanisation of lifting, construction and road works. The scope of their practical application is determined by their types and design features, which are steadily expanding. Due to the mass use of wheeled vehicles, the issues of conducting the large-scale scientific research aimed at improving the already developed and creating the latest designs of mechanical vehicles are becoming increasingly relevant [1].

In modern economic conditions, the issues of gradual increase in the productivity of technological units are given priority. At the same time, the quality of mechanical wheeled vehicles and their performance are of great importance, since they are the most important elements of the technological chain. Very often, when operating such vehicles in the mining industry and a number of other industrial sectors, a decrease in their productivity, conditioned by difficult operating conditions, is observed [2]. Thus, in relation to the existing types and sizes of transport equipment, operational issues are becoming highly relevant, since the proper organisation of transport and technological processes can significantly increase their efficiency in the current conditions of the road and transport loads. It is also necessary to consider the fact that the optimal organisation of the mechanical wheeled vehicles' operation cannot be carried out without a theoretical analysis of their operational characteristics. This means that with the practical use of such machines in difficult road conditions, the analysis of their most important operational qualities, such as traction capability and cross-country ability, becomes particularly relevant [3]. Considering the fact that the operating conditions of mechanical wheeled vehicles assume a variety of very different road situations, the compliance of the traction capability of such machines and their cross-country capability will largely determine the effectiveness of their use. The use of mechanical wheeled vehicles with all-wheel drive for operation in the most severe road conditions and with limited space implies the need for effective resolution of a number of tasks directly related to the issues of increasing their patency in terms and profile and power circulation in their transmission. This determines the relevance of evaluating and selecting rational types and parameters of mechanical machines for their subsequent practical application in industrial enterprises and to determine their main traction parameters [4].

It is a well-known fact that when mechanical wheeled vehicles with two driving axles are moving, there is a redistribution of traction forces between these axles and this is especially important when turning mechanical vehicles. This determines the essential relevance of the study of problems of traction forces redistribution that arise directly during the movement of such vehicles, at any stage of movement. For this reason, studies of various aspects of the development of a model for calculating the slip coefficients of a mechanical wheeled vehicle with two steering axles have significant practical significance in terms of the prospects for creating new models of modern equipment capable of withstanding a large number of load cycles in difficult operating conditions, without the need for major repairs and replacement of components [5].

The main problems of research conducted within the framework of the subject matter are the lack of computational information regarding the quality of the mathematical model being created for calculating the slip coefficients of a mechanical wheeled vehicle with two steering axles. In this study, the task was set to create a qualitative model for calculating these coefficients, as close as possible to the real conditions and reflecting the real prospects for creating a full-drive mechanical vehicle in the future, capable of effectively solving the problems of the passenger and cargo transportation in the most difficult operating conditions.

2 Materials and methods

The basis of the methodological approach in this study is a combination of system analysis of the principles of calculating the slip coefficients of a mechanical wheeled vehicle with an analytical investigation of problematic aspects of developing a model for calculating the slip coefficients of a vehicle with two steering axles. This combination of research methods assumes the establishment of the necessary theoretical basis and the subsequent application of mathematical modelling techniques to create a qualitative model for calculating the slip coefficients of a mechanical vehicle with two steering axles. The study uses equations for determining the slip coefficients of mechanical vehicles with 4x4 wheel arrangement with two steering axles and an on-board blocked transmission and equations for calculating the angles of turns of the driving axles of a mechanical wheeled vehicle.

The theoretical basis of this study is made up of numerous research papers by various authors devoted to creation of mathematical models for determining the slip coefficients of mechanical vehicles with several steering axles and topics related to the subject matter. To form the most complete and reliable picture of research and to facilitate the perception of the information provided, all the developments of foreign authors, taken in the order of citation and presented in this research paper, have been translated into English. Thus, the theoretical basis of this study is the foundation for further research, carried out in strict accordance with all the issues raised in its subject matter.

The study was carried out in several main stages. At the first stage, a theoretical analysis of research papers available within the framework of the stated topics was carried out, which contributes to the development of a high-quality research base for further investigation in this area. In addition, this stage involved a systematic analysis of the principles of calculating the slip coefficients of a mechanical wheeled vehicle, the results of which formed the basis for the study of the principles of constructing a calculation model of the slip coefficients of a mechanical wheeled vehicle with two steering axles.

