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IMPROVING SAFETY OF MOVEMENT OF MINING TRANSPORT BY APPLYING WHEELS WITH COUNTER-FLANGE

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ПІДВИЩЕННЯ БЕЗПЕКИ ПЕРЕСУВАННЯ РУХОМОГО СКЛАДУ ГІРНИЧОРУДНОГО ТА ШАХТНОГО ТРАНСПОРТУ ЗА РАХУНОК ВИКОРИСТАННЯ КОЛІС ІЗ КОНТРГРЕБЕНЕМ

Purpose. Development of a wheel pair with wheels that provide protection against derailment due to counter-flanges and substantiation of efficiency of its applying at mining transport.

Methodology. Mathematical and simulation modelling of geometric, friction and dynamic parameters of contact interaction between the wheel and rail of the proposed wheel pair by applying difference equations, elements of theoretical mechanics, mechanical system dynamics, analytical geometry, etc.

Findings. The authors have proposed scientifically grounded engineering solution for designing the wheel pair that has wheels with counter-flange which satisfies the existing standards of vertical and horizontal dynamics and movement stability index. Results of calculations for coefficients of dynamics and transverse stability for the wheel pair with wheels that have counter-flange are the same as computational data for freight cars with all-rolled wheels over the range of 10–15 % and no more than standard values.

Improved contour of the rail wheel with counter-flange has been developed. It provides the additional contact in horizontal plane while transverse vibrations of the wheel pair relative to rail track and makes carriage more stable and increase the resisting force of the wheel against derailment when passing curved section of line.

Originality. Methods for creating working contour of wheels for special-purpose rolling stock that takes into consideration counter-flange at the rolling surface were further developed. Force interaction patterns of wheel pair with wheels that have counter-flange and side edge of rail top have been obtained for the first time. Relation that describes the influence of transverse force during performance of car on curves at contact of wheel with counter-flange with rail.

Practical value. The authors have developed a wheel pair for mining transport whose contour has the additional running track and counter-flange that protects against derailment when base flange of wheel rolls in working surface of rail or there is way spacer due to rail elastic deformation. The wheel pair design suggested is covered by Ukrainian patents for utility modal.

Keywords: *wheel pair, two-flange wheel, derailment, wheel flange, railway track*

Introduction. One of the main criteria for safety of freight transportation by mine vehicle is prevention of derailment which may have disastrous consequences.

This is one of the most important problems for the railway transport and it is a part of movement safety control problem. According to the work [1], decrease in the number of derailments is one of the main tasks in researching wheel-rail interaction.

The basic kinds of derailment include derailment due to the wheeling onto the rail [2] and track thrusting – railhead is pressed-out by one wheel flange due to its spring decline and the other wheel falling off another rail [3].

Consequently, it is important to create such elements of truck (elements of the wheel-rail system) that provide movement stability and preclude the possibility of wheel flange rolling onto railhead as well as feature counteraction to derailment when spring rail deflection [4]. Currently, there are no mathematical models and relations which take into account influence of additional elements on vehicle safety [5].

Analysis of the previous research. Analysis of research studies on wheel-rail interaction proves that dynamic movement parameters, overcoming resistance forces and safety of movement in transport mainly depend on the processes in wheel-rail contact. Scientific works of V. A. Lazaryan, Ye. P. Blokhin, G. I. Bogomaz, M. F. Verigo, S. V. Vershinskiy, V. D. Danovich, Yu. V. Dyomin,

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V. N. Ivanov, M. B. Keglin, M. B. Kelrikh, A. M. Konyaev, M. L. Korotenko, L. A. Manshkin, O. M. Pshinko, M. O. Radchenko, O. M. Savchuk, V. F. Ushkalov and those by foreign researchers F. Carter, K. Muller, H. Heyman, etc. are dedicated to different aspects of wheel-rail interaction.

Parameters of wheel-rail interaction in different zones are non-unique: firstly, wheel-rail interaction must provide low resistance to train movement and reduce friction between the wheel flange and the side surface of a railhead. Secondly, providing necessary tractive force requires providing quite a high level of wheel-rail adhesion [6].

Analysis of existing research studies on derailment [7] shows that this problem should be solved on the basis of a complex approach that includes improvement of wheel design that is, first of all, responsible for safety of movement.

Unsolved aspects of the problem. One of effective methods to achieve an objective is improvement of wheel pair design. The article proposes a new design of the wheel pair that provides prevention of derailment due to counter-flange and makes its operation possible upon the availability of track switches and other structural elements of mine track (Fig. 1).

