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Svitlana Sapronova[1], Viktor Tkachenko[2], Nadiya Braykovska[3], Ivan Kulbovskyi[4]

[1]Professor, Department of Wagons and Wagon Management, State University of Infrastructure and Technologies, 9 Kyrylivska St., Kyiv, 04071, Ukraine. https://orcid.org/0000-0002-1482-1665

[2] Professor, Department of Electromechanics and Railway Rolling Stock, State University of Infrastructure and Technologies, 9 Kyrylivska St., Kyiv, 04071, Ukraine. https://orcid.org/0000-0002-5513-2436

[3]Professor, Department of Wagons and Wagon Management, State University of Infrastructure and Technologies, 9 Kyrylivska St., Kyiv, 04071, Ukraine. https://orcid.org/0000-0003-1556-4020

[4]Associate professor, Department of Automation and Computer-Integrated Transport Technologies, State University of Infrastructure and Technologies, 9 Kyrylivska St., Kyiv, 04071, Ukraine. https://orcid.org/0000-0002-5329-3842

Author responsible for correspondence: doc.sapronova@gmail.com

Study of guiding vehicle by railway track

The analysis of scientific publications related to the guiding of wheelsets of railway rolling stock along the rail track has been carried out. It is stated that for a valid simulation of the guiding of wheelsets by a rail track, an accurate description of the contact forces of adhesion is necessary. It was found that the flange wheel-rail contact exists only in combination with the angle of attack and in the presence of a lateral cohesive force. A scheme of power interaction of a wheelset with rails with a ridge contact of one of the wheels has been developed. The force contact interaction of a wheel and a rail is a process that is difficult to describe and, at the same time, very important for studying the dynamics of the frictional interaction of vehicles and track and the guiding of vehicles by the rail track. In the general case, the contact of the wheel with the rail occurs in two contact zones: on the rolling surface and on the flange. Simplified, the contact is considered as a two-point contact. The considered force factors cannot be unambiguously attributed to guiding factors or factors of resistance to movement. Specific values and guiding of forces and moments depend on the position of the wheelset relative to the rail track. It is argued that the longitudinal and transverse slips of the wheelsets cause resistance to movement and are overcome by guiding forces.

Key words: *guiding vehicle by railway track, wheelset, rolling stock, flange reactions, contact adhesion forces.*

Introduction. In the initial period of railway development, the issues of wheel-rail adhesion were considered exclusively in connection with the traction qualities of the rolling stock.

A large number of studies have been devoted to increasing the maximum traction force for adhesion. Their main goal is a more complete implementation of the propulsion function in a wheel-rail system. However, the problem of wheel-rail adhesion is much deeper than his analysis in terms of traction. Wheel-rail adhesion must be considered comprehensively, taking into account the full picture of the horizontal forces of interaction between the vehicle and the track. In particular, it should be taken into account that the horizontal components of the contact forces determine the horizontal dynamics of the vehicle. And in this sense, it would be appropriate not to single out, as separate problems, longitudinal phenomena associated with cohesive qualities, but transverse ones associated with horizontal transverse dynamics.

It is necessary to consider these phenomena jointly within the framework of full horizontal dynamics. Attempts to treat the issues of longitudinal and transverse cohesion as separate from each other, or at best as partially related, often lead to errors in the results of studies. For example, constructive improvements in dynamic performance can lead to a deterioration in other indicators: an increase in resistance to movement; increasing the intensity of wear of rolling surfaces of wheels, etc.

Analysis of recent research and problem statement. The monograph by H. Heyman can be considered the first fundamental study of the direction of carriages by a rail track. Heyman noted that the deviation of the movement of wheelsets from the trajectory of pure rolling can only be observed in the form of sliding. According to him, the main reason for longitudinal slips in wheel-rail contacts is the rigid connection of the wheels in the wheelset through the axle.

