Viktor TKACHENKO, Svetlana SAPRONOVA*
East Ukrainian National University named Dal
Molodyozhny block 20A, 91034, Lugansk, Ukraine
**Corresponding author*. E-mail: doc_Sapronova@mail.ru

STEERABILITY OF RAILWAY VEHICLES

Summary. The term steerability is widely used in the motion theory of wheel and track-laying machines, water and air vehicles, spacecraft. Steerability is a property of a transport machine to submit to the managing influence. Steerability of the machine is defined by its reaction to managing influence on the part of managing in the form of changing travelling course or lateral kinematical parameters. For example, in automobiles this influence is shown in the turn of a steering wheel, in planes it is a turn of steering wheel or controller handle and so on. Railway vehicles, as known, have no similar bodies of control. The change of the moving is carried out by a rail track under the influence of horizontal travelling forces. Using the terminology from the control of wheel carriers, the author considers qualitative parameters of steerability of rail vehicles, connecting them with additional influence on vehicles of the railway in the process of control.

УПРАВЛЯЕМОСТЬ РЕЛЬСОВЫХ ЭКИПАЖЕЙ

Аннотация. Понятие управляемости широко используется в теории движения колесных и гусеничных машин, водных и воздушных судов, космических аппаратов. Управляемость - свойство транспортной машины подчиняться управляющему воздействию. Управляемость машины определяется ее реакцией на управляющее воздействие со стороны органа управления в виде изменения путевых, курсовых или боковых кинематических параметров. Например, в случае автомобиля этим воздействием является поворот рулевого колеса, в случае самолета - штурвала или ручки управления и т. д. Железнодорожные экипажи, как известно, не имеют подобных органов управления. Изменение траектории их движения осуществляется рельсовой колеей под воздействием горизонтальных путевых сил. Используя терминологию из теории управления колесных машин, авторы рассматривают качественные показатели управляемости рельсовых экипажей, связывая их с дополнительным воздействием на экипаж со стороны пути в процессе управления.

1. INTRODUCTION

The research of the steerability characteristics of rail vehicles in the way, it is considered in the motion theory of wheel machines, is a trivial task. In this case there takes place control under a rigid program. Its result, except for cases of vehicle derail, is known beforehand. In particular, turnability, determined by minimal radius of a curve, in which vehicle negotiation is possible, is one of the similar characteristics of steerability. The term turnability is similar to curve negotiation of Ceglinskiy and Korolyov.

The qualitative parameters of the steerability of rail vehicles are connected to the additional influence on the vehicle of the rail as force reaction of the vehicle to controlling influence.

First of all, it is the horizontal influence on the rail. It is necessary to distinguish two control modes of a vehicle by a railway. Firstly, it is a mode of kinematical curve negotiation, at which none of the wheelsets have any crest contact of wheels and rails. And the second, one is a mode of force curve negotiation,in which the direction of wheelset with a crest contact is typical. Obviously, in the mode of kinematical curve negotiation the level of influence of the vehicle on the rail will be lower, than in the mode of force *curve negotiation*.

The second qualitative parameter of steerability is the additional resistance to movement connected to control. During the control of the vehicle by the railway observes circulation of power flows in the closed contours formed by elements of a running part, drive and a wheelset. Circulating flows of power are connected with directing function of wheelset. They, as a rule, are parasitic, result in significant additional sidings in wheel-rails contacts, mechanical losses and increase of resistance to traction. Especially it is typical for curve sites of the rail. Any additional slidings, not connected with traction, reduce limiting meanings of adhesion coefficient. It worsens the traction-dynamic and brake characteristics of the vehicle. Kinematical resistance to any movement, is closely connected to guiding forces and frictional wheel-rails interaction.

2. THE ANALYSIS OF THE FORCE FACTORS

The controlling process of a moving trajectory of movement of the vehicle is connected in two groups of the force factors: guiding factors and factors of resistance to movement.

The attribute of the guiding factor is the positive meaning of the moment in relation to a direction curve negotiation. The attribute of the resistance factor is a negative meaning of the moment. However, this division is nominal. Same on an origin of force or the moment can have the characteristic of the directing factors or factors of resistance, in different modes of movement, on different wheelset. Let's analyze the structure of the force factors working on wheelsets.