At the next stage, an analytical investigation of problematic aspects of the development of a model for calculating the slip coefficients of a mechanical wheeled vehicle with two steering axles was carried out. At the same time, this stage included an analytical comparison of the preliminary results obtained to the results and conclusions of other researchers on a similar subject or related to them. This is done to create an objective picture of scientific research, considering the maximum amount of results obtained during a detailed investigation of the issues included in the topic. At the final stage, based on the results obtained, the final conclusions were formulated, acting as an objective reflection of study results and summing up the entire complex of research efforts.

3 Results

The movement of mechanical wheeled vehicles in general and during the turns, in particular, is associated with the periodically arising need to determine the loss of speed due to slipping. As a rule, the slipping of a mechanical wheeled vehicle implies some loss of speed of the centre of the drive axle - the slipping of a conditional dummy wheel, which has a free radius equal to the radius of the driving wheels and is located in the centre of the drive axle [6-7]. A similar definition of slipping is applicable for cases of rectilinear motion. The movement of a wheeled vehicle directly during rotation can be estimated by the movement of its centre of mass. Therefore, the slipping of a wheeled vehicle, when making a turn, should be considered as a loss of speed of its centre of mass (1):

$$\delta = (v_{TC} - v_C)/v_{TC}, \tag{1}$$

here v_{TC}, v_C - theoretical and actual velocities of the centre of mass of the vehicle, respectively.

This study considers a 5VS-15M mechanical vehicle used for transporting rock, having a 4x4 wheel arrangement, two drive axles and an on-board blocked transmission. In this study, the slipping of a mechanical wheeled vehicle on a turn is investigated. In the case under consideration, the angular velocities of the driving wheels and the dummy wheel located at the centre of mass of the 5VS-15M vehicle are the same and equal to $w = w_1 = w_2$. The values of angular velocities can be expressed in terms of linear speeds and rolling radii of the wheels. Then:

$$r_{ki} = r_{ki}^0 (1-\delta_i), \tag{2}$$

where r_{ki} and r_{ki}^0 - the rolling radii of the wheel i - valid and free, δ_i - slipping of the car wheel.

As a result, the following relations are obtained:

$$\begin{aligned} \frac{v_C}{1-\delta_B} &= \frac{v_2'}{1-\delta_2'} = \frac{v_1'}{1-\delta_1'}; \\ \frac{v_C}{1-\delta_H} &= \frac{v_2''}{1-\delta_2''} = \frac{v_1''}{1-\delta_1''}, \end{aligned} \tag{3}$$

where, v_1', (δ_1'), v_1'', (δ_1'') - parameters of the speeds (slipping) of the lagging and running wheels of the front axle, v_2', (δ_2'), v_2'', (δ_2'') - the corresponding parameters for the rear axle.

Based on the data presented above, the equations for determining the values of the slip coefficients of mechanical wheeled vehicles with 4x4 wheel arrangement, with two drive axles and an on-board blocked transmission will have the following form:

$$\delta_B = 1 - \frac{(1-\delta_1')\cos(\varepsilon_1 - \alpha_1') + (1-\delta_2')\cos(\varepsilon_2 - \alpha_2')}{\cos(\varepsilon_2 - \eta_M) + \cos(\varepsilon_1 + \eta_M)}, \tag{4}$$

$$\delta_H = 1 - \frac{(1-\delta_1'')\cos(\varepsilon_1 - \alpha_1'') + (1-\delta_2'')\cos(\varepsilon_2 - \alpha_2'')}{\cos(\varepsilon_2 + \eta_M) + \cos(\varepsilon_1 - \eta_M)}. \tag{5}$$

Equations (4) and (5) determine the parameters of wheel slipping along the sides of a mechanical vehicle (lagging and running), while these equations include angles that are determined by the design of this machine and the angle that makes up the velocity vector of the centre of mass with its longitudinal axis and the rotation angles of the lagging and running wheels, respectively, of the front (rear) axles. The following equations are used to calculate the angle values:

$$\varepsilon_1 = \arccos\frac{a}{\sqrt{a^2 + (0.5B)^2}}, \tag{6}$$

$$\varepsilon_2 = \arccos\frac{b}{\sqrt{b^2 + (0.5B)^2}}, \tag{7}$$

$$\eta_M = arctg\frac{btg\alpha_1 - atg\alpha_2}{L}, \tag{8}$$

where a and b - the distance from the centre of mass of the car to the front and rear wheels, respectively; B - track; L - longitudinal base; a_1 and a_2 - angles of rotation of the front and rear axles, respectively.