When driving in curved sections of the track of a large radius, due to the conical shape of the wheels in the wheelset, the guiding forces between the wheel flanges and the rails are reduced. But, in curves of medium and small radius, the taper of the rolling surfaces is not sufficient, which causes the wheels to slip in the longitudinal direction. Longitudinal sliding forces cause an increase in the misalignment of the wheelset axis relative to the track axis and, as a result, an increase in the angle of attack of the wheels on the rail heads. An increase in the angles of attack is the cause of an increase in transverse reactions in wheel-rail contacts and additional resistance to movement. An indirect confirmation of this is the characteristic screech when the crew moves in curves. The results of studying this phenomenon are given in the article [1].

The authors of the article [3] used the theory of closed power circuits to describe the three-point contact of the wheelset with the rails. The article notes that in the system of contacting the wheelset with the rails there is a closed power circuit with nodal points in the main and flanges contacts. The characteristic for closed power circuits in wheel-rail contacts is parasitic sliding, which is the cause of additional power losses and wears on the rolling surface of wheels and rails. Wheelsets and rail together form separate closed power circuits. The contacts of the wheels with the rails are the nodal points in the power circuits “rail–wheel–axis–wheel–rail–sleeper”. Parasitic power flows can occur in interaxle closed power circuits of bogies. Parasitic power circulation in closed power circuits can reach significant values and is the cause of additional resistance to the movement of vehicles. The authors classify this resistance as “kinematic resistance to motion”.

When driving in tangent track, due to the horizontal irregularities of the rails and the conical shape of the wheel tread surfaces, intense self-oscillations of wheel sets hunting can occur with periodic contact of the flange of the right and left wheels of the wheelsets with the rails [3]. At a high speed of movement, the transverse loads on the rails increase and can reach significant values [4, 5]. This leads to intensive wear of the wheel flanges, increased resistance to movement and creates a risk of loss of stability.

Railway rolling stock belongs to a subgroup of land vehicles that are guided by guide rails. The rails provide vertical support for the vehicles and guide the wheelsets along the trajectory. Large values of interaction forces in the wheel-rail contacts can lead to the destruction of track components [6, 7, 8].

Therefore, an accurate description of the contact forces in the wheel-rail system is necessary for theoretical studies of the guiding wheelsets by the rail track.

When considering the process of guiding vehicle by railway track, ensuring stability against derailment of wheelsets is the most important task.

As is known, the criterion for the tendency of a wheelset to derail is the ratio between the lateral and vertical loads in the flange wheel-rail contact. This ratio proposed by *Nadal* has been refined many times, for example, in the studies of such scientists as *Shabana* [9], *Weinstock* [10], *Ohno* [11] and others.

The forces acting in wheel-rail contacts in the horizontal plane have a complex structure.

In Shahzamanian Sichani's dissertation [12] a new method is proposed which results in more accurate contact patch and pressure distribution estimation while maintaining the same computational efficiency. The experience gained through this Licentiate work illuminates future research directions among which, improving tangential contact results and treating conformal contacts are given higher priority. The dissertation also provides an analysis of the main types of derailment of rail crews. Three of them are related to the characteristics of the rail track, and two are related to the shape of the wheel and rail profile. It has been confirmed that the angle of inclination of the wheel flange is the main geometric parameter that affects the probability of derailment of vehicles.

Results of experimental studies of experimental investigation of transient traction characteristics in rolling-sliding wheel-rail contacts under dry-wet conditions are given in the article [13].

The authors of the study [14] provide statistical data and analyze the causes of large-scale railway accidents. The importance of ridge contact studies as the main safety factor is emphasized. As a quicker method, authors propose to estimate the derailment coefficient from analytically calculated lateral and vertical wheel loads, based on analytic equations and measured data. This paper describes the equations used, shows how the derailment coefficient is calculated, and compares it with the results achieved by measurements.

The paper [15] proposes a mathematical model for assessing safety by derailment of a wheelset. Loads in the wheel-rail contact take into account centrifugal forces, rail irregularities and deformations of the spring suspension of a railway vehicle. A method was proposed for calculating the critical safety factor, taking into account the angle of attack of the wheel on the rail and the equivalent coefficient of friction. This study of traffic safety and comfort is based on the results of numerical simulation of a nonlinear model of the movement of railway rolling stock along a straight track. Traffic safety is investigated in accordance with the UIC 518 code: through the ratio of the transverse Y to vertical Q forces at the point of contact of the wheel with the rail. The lateral and vertical accelerations of the vehicle body to which a passenger of a railway vehicle is subjected are used to assess ride comfort in accordance with the ISO 2631-1 standard. The influence of various parameters of the "railway transport - way" system on traffic safety and traffic comfort is analyzed.