The main vectors of lateral forces working on wheelsets by rail:

$$F_{y(jk)} = \sum_{i=1}^{2} \begin{bmatrix} \left(S_{I(ijk)} + S_{II(ijk)}\right)\sin(\psi_{(jk)} - \psi_{b(k)}) + \\ \left(T_{I(ijk)} + T_{II(ijk)}\right)\cos(\psi_{(jk)} - \psi_{b(k)}) + \left(U_{I(ijk)} + U_{II(ijk)}\right) \end{bmatrix}. \tag{1}$$

The main moments of travelling forces working on wheelsets:

$$M_{(jk)} = S_{I(1jk)}A_{I(1kk)} - S_{I(2jk)}A_{I(2jk)} + S_{II(1jk)}A_{II(1jk)} - S_{II(2jk)}A_{II(2j)}. \tag{2}$$

In the equations (1) - (2):

$S_{I(ijk)}, S_{II(ijk)}, T_{I(ijk)}, T_{II(ijk)}$ – longitudinal and lateral forces of adhesion in I and II wheel-rails contacts; $U_{I(ijk)}, U_{II(ijk)}$ – gravitational components of vertical loading in contacts; $\psi_{(jk)}$, $\psi_{b(jk)}$ – corners of turn towards the vertical axis, according to the wheelset and a bogie; $A_{I(ijk)}, A_{II(ijk)}$ – the distance from the center of the wheelset to the appropriate centers of contacts; i – number of wheel in the wheelset; j – number of wheelset; k – number of bogie.

The balance equations of the vehicle:

$$\overline{F}_y = \sum_{j=1}^{N}\sum_{k=1}^{L}\overline{F}_{y(jk)} + \overline{F}_J = 0\,; \qquad \overline{M} = \sum_{j=1}^{N}\sum_{k=2}^{L}\overline{M}_{(jk)} + \overline{M}_J = 0 \tag{3}$$

where N – number of axes in the bogie; L – number of bogies; $\overline{F}_J, \overline{M}_J$ – the main vectors of forces and moments of inertia.

The equations (3)–(4) represent stationary models of movement in the curve site of the rail.

As it was specified, the analyzed force factors cannot be definitely referred to the controlling factors or factors of resistance. The concrete meanings and directions of forces and moments depend on the distribution of wheelsets in the railway. Let's analyze opportunities of each factor in regard to the controlling process.

The longitudinal adhesion forces create the horizontal moment working on the wheelset. The positive meaning of the moment will be increased at lateral displacement of wheelset in the external side of a curve site of the rail. The longitudinal creep in contacts of wheels and rails $\varepsilon_{(ijk)I}$, $\varepsilon_{(ijk)II}$ depend on structures of tread surfaces of wheels – $R_{(ijk)}$, cross displacement of wheelset – $\delta_{(jk)}$ and radius of the curve – ρ:

$$\begin{cases} \varepsilon_{(1jk)I} = 1 - \dfrac{R_0}{R_{(1jk)I}}\left(1 + \dfrac{s}{\rho}\right); & \varepsilon_{(2jk)I} = 1 - \dfrac{R_0}{R_{(1jk)I}}\left(1 - \dfrac{s}{\rho}\right); \\ \varepsilon_{(1jk)II} = 1 - \dfrac{R_0}{R_{(1jk)II}}\left(1 + \dfrac{s}{\rho}\right); & \varepsilon_{(2jk)II} = 1 - \dfrac{R_0}{R_{(1jk)II}}\left(1 - \dfrac{s}{\rho}\right), \end{cases} \tag{4}$$

where 2s - width of the rail; $R_0, R_{(ijk)I}, R_{(ijk)II}$ – accordingly average radius of the tread surface wheel and radiuses in I and II points of contacts.

The maximal meanings of a creep at movement in direct sites of the rail without contacting the crest, at effective taper of profile 1:20 do not exceed 0,1 %. In curve sites of the rail having radius less than 1000 m, the considered factor becomes resistance. Thus, the longitudinal adhesion forces, as the force factor, are the guiding forces only in direct sites and in curve of large radius. The longitudinal adhesion forces create the moments of resistance in curves of average and small radius.