With a fixed value of the angles of rotation of the axles, there is a significant difference in the corresponding angles of rotation of the inner and outer wheels of a vehicle, relative to the centre of rotation. Equations are used to calculate these differences:

$$tg\alpha_i' = \frac{Ltg\alpha_i}{L - 0.5B(tg\alpha_1 + tg\alpha_2)}, \tag{9}$$

$$tg\alpha_i'' = \frac{Ltg\alpha_i}{L - 0.5B(tg\alpha_1 + tg\alpha_2)}, \tag{10}$$

here, a_1 and a_2 - the values of the rotation angles of the inner and outer wheels, respectively.

Thus, based on the obtained equations, it is possible to carry out the theoretical calculation of the slip coefficients of mechanical wheeled vehicles with two driving axles directly when turning. Respectively, all the possible losses, both speed and power, can be sequentially set [8]. To determine the value of the traction force of the wheels of the 5VS-15M mechanical vehicle under consideration, it is necessary to experimentally establish values of the moments in the drive of the machine by using strain-gauging techniques. Oscilloscopes H-117 were used to measure the values of the turning angles of the vehicle. The angles of rotation of the wheels of the 5VS-15M mechanical vehicle were set using a selsyn sensor of angular deviations. According to certain parameters of traction forces, the slipping coefficients are established. The results of calculations of the slip coefficients are presented in Table 1.

Since the location of the centre of gravity of a mechanical wheeled vehicle is not strictly between the front and rear drive axles (a = 1.47; b = 1.53), there will be significant differences in the values of the angles of rotation of these axles relative to each other directly when turning the car [9]. Therefore, the angles of rotation of the axles are in strict proportion to the distances of the corresponding axles for the three control actions and will be: a) α_1 = 4.9°; α_2 = 5.1°; b) α_1 = 9.8°; α_2 = 10.2°; c) α_1 = 14.7°; α_2 = 15.3°.

At a given angle of rotation of the axles, the

Table 1 Parameters of the wheel slip coefficient of a mechanical vehicle

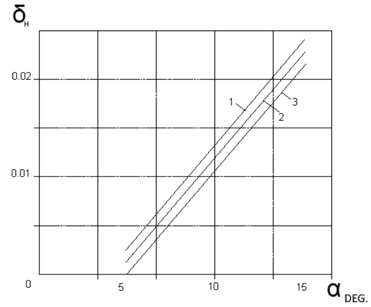
Mechanical vehicle	Value of the angle rotation of axles, °.	δ_1	δ_2	δ_3	δ_4
5VS-15M	5	0.120	-0.0646	0.0551	0.0549
	10	0.233	-0.0699	-0.0552	0.0406
	15	0.231	-0.0709	-0.0371	0.0400

Table 2 Calculation data of rotation angles of the inner and outer wheels of the 5VS-15M mechanical vehicle

α_1, deg.	α_2, deg.	α'_1, deg.	α'_2, deg.	α''_1, deg.	α''_2, deg.
4.9	5.1	5.14	5.35	4.68	4.87
9.8	10.2	10.8	11.2	8.97	9.33
14.7	15.3	17.05	17.7	12.9	13.4

Table 3 The results of calculations of the coefficients of slipping on the inner and outer sides of the mechanical vehicle

Mechanical vehicle	Angle of rotation of axles, deg.	δ_B	δ_H	Angle of structure, deg.
5VS-15M	5	-0.028	0.057	0.08
	10	-0.02	0.115	0.0145
	15	-0.0137	0.2354	0.11085