It is believed that the coefficient of friction in contact between the wheel flange and the rail has a strong influence on the derailment of wheelsets. However, the coefficient of friction varies greatly depending on the condition of the wheel-rail contact, atmospheric conditions, speed, etc. It is also considered that the direct measurement of the coefficient of friction is very difficult. The authors of the article [16] managed to obtain data on the derailment of wheels during the practical operation of electric trains. The experiments were carried out on a curved section of the track with a radius of 100–110 m. Such quantities as the derailment coefficient, the angle of attack of the wheel on the rail, and the separation of the wheel from the rail were measured. As a result of the experiments, it was found that reducing the coefficient of friction in the contact between the flange and the wheel (lubrication) is an effective means of reducing the derailment coefficient according to the Nadal criterion.

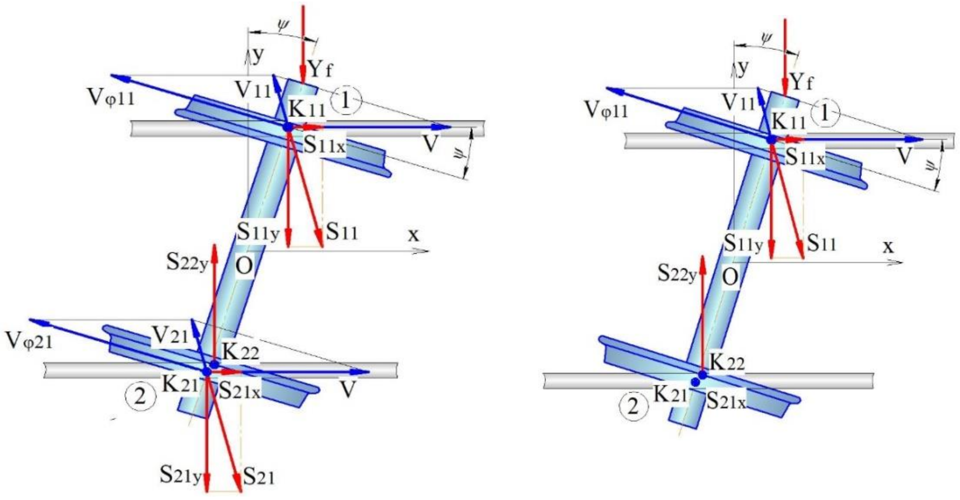
The purpose and tasks of the study. The purpose of the study is to refine the mathematical description of wheel-rail reactions based on the scheme of three-point contacting of wheelsets and rail track.

Therefore, the following tasks were set: analysis of scientific research on the guiding vehicle by railway track; study of kinematics and dynamics of wheel-rail contact; mathematical description of contact forces and adhesion forces in a wheel-rail system.

Materials and methods of research. As a rule, many scientists use a two-point wheel-rail contact model when modeling the interaction of vehicles with a rail track. However, in fact, it is correct to consider the complex picture of the contact of the wheelset with the rail track, and not the individual wheel with the rail. This approach was substantiated by the co-authors of this article in [17].

It is a typical case when the flange contact is combined with of the angle attack and the flange friction force. The following shows a picture of the force interaction of the wheelset with the rails during the flange contact of the one wheel. The movement of the wheelset is modeled in the skewed position in the rail track with of the angle attack ψ. On fig. 1 shows the vectors of speeds in the contacts of the wheelset with the rails. vectors are represented as projections of speeds and forces on the horizontal plane Oxy. Two cases of contact are shown: with a three-point contact of the wheelset with the rails (contacts K11, K21, K22) (fig 1a) and with two-point contact of the wheelset with the rails, when the second wheel comes off the main contact K21 (fig 1b).