The lateral adhesion forces appear because of lateral creep, which depends on the angle of attack of wheelset on rails $\psi_{(jk)}$. The maximal, average and minimal meanings of creep can be determined depending on installation of wheelset under the formulas:

$$\varepsilon_{(jk)y}^{max} = \sin\left[\frac{\pi}{2} - 2\frac{\rho\delta_{(jk)} + C^2}{C\left(\rho + \delta_{(jk)}\right)}\right]$$

$$\varepsilon_{(jk)y}^{av} = \frac{C}{\rho + \delta_{(jk)}}; \tag{5}$$

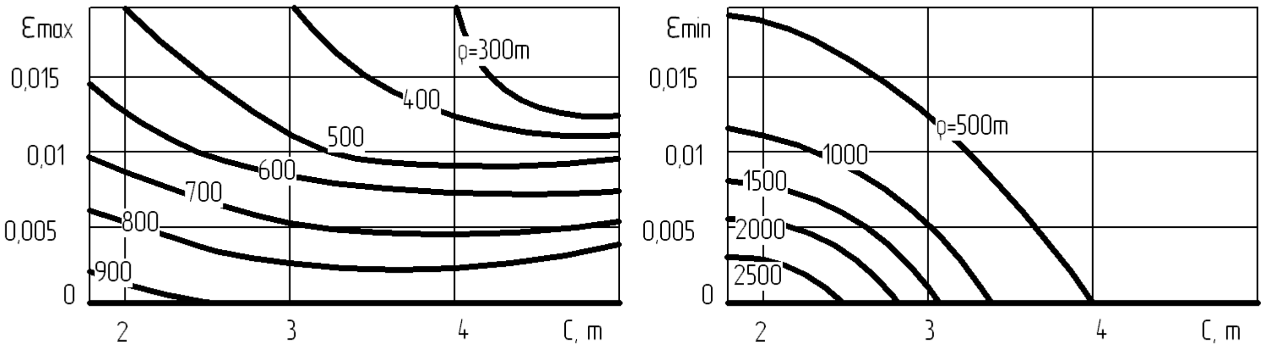
$$\varepsilon_{(jk)y}^{min} = \sin\left[\frac{\pi}{2} - 2\frac{\rho\delta_{(jk)} - C^2}{C\left(\rho - \delta_{(jk)}\right)}\right]$$

In the formulas (5) C – base of the bogie.

In a fig. 1, the calculated dependences of the maximal and minimal relative creep of outer wheelset on the base of the bogie and radius of the curve for the diesel locomotive 2TE116 are shown in the form of contour isodiagram.

As the analysis of the given ratio shows, the lateral adhesion forces can carry out the role of the controlling factor only at installation of the bogies with a skew and attack of first wheelset on the internal rail. The considered factor renders traction resistance at other installations of bogies. The level of the resistance moments is high, as the meanings of lateral creep are in the field of critical sizes. Besides the dependence of the moment of resistance on angle of attack has negative rigidity, that brings certain instability in to the process of movement.

When using the guides of wheelsets established on the carrier in front of the bogie, it is seen especially strikingly. The experimental data for the diesel locomotive 2TE116 have shown, that the elimination of unilateral installation of bogies requires a long period of time in the support-returning device even in direct sites of the rail.



a) b)

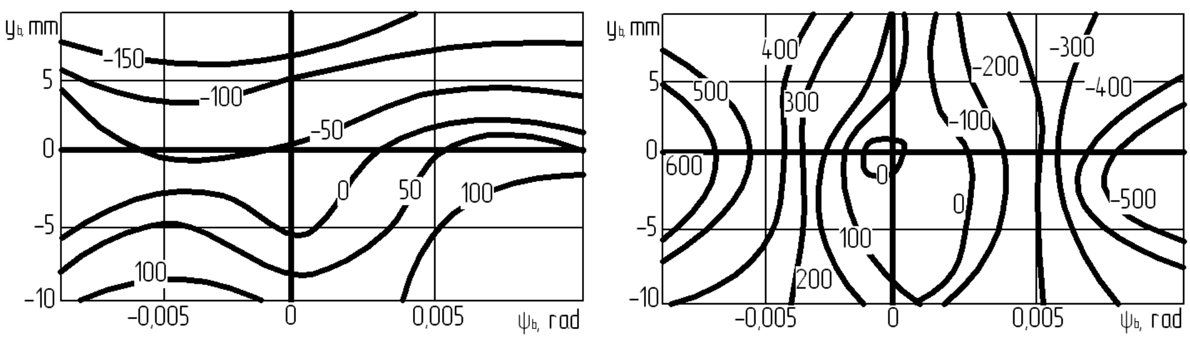
Fig. 1. Dependences of maximal (a) and minimal (b) relative creep of first leading wheelset from base of the bogie C and radius of the curve ρ for the diesel locomotive 2TE116

Рис. 1. Зависимости максимальных (а) и минимальных (б) относительных скольжений набегающей колесной пары от базы тележки C и радиуса кривой ρ для тепловоза 2ТЭ116

The gravitational components of reactions of the right and left wheels of the wheelset are equal among themselves and are oppositely directed at the identical effective tapers of the wheels tread. The difference of tapers of treads for the majority of profile is so small, that it practically does not influence the process of negotiation.

