ORIGINAL ARTICLE
DOI: https://doi.org/10.30932/1992-3252-2024-22-1-4

World of Transport and Transportation, 2024,
Vol. 22, Iss. 1 (110), pp. 176–181

Updated Approaches to Criteria of Assessment of Dynamics in Wheel–Rail Contact Area


Petr E. EGOROV


Roman V. KOBLOV


Yaroslav A. NOVACHUK

Petr E. Egorov [1]***, Roman V. Koblov*** [2]***, Yaroslav A. Novachuk*** [3]
[1, 2, 3]*Far Eastern State Transport University (FESTU), Khabarovsk, Russia.*
✉ [2] *romashka.one2007@rambler.ru.*

ABSTRACT

According to the Transport Strategy of the Russian Federation, unprecedented volumes of transportation along BAM and Trans-Siberian Mainline are planned thanks to an increase in train weight standards, traffic speed along the sections, efficiency of traction capacity of diesel locomotives. Similar tasks were already set in the 1970s. Their solution was complicated by insufficient experience (in light of the present state of knowledge) in development and use of frame support and combined traction drives on cargo diesel locomotives, and the lack of an objective idea of operating conditions in which the designed diesel locomotives would have to work. In this regard, the design of wheel-motor units (WMU) of diesel locomotive bogies with axial-supported suspension of traction drives was carried out based on generalised results of empirical studies of the dynamics of various types and series of locomotives.

The objective of the work is to develop a model of mathematical analysis and an algorithm for calculating the categories of dynamic forces and the speed of interaction of wheels of a cargo diesel locomotive in contact with rails at the design stage of development of traction drives to ensure their high technical and economic performance indicators under operating conditions.

Long-term monitoring of dependability of diesel locomotives on the Eastern section of BAM has allowed to identify system failures of the equipment of the locomotive's underframe, which confirm the bias of the calculated design solutions for traction drives of diesel locomotives of modern TE25A, 2TE25KM and 3TE25K2M series, created in 21st century. System failures of WMU equipment of modern series (TE25KM) are a consequence of direct «mechanistic» borrowing of unsuccessful design solutions of universal diesel locomotive underframes (TE10 and TE116).

The article proposes a clarification of theoretical provisions for modelling qualitative criteria for dynamics in the contact areas of wheels with rails of traction drives of diesel locomotives at the design stage. The mechanism of interaction «wheel – rail» is supported by the mathematical theory of cycloid, a circle motion. The algorithm for estimating forces in the contact areas of wheels with rails is built on the theorems of classical theoretical mechanics of non-free movement of a wheelset and the laws of dynamics as an unchangeable holonomic system.

Clarifications were obtained for kinematics characteristics (angular velocity, angular acceleration); real centres of speed and acceleration of wheels; moments of inertia of rotating unsprung mass of wheel-motor units with axial-supported suspension of traction drives. The new approach makes it possible to quantify the criteria for dynamics in wheel-rail contact areas at the design stage, which were previously not amenable to calculation.

Keywords: *railway transport, locomotives, non-free plane-parallel motion of wheels, translational speed of rolling stock, angular velocity, angular acceleration of interaction of tread circle of wheels with rails.*

For citation: Egorov, P. E., Koblov, R. V., Novachuk, Ya. A. Updated Approaches to Criteria of Assessment of Dynamics in Wheel–Rail Contact Area. World of Transport and Transportation, 2024, Vol. 22, Iss. 1 (110), pp. 176–181. DOI: https://doi.org/10.30932/1992-3252-2024-22-1-4.

The original text of the article in Russian is published in the first part of the issue.
Текст статьи на русском языке публикуется в первой части данного выпуска.

STATEMENT OF THE PROBLEM

Relevance of Research

Despite the well-known achievements in design and development of domestic locomotives, the negative phenomena of structural failures of mechanical equipment of underframe have recently become the subject of active discussion in the circles of researchers, railway engineers and machine builders [1]. The reasons for this are:

1) To date, neither the customer, nor the transport machine builders meeting the orders, have a mathematical theory for design of more powerful mainline diesel locomotives with increased dependability indicators, improved dynamics and increased traction properties [2].