The profile of the new wheel pair incorporates the following feature – it has the counter-flange in addition to the main flange. The rolling surface is connected with the counter-flange by ease curve with a curve radius in transfer points R_2, R_3, R_4 and creates extra rolling profile. The overall width of the rim of the wheel is increased due to the rail width and free split (Fig. 1). Extra-profile allows the wheel to return to the standard position at tread circle due to the curved surface. The height of the counter-flange, which is less relatively to wheel tread circle, does not allow the wheel to contact track switch and other equipment of the rail track [8].

In the case of emergency, when one wheel of the wheel pair rolls onto railhead by its inner flange, the other wheel contacts the outer side due to the counter-flange and creates a force that reacts against derailment. It is noteworthy that wheel rolling on extra-profile is emergency cycle of operation.

Researching the efficiency of derailment prevention due to the counter-flange is a task and content of the present paper.

Objective of the article. Creation of the wheel pair for mine vehicle that has the wheels that provides prevention of derailment due to counter-flange and substantiation of its efficiency on the basis of mathematical and simulation modelling of interaction of wheel profile geometry, dynamics of contact interaction with the use of differential equations, elements of theoretical mechanics, analytical geometry, etc.

Presentation of main research. Mathematical formulation of wheel-rail force interaction during movement is performed considering its changes in plan, i.e. in curved parts of track. This calculation is based on the model of the wheel pair that has a counter flange to prevent derailment.

When calculating normal forces of wheel-rail interaction, their contacts areas are presented as points *A* and *B* (Fig. 2).

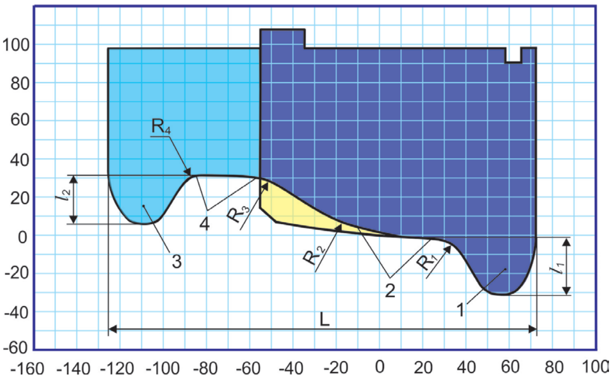


Fig. 1. Comparison of profiles of the standard solid-rolled wheel and the proposed wheel:

■ + □ – *solid-rolled wheel profile (National State Standard 9036-76);* ■ + ▨ – *proposed wheel with counter-flange; 1 – inner solid-rolled flange of wheel; 2 – the main rolling profile; 3 – counter-flange;* R_1, R_2, R_3, R_4 – *curve radius in transition sections of the curved surface that connects the counter-flange and the wheel; 4 – extra rolling profile*

A part of centrifugal force of inertia C_T acts on the bogie. This force depends on movement speed and directs from the side of exterior rail Y_1 [9]

$$C_T = 2m\pi\left(\frac{\upsilon^2}{gR} - \frac{h}{2s}\right),$$

where h is raise of the exterior rail, presented as $h = 2s\upsilon^2/gR = 12.5\upsilon^2/R$; m is the number of bogie axles; $g = 9.81$ m/s^2 – acceleration of gravity (free falling); $2s$ is the distance between taping lines of the wheel pair; υ is the movement speed; R is the curve radius in curved part of track.

Force of inertia can be represented as H_i [9]

$$H_i = \frac{P_w\upsilon^2}{gR},$$

where P_w is carriage shipping weight (kg); υ is the movement speed, m/s; R is the radius of curve, m.

We will use the concept of outstanding acceleration instead of centrifugal force [9]

$$a_c = \frac{\upsilon^2}{R} - \frac{h}{2s}g,$$

where $a_c = 0.7$ m/s^2 is considered as overload capacity.