The guiding role of gravitational forces can be very great at the crest contact of wheels and rails. It depends on redistribution of normal loadings between I and II contacts of the point-to-point contact. For example, at vertical loading on a wheel equal to 115 кN, the gravitational force can reach 200 кN for the crest cone of 60^{o} and 325 кN for 70^{o}.

The returning moment of the support-returning device is the internal moment of the system and, usually, indirectly, through the above described force factors, creates resistance to movement. It is considered, that in the curve sites of the rail the returning moment should be minimal or even negative, that would allow to improve the characteristics of steerability at the expense of compulsory installation of bogies against the axis of the rail.



a) b)

Fig. 2. Change of the main vector (a) and main moment (b) of lateral contact forces depending on installation of the bogies TE116 in the curve of 900 m

Рис.2. Изменение главного вектора (а) и главного момента (б) боковых контактных сил в зависимости от установки тележки ТЭ116 в кривой 900 м

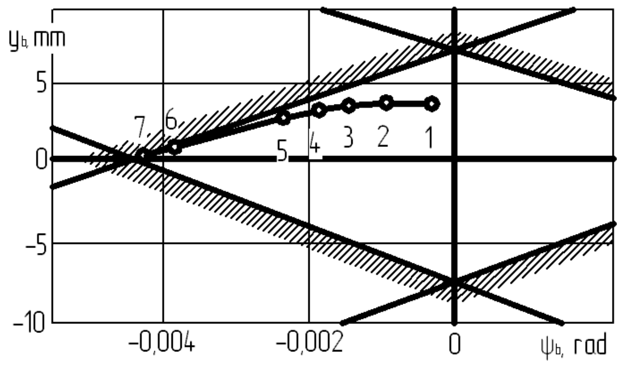


Fig. 3. A blocking contour of the bogies 2TE116 installation in the curves: 1 - 4000 m; 2 - 2000 m; 3 - 900 m; 4 - 700 m; 5 - 500 m; 6 - 400 m; 7 - 250 m

Рис.3. Блокирующий контур установки тележки ТЭ116 в кривых различного радиуса: 1 — 4000 м; 2 — 2000 м; 3 — 900 м; 4 — 700 м; 5 — 500 м; 6 — 400 м; 7 — 250 м

The model with parameters of the diesel locomotive 2ТЭ116 was used for research of the characteristics of steerability of rail vehicles. On fig. 2, the contour diagrams of dependences of the main vector and main moment of external forces from installation of bogies in a rail track are represented. On fig. 3 the dependence of balance position of bogies on curve radius and restriction on derail conditions as a blocking contour is shown.

The calculations shows, that at any radius of the curve the bogies are installed with a negative skew. In curves of radius more than 980 m the kinematical negotiation is possible. At radiuses of curves within the limits of 980...470 m unilateral crest contact of the first wheelset of the outside rail takes place. In curves of radius less than 470 m it's bilateral: the first wheelset – the outside rail, the third wheelset – the internal rail. The longitudinal and lateral creep of the leading wheelset, causes resistance to movement, which is overcome by guiding efforts.

3. THE KINEMATICAL RESISTANCE TO MOVEMENT

The kinematical contradiction of geometrical parameters of wheels contacts with rails and kinematical parameters of movement causes parasitical creeps. They, in turn, are the reason of occurrence of the kinematical resistance to movement of the vehicle [1].

The kinematical resistance has two components: differential resistance (w_d) and circulation resistance (w_c). The differential resistance is shown because of volumetric geometry of contact. The circulating resistance grows out of group of multi-contact interaction of wheel and wheelset system with a railway during directed movement in the rail gage. The reason of this kind of resistance is the circulation of parasitic capacity in contours formed in wheelsets, incorporated by a frame of the bogie. The meaning of this resistance depends on distribution of creep in contacts of wheels with rails, which are influenced by constructive of the vehicle and mode of its movement. The losses of energy on overcoming of friction connected with differential and circulating creeps causes the kinematical resistance to movement.

As shown in monograph [2], the occurrence of additional differential creep is typical for crest wheel-rail contact characteristic. The pattern of distributing differential creeps depends on the angle of attack of a wheel on a rail [3]. At movement of wheelset in a rail track each cross position towards the axis of the rail corresponds to instant radius of the turn, at which it can move without creep in contacts along equilibrium trajectory.