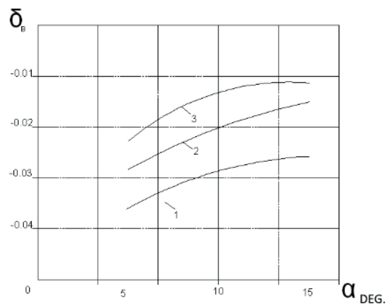


Figure 1 *The dependence of certain parameters of the on-board slip coefficients of a 5VS-15M mechanical vehicle on the angle of rotation of the wheels*
Note: 1 - at a = 1.25; 2 - at a = 1.47; 3 - at a = 1.75

corresponding angles of rotation of the inner and outer wheels of the 5VS-15M mechanical vehicle have significant differences relative to the centre of rotation. Equations (9) and (10) are used to calculate this difference. The calculation data are presented in Table 2.

Equations (4) and (5) allow calculating the parameters of the slip coefficients on the sides of a mechanical wheeled vehicle (internal and external). The data of these calculations are presented in Table 3.

A comparative analysis of the results obtained during the calculations and presented in Table 3 is presented in the form of a graphical dependence in Figure 1.

Comparison of the obtained results with the previous results clearly demonstrates that with the value of the turning angles of the axle of the vehicle at 10° and a = 1.47, the value of δ_H = 0.115, while with a = 1.25, δ_H = 0.122. At the same time, when a = 15° and a = 1.47, δ_H = 0.2354; at a = 1.25, δ_H = 0.24; at a = 1.75, δ_H = 0.2363. The comparative analysis indicates that when a = 10° and a = 1.25, δ_H is 6% higher, while a = 1.47; despite the fact that when a = 1.75, this figure is lower by 12%, than at a = 1.47 and lower by 11%, than when a = 1.25.

This is despite the fact that if a = 15° and a = 1.25, this parameter is 2% higher than in the case when a = 1.47. As for the analysis of slipping, when slipping along the inner radius when turning at an angle of a = 11°, the smallest value of the parameter of the slipping coefficient can be obtained only at a = 1.47. This indicates that the displacement of the centre of mass to the rear of the car is most favourable for this factor. A similar situation exists with a = 15°, since the most advantageous option, in this case, is when a = 1.75, but the slippage does not differ so significantly, namely, only by 13% compared to a = 1.47 and 50% compared to a = 1.25. The question arises why the deviations at

a= 12.5 are higher. The reason is that within the limits of slipping up to $\delta_H = 0.2$, the soil still retains its coupling ability and therefore the redistribution of traction forces is higher with various normal reactions of the wheels.

4 Discussion

Numerous theoretical problems of creating mechanical wheeled vehicles with several driving axles, to improve the cross-country ability and obtain universal vehicles capable of performing their main functions under any road and weather conditions, have long attracted the attention of researchers. In particular, these studies were carried out in relation to road vehicles with a mechanical transmission. The results obtained contribute to establishment of a developed segment of the high-traffic vehicles equipped with all-wheel drive in the modern fleet of vehicles. At the same time, tractors with all-wheel drive and agricultural and special-purpose vehicles are currently quite common. Almost all such equipment is equipped with mechanical transmissions with a step-change in gear ratios. In gearboxes, in addition, either overrunning clutches or differentials are used in transmissions of this kind, which completely exclude the appearance of power fluctuations in transmissions [10].

High efficiency indicators, combined with stable performance characteristics and extreme reliability in conditions of relatively low cost, largely predetermined the further spread of transmissions of this kind on mechanical wheeled vehicles with two or more drive axles. At the same time, on wheeled vehicles in which the number of steering axles exceeds two, at least a pair of driving axles has the maximum convergence between each other. In particular, this is conditioned by the fact that the developers of such vehicles are trying to find the optimal solution to improve the cross-country characteristics and at the same time reduce the variability of rolling conditions of the driving wheels. This is conditioned by the fact that one of the main disadvantages of the differential drive is the loss of the patency of the entire car, in case of problems with the coupling of one of the wheels of the drive axle with the road surface [11]. With the currently existing and implemented design developments of mechanical transmissions of wheeled vehicles with multiple axles, to eliminate the likelihood of problems of wheel coupling with the road, the possibility of forced locking of differentials is provided or differentials with a high internal friction index are used. Both presented options significantly complicate the design of the transmission and negatively affect the overall reliability of the entire car. The practical application of such differentials on mechanical wheeled vehicles with several driving axles is fraught with some difficulties. In a number of situations, in particular, in the case of activation of trailer links of road trains or for some agricultural machines and special-purpose equipment, such difficulties cannot always be overcome. In this context, it is necessary to consider the fact that in the case when developers should make efforts to constructively resolve these difficulties, the situation, as a rule, turns into a significant decrease in the energy efficiency of the developed equipment in practice.