Force of wheel compression on the rail head is calculated according to the formula

$$Y = A\left(4k\frac{l_T}{R}\right) + BF_{TK} + C\frac{H_i}{2},$$

where *A, B, C* are observed adjustment coefficients that take into account the impact of the assumptions introduced; k is the creep coefficient (pseudo sliding) $k = (60 \div 80)\sqrt{Nr}$ (N is loading, normal pressure at the contact point; r is the wheel radius); l_T is half the dis-

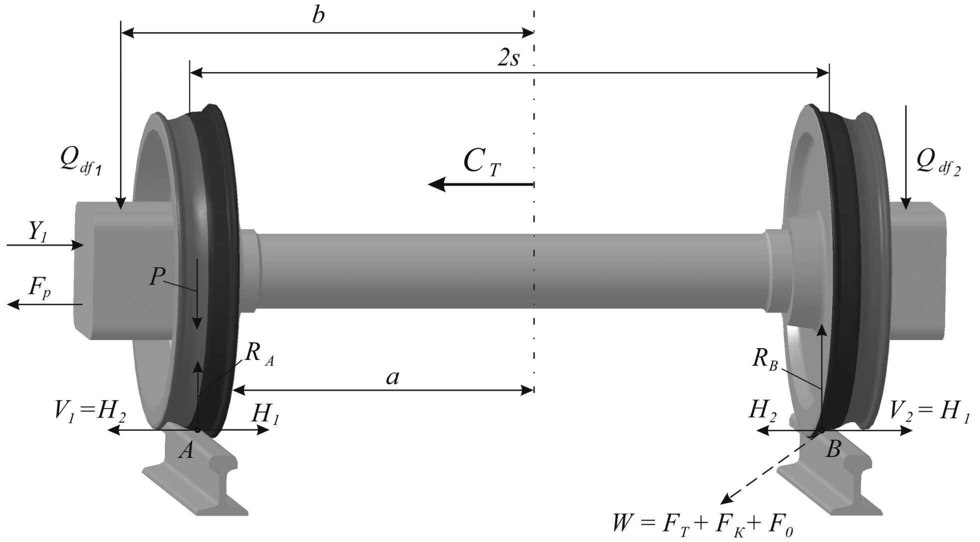


Fig. 2. Analytical model of is the wheel pair that has the wheels with counter-flange loaded with static and dynamic components of forces:

■ is the main profile of the wheel; ▨ is an extra profile of the wheel; H_1 is the side pressure on the wheel that guides (overruns); H_2 is a component of frictional force [8]. V_1, V_2 are the forces generated when counter-flange contact

tance between neighbouring axles of the wheel pairs; R is the radius of curvature made from the curve centre through the centre of gravity of the wheel pair to the outer rail; $F_{TK} = N \cdot \mu$ is lateral friction force of the wheel on rails (0.25), it can change according to the weather and physic-chemical parameters of the surface; N is vertical loading of wheel on rail).

The rail lateral pressure on the overrunning wheel H_1 is presented as total forces Y_p, Y_i and H_2 according to [9]

$$H_1 = Y_p + Y_i + H_2,$$

where $Y_p = k_h Q/2$ is the lateral pressure of the frame on the wheel pair ($k_h = 0.3 \div 0.6$ is the coefficient of frame pressure that depends on dynamic parameters of the carriage in the horizontal plane, movement speed and track condition; Q, kgf, wheel pair static loading on the rail); $Y_i = 2\left(1-\delta\right) j_h \frac{Q}{2}$ is the lateral force of inertia of the wheel pair and rigidly connected parts which occurs when passing horizontal track inequalities ($\delta = 0.65 \div 0.9$ is the amortization coefficient in the vertical plane; j_h is the acceleration coefficient of the wheel pair); $H_2 = fQ/2$ is the lateral component of friction force between inside wheel and the rail ($f = 0.15 \div 0.25$ is the friction coefficient between the wheel and rail).

Provided a balanced state of the car, the vertical reaction force R_A of the outer rail to the car wheel is [9]

$$R_A = (1/2s)[Q(s - h_c\theta) + P_c h_c + P_w h_w - P_h h_h],$$

where Q is the car weight; $2s$ is the distance between taping lines of the wheel pair; h_c, h_w, h_h stand for height of force points above the level of rail heads, correspondingly P_c, P_w, P_h; θ is the car inclination (rolling motion); P_c, P_w are centrifugal force ($P_c = C_T$) and wind pressure force, correspondingly; $P_h = \psi h N$ is the horizontal cross component of force N (according to calculate norms $N \leq 2{,}5MN$) in connection ($\psi_h = L_c/R$ is the angle between longitudinal axles of car body and adhesion at curve part of track in radius of R).