However, due to the interaction between wheelsets through the frame of the bogies the actual trajectory of movement of each wheelset differs from equilibrium one. The rigid connection between wheels results in circulation of capacity in contours "railway-wheelset", redistribution of the power flow between wheels and, as a consequence, in increasing of resistance to movement. In case of locomotives, besides, it worsens the characteristics of adhesion. In case of group drive of wheelsets the power contour of a drive has some branching circuits. The energy of circulation of power contours is absorbed in contacts of wheels with rails and partially in restoring connections of the bogies. The non-uniformity of distribution of the power flow between wheels can be caused by several factors: by the rigidity of the adhesion characteristics, by torsional rigidity of the axis. The important role is played by the geometrical characteristics of the wheelset: taper and diameter of wheels; width of a track; base of the bogies; parameters of longitudinal and lateral connections of wheelset with a bogie frame. As it was specified, the circulating resistance is a consequence of circulation of power flows in closed contours. The wheels-rail contacts carry out a role of untying central points. The level of circulating capacity is limited by meanings of adhesion forces in contacts, due to complete or imaginary creep. Therefore, the resistance to movement of the vehicle is lower under bad conditions of wheels-rail adhesion, than under good conditions.

4. REDUCTION OF FORCES AND MOMENTS OF RESISTANCE

The definition of kinematical resistance to movement is based on reduction of horizontal contact reactions and their moments, to the vehicle centre of gravity. In the method of reduction the principle of equality of efforts sum caused by actions of contact forces on possible moving, and effort of total force of resistance is used:

$$\sum A_F = \sum A_w \tag{6}$$

The meaning of the given relative resistance to movement can be determined by the formula:

$$w_k = \frac{\sum F_{(i)} \cdot V_{(i)} \cdot \cos\left(\vec{F}_{(i)}, \vec{V}_{(i)}\right)}{V \cdot Q} \tag{7}$$

where $F_{(i)}$ – contact forces; $V_{(i)}$ – absolute speeds of points of the application of the contact forces $F_{(i)}$; V – absolute speed of movement of the centre of vehicle; Q – weight of the vehicle.

Taking into account the structure of contact forces, numerator of the formula (7) represents the sum of capacities of contact forces.

5. INFLUENCE OF PARAMETERS OF A RUNNING PART ON STEERABILITY OF VEHICLES

The researches of serial locomotives and cars have allowed to reveal major factors influencing the steerability of vehicles. Such parameters are: the base of the bogie; profile of tread surfaces of wheels; rigidity in elastic connections of wheelsets with a frame of the bogie and backlashes in journal-box. On the example of four-axis two-bogies vehicle the influence of the factors on the kinematical resistance to movement in curve sites of the rail, as a basic parameter of steerability has been analyzed.

The researches on mathematical models of locomotives and cars movement have shown the significant influence of the form of tread surfaces on kinematics and dynamics of frictional interaction of a vehicle and rail. It's difficult to answer a question, what exactly renders decisive influence on parameters of this interaction – a form of a tread surface of a wheel or a form of a crest. However, with sufficient accuracy it is possible to assert, that higher meanings of kinematical resistance to movement are typical for structures with a large corner taper. For example, for profiles with the crest cone of 60^{o} the meaning of resistance to movement are 1,5...1,7 times lower, than for the profiles with crest cone of 70^{o}

The influence of rigidity of longitudinal connection of wheelset with a frame of the bogie on parameters of resistance to movement was investigated in a range of longitudinal rigidity of a journal-box link $G_x = 1...20\,\text{kN/mm}$. On fig. 4 the contour isodiagrams are shown as the dependences of kinematical resistance from radius of a curve (200…1000 m) and speeds of movement at rigidity $G_x = 1$ and 20 kN/mm. As it has appeared, for speeds more than 15 m/s increase of rigidity more than 5 kN/mm practically do not influence parameters of resistance, especially in curves of small radius. Within limits of 5 up to 1 kN/mm the increase of resistance for 1,6…1,8 times is observed. The minimal meanings of resistance take place at combinations of speeds and radiuses of the curve close to the equilibrium mode of movement.

The low meaning of resistance to movement in the equilibrium mode of movement is connected with the minimal meanings of lateral loadings of wheelset on rails. The curve $\rho = 0{,}675V^2$ on fig. 4 corresponds to the combinations of speed and radius of the curve for outstanding centripetal acceleration, allowed by the norms of comfort.