The case is considered when the approaching wheel is in the state of derailment. As a starting condition, the equality of zero load in the main contact of the running wheel is accepted.



a) *b)*

Fig 1. **Vector scheme of velocities and forces in the wheelset-rails contacts: a) with three-point contact of the wheelset with the rails; b) at the moment of separation of the main contact of the second wheel from the rail**

When modeling the kinematic characteristics of the wheelset-rails contact, the following parameters and their designations are considered:

V – is the velocity movement of the wheelset center along the track axis;

$V_{\varphi 11}$, $V_{\varphi 21}$ – is the circumferential velocity of the wheel at the contacts K_{11}, K_{21}, associated with the rotation of the wheelset relative to its own axis;

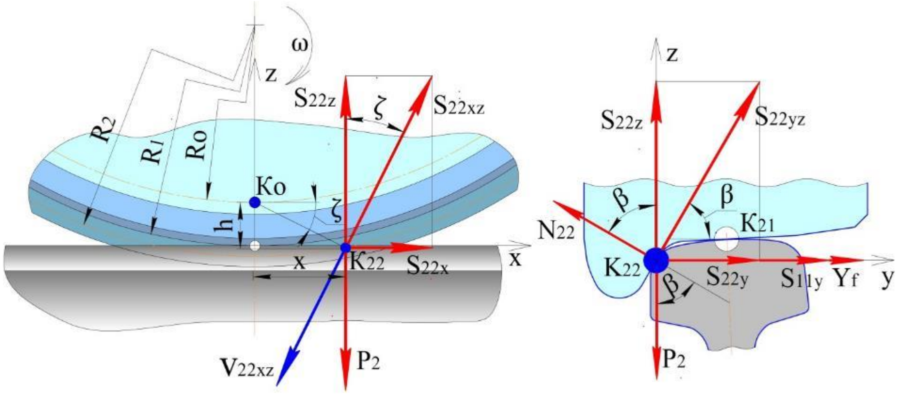
V_{11}, V_{21} – wheel sliding velocity on the rail at the contact points K_{11}, K_{21};

Y_f – axial reaction in the axle assembly acting on the wheelset – frame force;

S_{11y}, S_{22y} – projections of friction forces S_{22} in contacts K_{11}, K_{22} on the Oy axis;

S_{11}, S_{21}, S_{11x}, S_{11y}, S_{21x}, S_{21y}, S_{22y} – friction force and projections of friction force in contacts K_{11}, K_{21}, K_{22} respectively, on the Ox, Oy axis;

On fig. 2 shows a diagram of the contact forces in the flange contact in projections onto the later vertical plane Oxz and the transverse vertical plane Oyz.



а) б)

Fig.2. **Projections scheme of forces in the flange contact: a) projections onto the longitudinal vertical plane Oxz; b) projections onto the transverse vertical plane *Oyz* [17]**

On fig. 2 advancing signs are accepted:

ζ – angle, which determines the position of the vector S_{22xz} along the vertical axis;

β – flange angle;
ω – angular speed of rotation of the wheel around its axis;
N_{22} – normal load in the flange contact K_{22};
K_0 – instantaneous center of the wheel rotation;
R_0 – the distance from the wheel center to the instantaneous center of the wheel rotation K_0;
R_1, R_2 – the radius of the wheels in the main and flange contacts;
P_2 – vertical load in the flange contact K_{22}.

In general, the total horizontal side load in the flange contact K_{22} is equal to the sum of the frame force Y_f and the contact forces S_{11y}, S_{21y} in the contacts K_{11}, K_{21}:

In general, the total guiding force Y acting on the wheelset is equal to the sum of the frame force Y_f and the contact forces S_{11y}, S_{21y}, S_{22y} in the contacts K_{11}, K_{21}, K_{22}:

$$Y = S_{22y} - Y_f - S_{11y} - S_{21y}, \tag{1}$$

At the moment of separation of the second wheel from the main contact, the total guiding force increases:

$$Y = S_{22y} - S_{11y} - Y_f. \tag{2}$$

Contact forces S_{11y}, S_{21y}, S_{22y} in contacts K_{11}, K_{21}, K_{22} in the control theory of wheeled machines are called guiding forces. Guiding forces are frictional forces and are directed opposite to the corresponding sliding velocity vectors V_{11y}, V_{22y}.