Horizontal force of dynamic pressure of the wheel on the rail head P_B and vertical force P_w are used to calculate pressure force of the wheel on the rail [9]

$$P_B = 2Q_{st}\left[\frac{b-a_{1,2}}{l}\left(1-k_{dw}\right) \pm \frac{b}{l}k_{drm}\right] \pm F_p\frac{r}{l} + q_{wp}\frac{b-a_{1,2}}{l},$$

where Q_{st} is the static loading on the neck of axle; q_{wp} is the wheel pair weight ($q_{wp} = m\kappa_{ng}$); k_{dw} is the coefficient of dynamics due to vertical oscillations of carriage

$$k_{dw} = \frac{Q_{df1} + Q_{df2}}{2Q_{st}};$$

k_{drm} is the coefficient of dynamics due to body rolling motion

$$k_{drm} = \frac{Q_{df1} - Q_{df2}}{2Q_{st}};$$

Q_{df1} and Q_{df2} are dynamic vertical forces acting on the neck of axle;.F_p is the force acting from the frame; b is half of the distance between the axles of spring groupings of the car; a is the distance between the wheel flanges of the wheel pair.

External friction force in the contact zone is presented as

$$W = F_T + F_k + F_0,$$

where F_0 is the sliding frictional force $F_0 \leq N f_{tr}$ (N is the normal force acted at the wheel; f_{tr} – is the wheel-to-rail traction coefficient); F_T is the dry friction force: $F_T = \mu N$ (μ is the dry friction coefficient (0.25); N is the normal pressure force at the point of the rail-road contact); F_k is the friction force of the wheel rolling along the rail $F_k =$

$=\left(G+G_{cr}\right)\frac{2k}{D}$. ($G$ and G_{cr} is the weight of cargo and carriage, D is the wheel diameter on tread circle; k is the friction coefficient of the wheel rolling along the rail).

The numerical implementation and analysis above show that providing stable movement of the wheel that has a counter-flange requires taking into consideration interdependency of individual components of their force interaction in the design: the friction coefficient in the wheel-rail contact, the angle of inclination of the wheel flange, forces of wheels that roll onto and off, car axle-loads, weight of a train, movement speed, sliding forces, temperature, specific pressure in the wheel and the rail rolling surface contact point [10]. Redistribution of forces due to applying counter-flanges that prevent crawling (sliding) of wheels on the rail head must be taken into consideration in addition to classical distribution of forces.

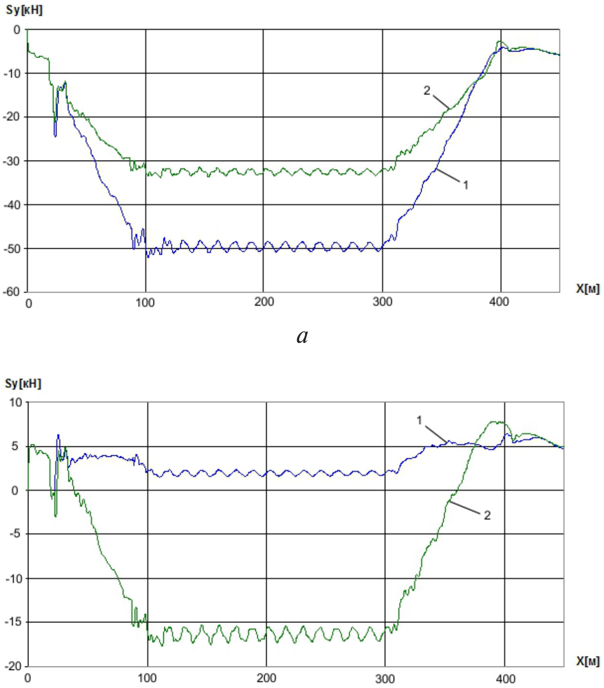
To check the efficiency of the wheels with additional counter-flange the authors have performed simulation modelling of movement of a loaded tank-car along the right curved track of 300 m radius. To receive demonstrable data, the following assumptions were chosen:

- length of curve – 400 m (100 m of in-coming curve + 200 m of circular curve + 100 m of elution curve);
- movement speed was chosen to be higher than acceptable for such curves;
- rails without unevenness;
- the distance between the outer side of rail and the additional flange δ_h – 15 mm.

To analyse the process of interaction of wheels that have counter-flange with the rails, the following oscillograms were recorded while modelling:

- lateral assignment of the first in the direction of the motion wheel pair;
- lateral forces of interaction of the first wheel pair and the left rail;
- lateral forces of interaction of the firs wheel pair and the right rail.