However, the optimum meaning of rigidity of longitudinal connection in journal-box is difficult to define, as the mode of movement influences the principle of kinematical resistance minimum in coordinates $\rho(V)$. For the equilibrium mode of movement the meaning $G_x = 4{,}2...7{,}5 kN/mm$ are optimum. For a zone of comfort the optimum meanings are $G_x = 3{,}6...6{,}8 kN/mm$. For a speed exceeding the speed of comfort the optimum meanings are $G_x = 8{,}0...12{,}0 kN/mm$.

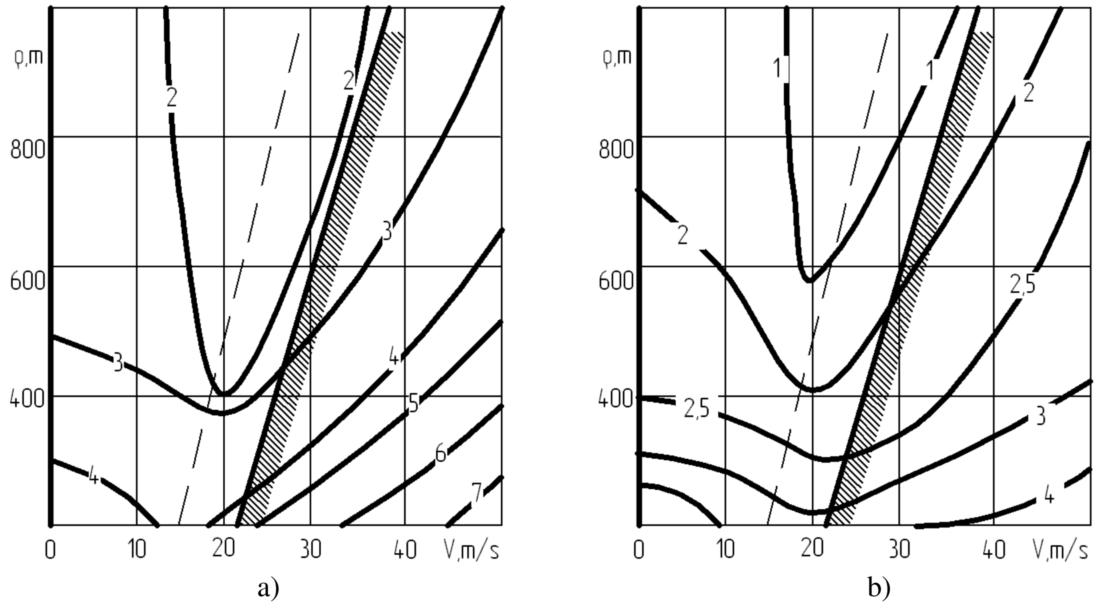


Fig. 4. Dependences of the kinematical resistance to movement (in N/kN) from speed of movement V, radius of the curve ρ and longitudinal rigidity of box connections Gx: a) $G_x = 1{,}0\ kN/mm$; b) $G_x = 20\ kN/mm$

Рис.4. Зависимости кинематического сопротивления движению (Н/кН) от скорости движения V, радиуса кривой ρ и продольной жесткости буксовых связей Gx: a) $G_x = 1{,}0\ кН/мм$; b) $G_x = 20\ кН/мм$

6. CONCLUSION

In the article the guiding of vehicles by a rail track is considered, as a process of guiding moving trajectory. Using the terminology from the theory of guiding wheel machines, the author, at the same time, considers qualitative parameters of steerability of rail vehicles movement, which are not mentioned in the theory. The quality of guiding process is connected with additional influence on vehicles, the part of the rail, as a controlling body. According to the technique, given in the article, the estimation of quality curve negotiation is carried out under the parameters of steerability. The kinematical resistance to movement is accepted as the universal characteristic of steerability. The given opinions of the authors allows developing the common approaches to designing running parts of the vehicles on the basis of the complex estimation of qualitative parameters of railway vehicles.

Literature

1. Ткаченко В.: *Кинематическое сопротивление движению рельсовых экипажей*. Луганск, ВУГУ, 1996, 200 с.
2. Ткаченко В.: *Оценка управляемости рельсовых экипажей с различными конструктивными схемами ходовой части.* Приднепр. науч. Вестник, сер. Машиностроение, 1997, №50(61), С. 16-17.
3. Ткаченко В., Сапронова С.: *Моделирование горизонтальных сил взаимодействия рельсовых экипажей и пути.* Луганск, ВУГУ, 1995, 39 с.

Received 14.10.2007; accepted in revised form 12.12.2007