Thus, the guiding forces in the main contacts when the wheelset is misaligned are the forces of the negative guiding, which impede the process of reliable guidance the wheelsets by rail track. In fact, reducing the vertical load in the main contact (up to the separation of the main contact from the rail) on the oncoming wheel improves the conditions for guiding the wheelset by rail track.

The moment of guiding forces in the horizontal plane M is an additional factor that affects the process of guiding wheelsets by rails. Accounting for the moment of guiding forces is especially important at large misalignment angles of the wheelset. The moment of guiding forces in the horizontal plane can be determined by the following formula:

$$M = \left[(-S_{11y} + S_{21y} - S_{22y} - Y_f)\cdot\psi - S_{11x} - S_{21x}\right]\cdot s. \tag{3}$$

The forces S_{11y}, S_{21y} can be approximately determined by the formulas of Coulomb's law. At the same time, the most dangerous case in terms of derailment is considered, when the angle ζ=0.

$$S_{11y} = P_0\cdot\mu; \quad S_{22y} = N_{22}\cdot\mu\cdot cos\beta, \tag{4}$$

where P_0 – is the vertical load in the contact K_{11} at the moment of separation of the second wheel from the main contact (P_{11}=P_0);
μ – the coefficient of sliding friction in the wheels-rails contacts.

Then

$$Y = \mu\cdot\left(N_{22}\cdot\cos\beta - P_0\right) - Y_f \tag{5}$$

he force contact interaction of a wheel and a rail is difficult to describe, but a very important issue for studying the direction of vehicles on a rail track. In the general case, the contact of the wheel with the rail occurs along two contact planes: on the rolling surface and on the flange. Simplified, the contact is considered as a two-point contact. At the same time, the main vector of contact forces interaction of the *i*-th wheel (*i*=1 – for the left wheel, *i*=2 – for the right wheel), the *j*-th wheelset, the *k*-th bogie with the rail has the following structure.

$$\vec{F}_{ijk\mathrm{I}} = \vec{N}_{jk\mathrm{I}} + \vec{N}_{jk\mathrm{II}} + \vec{S}_{jk\mathrm{I}} + \vec{S}_{jk\mathrm{II}}, \qquad (6)$$

where $\vec{N}_{jk\mathrm{I}}$, $\vec{N}_{jk\mathrm{II}}$, $\vec{S}_{jk\mathrm{I}}$, $\vec{S}_{jk\mathrm{II}}$ – main vectors of normal reactions and adhesion force of the first (main) and second (comb) contacts

$$\vec{N}_{ijk\mathrm{I}} = \vec{P}_{ijk\mathrm{I}} + \vec{H}_{ijk\mathrm{I}}; \quad \vec{N}_{ijk\mathrm{II}} = \vec{P}_{ijk\mathrm{II}} + \vec{H}_{ijk\mathrm{II}}, \qquad (7)$$

where $\vec{P}_{ijk\mathrm{I}}$, $\vec{H}_{ijk\mathrm{I}}$, $\vec{P}_{ijk\mathrm{II}}$, $\vec{H}_{ijk\mathrm{II}}$ – vertical and horizontal transverse components of normal contact reactions, and

$$H_{ijk\mathrm{I}} = P_{ijk\,\mathrm{I}} \cdot g_{ijk\mathrm{I}}; \quad H_{ijk\mathrm{II}} = P_{ijk\,\mathrm{II}} \cdot g_{ijk\mathrm{II}}, \qquad (8)$$

where $g_{ijk\mathrm{I}}=tg(\gamma_{ijk\mathrm{I}})$, $g_{ijk\mathrm{II}}=tg(\gamma_{ijk\mathrm{II}})$ – conditional tapers of wheel profiles at the corresponding contact points;
$\gamma_{ijk\mathrm{I}}$, $\gamma_{ijk\mathrm{II}}$ – obliquity to the horizon of tangents at the corresponding points of wheels-rails contact.