Oscillograms of lateral assignment of the first wheel pair are illustrated in Fig. 3.



a

b

Fig. 3. Oscillograms of lateral forces of interaction of left (a) and right (b) wheel of the first wheel pair with left and right rail correspondingly

Lines 1 illustrate the wheel without additional flange and lines 2 show the wheel with the additional flange.

Demonstrated results show cross movement of the wheel pair along the track. At first, the left wheel moving along the transition part at the beginning of curve ($0 < X < 100$ m) comes close and presses to the outer rail. Then moving along circular curve (100 m $< X < 300$ m) the left wheel is fully pressed to the outer rail and keeps moving to the left, rolling onto the rail. Finally, when coming out of the curve (300 m $< X < 400$ m), the wheel gradually extends away from the outer rail and returns inside the tack. Modelling results prove the efficiency of applying the wheel pair with counter-flange. It improves carriage stability and increases the resistance against derailment when passing curve parts of the track.

Conclusions and prospects for further development.

1. The authors have developed a wheel pair for mine transport that profile has the additional running track and counter-flange that provides the additional contact in a horizontal plane while lateral vibrations of the wheel pair relatively to the track, provides the stability and increases the resistance against derailment when passing curved part of the track and in the case of spring deflection of the rail as a result of force interaction.

The design of the wheel pair that has the additional counter-flange is covered by Ukrainian patents for utility modal.

2. Providing stable wheel movement on the rail requires taking into account interdependence of geometrical, frictional and dynamical parameters of the wheel-rail interaction at the stage of designing. It is necessary to consider redistribution of forces due to presence of the wheels with counter-flange in addition to classic distribution of forces in the wheel-rail contact zone.

3. The authors have found analytic dependencies for wheel pairs with the wheels that have counter-flange that characterize influence of lateral forces on stability of movement under the conditions of counter-flange and rail contacting.

4. The efficiency of applying the wheel pair with counter-flange has been proved on the basis of mathematical and simulation modelling of geometrical, frictional and dynamical parameters of interaction of the wheel pair that has the wheels with counter-flange. It increases stability and resistance to derailment when passing curved parts of the track.

5. Implementation of the proposed wheel pair that has counter-flange at mine transport and special-purpose rolling-stock will provide improving safety of movement and carriage integrity as well as social and

economic effect due to decrease in emergency and disastrous consequences.

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Мета. Створення колісної пари, що має колеса з захистом від сходу з рейкової колії у вигляді контргребенів, та обґрунтування ефективності її використання для рухомого складу гірничорудного й шахтного транспорту.

Методика. Математичне та імітаційне моделювання геометричних, фрикційних і динамічних параметрів контактної взаємодії колеса з рейкою запропонованої колісної пари з використанням диференційних рівнянь, елементів теоретичної механіки, динаміки механічних систем, аналітичної геометрії тощо.

Результати. Запропоноване науково-обґрунтоване технічне рішення конструктивного виконання колісної пари, яка має колеса з контргребенем, що відповідає існуючим нормам за критеріями вертикальної та горизонтальної динаміки, а також показникам стійкості руху. Результати розрахунку коефіцієнтів динаміки й поперечної стійкості для колісної пари з колесами, що мають контргребінь, збігаються з розрахунковими, даними для вантажних вагонів із суцільнокатаними колесами в межах 10–15 % і не перевищують нормативних значень.

Розроблено вдосконалений профіль залізничного колеса з контргребенем, що забезпечує додатковий контакт у горизонтальній площині при поперечних коливаннях колісної пари відносно рейкової колії, додає екіпажу стійкості та збільшує сили опору коліс проти сходу з рейок при проходженні криволінійних ділянок колії, а також при пружному відхиленні рейок у результаті силової взаємодії.

Наукова новизна. Отримала подальший розвиток методика створення робочого профілю коліс для спеціального рухомого складу, що враховує контргребінь на поверхні кочення. Уперше отримані закономірності силової взаємодії колісної пари з колесами з контргребенем та бічної грані головки рейки. Уперше отримана залежність, що характеризує вплив поперечних сил при вписуванні екіпажу у криві при контакті колеса з контргребенем із рейкою.