The current situation has turned into the fact that since the second half of the 20th century in a number of Western European countries, adjustable continuously variable transmissions have been actively used in development of the drive design of mechanical wheeled vehicles [12]. As such, electric and hydrostatic transmissions were mainly used, which have significant advantages over conventional mechanical transmissions. In particular, electric transmissions are distinguished by a higher overall efficiency (up to 85 %), ease of installation of the main elements and connections between the aggregate units. A lower value of the cost of electric transmissions has a significant impact on the use of relatively rare alloys and metals in their design. In terms of unit costs, electric transmissions are not significantly superior to hydrostatic transmissions. Mechanical wheeled vehicles with high cross-country capability, equipped with electric transmissions, have structural difficulties with the placement of elements of the air cooling system of electric vehicles, moreover, as with hydrostatic transmissions, the cooling of the body frame is carried out by pumping the working fluid directly through them [13]. The most important feature of an electric transmission should be considered its dynamic external characteristics, in which the internal automatic control is poorly controlled by the gear ratio. In turn, the hydrostatic transmission is much better adapted to automatic regulation, while not creating visible interference to radio communications. At the same time, transmission of this kind has some advantage over an electric one in terms of dimensions, since it is not so bulky.

When creating a mathematical description of the mechanical wheeled vehicle transmission operation, specific mathematical models, describing the operation of individual components of this transmission, should be considered. Such descriptions allow qualitatively assessing the amount of energy losses in transmissions of various kinds and the dependence of these losses on the selected transmission mode. A number of modern studies contain information on the operation of mechanical drives of various vehicles and on the dependencies of energy losses on various aspects of the functioning of these machines. At the same time, it is noted that the definition of such dependencies is fraught with significant difficulties, since there is a largely random nature of changes in the determining parameters that are important from the standpoint of describing the phenomenon of friction in the nodes of mechanical drives. In addition, the issues of describing the processes of viscous friction caused by the presence of lubricant are of considerable complexity from the standpoint of creating a qualitative mathematical description of this process [14].

The use of automatic control systems for the modes of operation of hydrostatic transmissions involves the use of a scheme that ensures the operation of transmissions of this kind in the mode of stable values of transmitted power. The result is a significant increase in the efficiency of such units, when they work on soils of medium and high load-bearing capacity, while when driving on the ground with a low coefficient of adhesion, a gradual increase in the rotational speed of the front wheels of a mechanical vehicle was observed with a slight torque [15]. At the same time, there was intensive milling of the soil under these wheels, a sharp increase in the depth of the natural track, which resulted in a decrease in the cross-country characteristics of this vehicle. This circumstance indicates the fact that the use of simple algebraic solutions, made without considering the quality of the coupling of the wheels of the drive axle with the ground, when creating a mathematical control model of hydrostatic transmissions, in most cases does not allow obtaining the desired result. Notably, to obtain it, it is necessary to conduct a comprehensive study of the automated object, involving the use of the most modern methods of mathematical modelling for qualitative verification of various operating conditions of the projected mechanical vehicles.

The development and industrial production of mechanical wheeled vehicles with low slip coefficient and characterised by increased cross-country ability, operating when placing hydrostatic transmissions on them, will be realistic only if they have no less working efficiency compared to similar models with mechanical-type transmissions, subject to the condition that their operational life will be completely sufficient to recoup all the possible costs associated with the need to equip them with hydrostatic transmissions. Achieving such results will be possible only if such transmissions are equipped with modern adaptive automatic control systems, which will be able to accurately select the mode of operation of the hydrostatic transmission from the entire variety of options offered, which can fully ensure the high efficiency of the entire system [16].