Static vertical wheel load:

$$P_0 = P_{ijk\,\mathrm{I}} + P_{ijk\,\mathrm{II}}. \qquad (9)$$

The total gravitational component $\vec{H}_{ijk}$ from two contacts of one wheel is defined as the sum of two reactions $\vec{H}_{ijk\mathrm{I}}$, $\vec{H}_{ijk\mathrm{II}}$ and

$$H_{ijk} = P_0 \cdot \left[k_{ijk} \cdot g_{ijk} + \left(1 - k_{ijk}\right) \cdot g_{ijk}\right], \qquad (10)$$

where k_{ijk} – a coefficient that takes into account the redistribution of the vertical load between contacts I and II with values from 0 to 1.

With a linear law, the change of loads from $P_{ijk\mathrm{I}}$ to $P_{ijk\mathrm{II}}$ with two-point contact will be:

$$P_{ijk\mathrm{I}} = P_0 \cdot k_{ijk\mathrm{I}}; \quad P_{ijk\mathrm{II}} = P_0 \cdot \left(1 - k_{ijk\mathrm{I}}\right), \qquad (11)$$

where; $k_{ijk\mathrm{I}} = \dfrac{d_{yjk} - d_{yI}}{d_{yII} - d_{yI}}$

d_{yjk} – the transverse current displacement of the wheel relative to the rail;
$d_{y\mathrm{I}}$, $d_{y\mathrm{II}}$ – the transverse displacements of the wheel profile relative to the rail at the entry and exit points of the two-point contact.

The values of dyI and dyII depend on the profile shape of the rolling surface of the wheel and rail. Contact adhesion forces have a spatial structure:

$$\begin{aligned}\vec{S}_{ijk\mathrm{I}} &= \vec{S}_{xijk\mathrm{I}} + \vec{S}_{yijk\mathrm{I}} + \vec{S}_{zijk\mathrm{I}};\\ \vec{S}_{ijk\mathrm{II}} &= \vec{S}_{xijk\mathrm{II}} + \vec{S}_{yijk\mathrm{II}} + \vec{S}_{zijk\mathrm{II}},\end{aligned} \tag{12}$$

where $\vec{S}_{xijk}$, $\vec{S}_{yijk}$, $\vec{S}_{zijk}$ – longitudinal, transverse and vertical components at the respective contact points.

The reaction $\vec{S}_{zijk\mathrm{I}}$ can be neglected because its magnitude is negligible.

The values of other components are determined from the following equations:

$$\begin{aligned}S_{xijk\mathrm{I}} &= N_{ijk\mathrm{I}} \cdot \psi_0 \cdot K_x \cdot \left(\varepsilon_{xijk\mathrm{I}}, \varepsilon_{yijk\mathrm{I}}\right);\\ S_{xijk\mathrm{II}} &= N_{ijk\mathrm{II}} \cdot \psi_0 \cdot K_x \cdot \left(\varepsilon_{xijk\mathrm{II}}, \varepsilon_{yijk\mathrm{II}}\right);\\ S_{yijk\mathrm{I}} &= N_{ijk\mathrm{I}} \cdot \psi_0 \cdot K_y \cdot \left(\varepsilon_{xijk\mathrm{I}}, \varepsilon_{yijk\mathrm{I}}\right);\\ S_{yijk\mathrm{II}} &= N_{ijk\mathrm{II}} \cdot \psi_0 \cdot K_y \cdot \left(\varepsilon_{xijk\mathrm{II}}, \varepsilon_{yijk\mathrm{II}}\right);\\ S_{zijk\mathrm{II}} &= N_{ijk\mathrm{II}} \cdot \psi_0 \cdot K_z \cdot \left(\varepsilon_{zijk\mathrm{II}}\right),\end{aligned} \tag{13}$$