Практична значимість Розроблена колісна пара для рухомого складу гірничорудного й шахтного транспорту, профіль якої характеризується наявністю додаткової доріжки кочення та контргребеня, що забезпечує протидію сходу колісної пари з рейок у той час, коли основний гребінь колеса вкочується на робочу поверхню рейки або має місце розпір колії в результаті пружної деформації рейок. Запропонована конструкція колісної пари захищена патентами України на корисну модель.

Ключові слова: *колісна пара, контргребінь, схід з рейок, гребінь колеса, рейкова колія*

Цель. Создание колесной пары, которая имеет колеса с защитой от схода с рельсового пути в виде контргребней, и обоснование эффективности ее использования для подвижного состава горнорудного и шахтного транспорта.

Методика. Математическое и имитационное моделирование геометрических, фрикционных и динамических параметров контактного взаимодействия колеса с рельсом предложенной колесной пары с использованием дифференциальных уравнений, элементов теоретической механики, динамики механических систем, аналитической геометрии и т.д.

Результаты. Предложено научно-обоснованное техническое решение конструктивного исполнения колесной пары, которая имеет колеса с контргребнем, что соответствует существующим нормам по критериям вертикальной и горизонтальной динамики, а также показателям устойчивости движения. Результаты расчета коэффициентов динамики и поперечной устойчивости для колесной пары с колесами, имеющими контргребень, совпадают с расчетными данными для грузовых вагонов с цельнокатаными колесами в пределах 10–15 % и не превышают нормативных значений.

Разработан усовершенствованный профиль железнодорожного колеса с контргребнем, что обеспечивает дополнительный контакт в горизонтальной плоскости при поперечных колебаниях колесной пары относительно рельсового пути, добавляет экипажу устойчивости и увеличивает силы сопротивления колес против схода с рельсов при прохождении криволинейных участков пути, а также при упругом отклонении рельсов в результате силового взаимодействия.

Научная новизна. Получила дальнейшее развитие методика создания рабочего профиля колес для специального подвижного состава, которая учитывает контргребень на поверхности качения. Впервые получены закономерности силового взаимодействия колесной пары с колесами с контргребнем и боковой грани головки рельса. Впервые получена зависимость, характеризующая влияние поперечных сил при вписывании экипажа в кривые при контакте колеса с контргребнем с рельсом.

Практическая значимость. Разработана колесная пара для подвижного состава горнорудного и шахтного транспорта, профиль которой характеризуется наличием дополнительной дорожки качения и контргребень, что обеспечивает противодействие схода колесной пары с рельсов в то время, когда основной гребень колеса вкатывается на рабочую поверхность рельса или имеет место распор пути в результате упругой деформации рельсов. Предложенная конструкция колесной пары защищена патентами Украины на полезную модель.

Ключевые слова: *колесная пара, контргребень, сход с рельсов, гребень колеса, рельсовый путь*

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EFFECT OF ANTILOCK BRAKE SYSTEM ON BASIC PARAMETERS OF TRANSPORT VEHICLE TRANSMISSION

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ВПЛИВ АНТИБЛОКУВАЛЬНОЇ СИСТЕМИ НА ОСНОВНІ ПАРАМЕТРИ ТРАНСМІСІЇ ТРАНСПОРТНОГО ЗАСОБУ

Purpose. The objective of the paper is to study antilock brake systems (ABS) effect upon the basic parameters of hydrostatic mechanical transmission (HMT) in the process of emergency braking.

Methodology. The research has involved current methods of solving differential equations of mathematical model of transport vehicle braking process as well as the comparing methods to analyze braking process involving ABS and emergency braking at the expense of braking system in terms of kinematic disconnection of engine from a driving wheel with HMT of various schematic designs.

Findings. As a result of the complex theoretical research, the effect of ABS upon operating pressure differential within hydrostatic drive, angular velocity of hydraulic pump shaft, range of values of angular velocity and driving and driven clutch shafts, braking efficiency of a transport vehicle, and transport vehicle deviation from the specified trajectory have been determined.

Originality. It is the first time when quantitative assessment of ABS effect upon HMT kinematic and power parameters has been performed; it allows increasing technical level of transmissions even at the wheeled vehicle design stage at the expense of timely considering of possible overload occurring while operating in the process of ABS braking.

Practical value. The proposed methods and applied mathematical models have made it possible to develop the approach to determine and take into account possible HMT overloads arising in terms of wheel transport vehicle with ABS braking even within the design period.

Keywords: *hydrostatic and mechanical transmission, transmission, wheel transport vehicle, braking process, controllability, braking efficiency*