Currently, there is practically no production of mechanical wheeled vehicles with hydrostatic transmissions and all-wheel drive in industrial volumes. Dynamic studies of transmissions of this type were carried out at the highest scientific level, involving the development of complex mathematical models. At the same time, the disadvantage of these models was a weak reflection of the operating conditions of hydrostatic transmissions on mechanical transport vehicles that are in operational use at the moment. As a rule, these mathematical models served to describe the processes occurring directly in such machines themselves [17]. Transmissions of the described nature were mainly created using the power supply scheme of all the hydraulic motors from one common station, which implies the creation of a complete hydraulic differentiated drive for the entire driving wheels. At the same time, there was absolutely no provision for any blocking, both inter-wheel and inter-axle, which could contribute to a significant increase in the number of operational parameters of the vehicle.

The assessment of possible losses in various structural elements of a mechanical wheeled vehicle involves considering the functioning of such elements as a gearbox, transfer case, transmission, gimbal pivot and in this context, application of the recommendation is relevant, according to which the mechanical efficiency of various mechanical elements under different operating modes remains unchanged. This becomes possible only with the rectilinear movement of a mechanical machine with equal parameters for regulating the working surfaces and volumes of hydraulic motors [18]. The development of a system of equations necessary to perform a mathematical description of the operation of the hydrostatic transmission of the drive axle wheels under uniform loads involves the sequential creation of a number of algebraic expressions necessary to determine the parameters of losses in high-pressure pipelines and the values of pressure drops in hydraulic engines. At the same time, to calculate special coefficients characterising the magnitude of losses in hydraulic engines, it is necessary to develop special computer software that allows qualitative calculations of these parameters in a given unit of time [19].

Modern mechanical engineers have until recently experienced considerable difficulties with the design and creation of mechanical wheeled vehicles with low values of wheel slip coefficients of driving axles when making turns [20]. In the last few decades, significant progress has been made in this area, in connection with the development and industrial implementation of a hydrostatic transmission of wheels for driving axles of a number of special and transport vehicles [21]. In recent years, promising results have been achieved in terms of an increase in the maximum operating pressure in hydrostatic systems, which contributes to the overall improvement of the operational and mass-dimensional parameters of various elements included in the transmissions of this type [22]. The operating range of speed control of the hydraulic motor shaft is expanding, which improves operating conditions and allows obtaining an optimal combination of the parameters of the hydraulic motor shaft speed to the lowest possible speed of its rotation under load, which allows increasing the efficiency of the system as a whole [23].

In general, the issues of developing an effective model for calculating the slip coefficients of a mechanical vehicle with two steering axles require further research in connection with the introduction of various technical improvements in the design of both such machines themselves and their suspension and transmission elements, which favourably affect their performance characteristics in general.

5 Conclusions

In the course of studies of the kinematic characteristics of a mechanical wheeled vehicle with two driving axles, a mathematical model of equations was obtained for calculating the coefficients of slipping of such machines. Calculations of the slip coefficients of a mechanical wheeled vehicle are performed directly upon entering the turn. The results obtained indicate that there is a clear relationship between the parameters of the slip coefficients of a mechanical wheeled vehicle and the angles of rotation of the axles directly upon entering the turn, which necessitates considering these characteristics when designing the driving axles of such vehicles. In the event that the value of the slipping coefficient exceeds 0.2, there is no significant difference in the slipping of the wheels of the driving axles, since with an increase in the resistance to movement, conditioned by an increase in the angle of rotation of the axles, the traction forces on the wheels increase significantly, which leads to an increase in their slipping. At the same time, the redistribution of forces gradually aligns, regardless of the difference in normal reactions. This is conditioned by the fact that in this case, the plastic properties are already more characteristic of the soil than the elastic ones.

In general, the findings indicate that there is a clear relationship between changes in values of the wheel slip coefficients of a vehicle and the axles' rotation angles, including a number of other parameters that are important from the standpoint of the prospects for development of effective mechanical wheeled vehicles in the future. The results of this study and the conclusions formulated based on them, can serve as a qualitative scientific basis for subsequent research devoted to investigation of the construction of computational models of the slip coefficients of a mechanical wheeled vehicle with two or more steering axles.

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