where: $\varepsilon_{xijk\mathrm{I}}$, $\varepsilon_{yijk\mathrm{I}}$, $\varepsilon_{xijk\mathrm{II}}$, $\varepsilon_{yijk\mathrm{II}}$, $\varepsilon_{zijk\mathrm{II}}$ – longitudinal, transverse and vertical components of relative slips in the corresponding contacts;
$N_{ijk}\mathrm{I}$, $N_{ijk\mathrm{II}}$ – normal reactions in the 1st and 2nd contacts;
ψ_0 – boundary (physical) adhesion coefficient;
$K_x(\varepsilon_{xijk}, \varepsilon_{yijk})$, $K_y(\varepsilon_{xijk}, \varepsilon_{yijk})$, $K_z(\varepsilon_{zijk})$ – experimental adhesion characteristics.

The adhesion characteristics are entered as external functions. The methodology and results of experimental studies of adhesion characteristics are described in [17].

Conclusions. Based on the study, the following conclusions can be drawn:

- the force contact interaction of the wheel and the rail is difficult to describe and at the same time very important for studying the dynamics of the frictional interaction of the vehicles and the rails and guiding of the vehicles by the rail track;
- the authors propose to use a three-point contact scheme of the wheelset-rails contact in the study of the wheelsets guiding by the rail track: two-point contact – for the oncoming wheel and one-point contact – for the second wheel;
- guiding forces in the main contacts with a positive misalignment of the wheelset are the forces of the negative guiding, which prevent the process of guiding the wheelsets by the rail track;
- reducing the vertical load in the main contact of the oncoming wheel (up to the separation of the main contact from the rail, which precedes the derailment of the wheelset) improves the direction of the wheelset by the rail track;
- flange reactions play a decisive role in the process of guiding the wheelsets of the vehicle by the rail track;
- the gravitational component of the vertical load in the flange contact increases by 95% with an increase in the flange angle cone β from 60° to 70°.

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***Світлана Сапронова*[1]*, Віктор Ткаченко*[2]*, Надія Брайковська*[3]*, Іван Кульбовський*[4]**

[1]Професор, професор кафедри вагонів та вагонного господарства, Державний університет інфраструктури та технологій, 04071, Україна, м. Київ, вул. Кирилівська, 9

[2]Професор, завідувач кафедри електромеханіки та рухомого складу залізниць, Державний університет інфраструктури та технологій, вул. Кирилівська, 9, м. Київ, 04071, Україна

[3]Професор, професор кафедри вагонів та вагонного господарства, Державний університет інфраструктури та технологій, вул. Кирилівська, 9, м. Київ, 04071, Україна

[4]доцент, доцент кафедри автоматизації та комп’ютерно-інтегрованих технологій транспорту, Державний університет інфраструктури та технологій, вул. Кирилівська, 9, м. Київ, 04071, Україна

Дослідження спрямування екіпажів рейковою колією

Проведено аналіз наукових публікацій, присвячених питанням спрямування колісних пар залізничного рухомого складу рейковою колією. Встановлено, що для правильного моделювання процесів спрямування колісних пар рейковою колією необхідний точний опис контактних сил зчеплення. Встановлено, що контакт гребня колеса з рейкою існує лише в поєднанні з кутом атаки та за наявності бічної сили зчеплення. Розроблено схему силової взаємодії колісної пари з рейками з гребеневим контактом одного з коліс. Силова контактна взаємодія колеса і рейки є складним для опису процесом, який водночас дуже важливий для вивчення динаміки фрикційної взаємодії транспортних засобів і колії та спрямування транспортних засобів рейковою колією. У загальному випадку контакт колеса з рейкою відбувається в двох зонах контакту: на поверхні *кочення і на реборді. Спрощено, контакт розглядається як двох-точковий контакт. Розглянуті силові фактори не можна однозначно віднести до напрямних чи факторів опору руху. Від положення колісної пари відносно рейкової колії залежать конкретні значення і орієнтування сил і моментів. Стверджується, що поздовжнє і поперечне ковзання колісних пар викликає опір руху і долається спрямовуючими силами.*

Ключові слова*: колісна пара, рухомий склад, гребеневі реакції, контактні сили зчеплення, спрямування екіпажу залізничною колією.*