2) Design of the mechanical equipment of the underframe is carried out in accordance with GOST R [Russian state standard] 55513-2013 for static axial load, static safety factors and cyclic fatigue resistance, which cannot fully reflect the real criteria of forces and reactions of the loaded mechanical part of traction drives in operating conditions.

3) Solving problems of underframe dynamics in the case of non-free movement of material points of the wheel poles in contact with the surface of rails is carried out using approximate methods based on the average algebraic translational speed of the wheel centres, and «this is due, in particular, to the lack of a method for determining the angular speed ω of wheels» [3].

4) Paradigms for modelling dynamic loads acting on the contact areas of wheels with rails and the sprung masses of the underframe of diesel locomotives are based only on the characteristics of geometric disturbances from the state of the rail surfaces (reduced to gravitational acceleration), which are used to evaluate the dynamic properties, strength and durability of structures at the design stage.

Based on own research experience, it can be noticed that until the present period, the most important laws of dynamics, the categories of forces and speeds of interaction of wheels and rails that underlie the processes of operation of mechanisms, have not been fully studied and adapted. The resulting cause-and-effect state in this process was reinforced by the erroneous position of researchers and engineers declaring in fact that nature has deprived railwaymen of the laws of mechanics. Let's look at whether this is true using domestic examples.

Domestic Scientific and Theoretical Base for Research

The practical need for in-depth scientific and theoretical studies of assessment of dynamic constant and variable forces and reactions of interaction of steam locomotive wheels in contact with rails, depending on the speed of movement, was determined by train accidents (1883, 1888) on the Russian railways. The wrecks became the main motive of Professor Nickolay P. Petrov [1836–1920] for studying the influence of several phenomena that accompanied mediums of causes that at the epoch did not have theoretical rationale and algorithms for assessing, namely the permissible limits of stress [σ] in rails (in contact with wheels) [4].

Knowing the law of unfree and forced movement of a material point along a given fixed surface, considering the connections imposed on it, Professor N. P. Petrov began to identify the forces acting on it. Using this approach, a simulation mathematical model of analysis and algorithms for determining the numerical values of the vectors were developed, namely of horizontal traction forces, which in a certain way depend on time and on speed of the locomotive; vertical centrifugal forces of rotating masses perceived by rails at translational and rotational speeds of wheels, their adhesion to rails. The simulation mathematical models were based on the Zimmermann and Clapeyron equations. Model based on Clapeyron's equations proved to be the priority one because of the most objective convergence with reality.

To confirm the scientific validity of the theory, N. P. Petrov clarified and corrected the results of previous experiments performed by other scientists. Calculated values of dynamic loads from wheels on rails had convergence with experimental data in the range from plus 3,9 % to minus 1,8 % (in kilograms of force) [4].

According to the conclusion of N. P. Petrov, this theory «freed us from the need to make assumptions about some semblance of existing reality and allows us to evaluate the complete separate influence of each factor, which was impossible in experiments». Subsequently, N. P. Petrov's theory was developed in the research and scientific works of Professors S. P. Timoshenko, A. L. Vasyutinsky, G. M. Shakhunyants and others, in the field of interaction of rolling stock and track.

In 1897, according to the design of N. P. Petrov, a passenger steam locomotive was created at Putilov plant. The diameter of the locomotive's driving wheels was 2000 mm. With a train weighing 250 tons, it reached an average speed of 78 km/h. Steam locomotives of this series were used until 1911 for courier trains [long distance trains with comfortable compartments running at higher speed], and until the 1930s, in local traffic [5].

Problems of the Current Moment

The intensive transition to advanced types of traction (diesel locomotives, electric locomotives) has determined several new dynamic properties of bogie underframes with individual wheelset drives. The problems that arose had not got previously an objective scientific and theoretical analysis and explanation, which led to the need to study them in the process of experimental research.

It should be noted that during the experiments a few main factors were not identified: the traction force of WMU and individual units of multiple locomotives, the maximum moments of the inertia of the rotating masses of WMU and a number of others [6]. Numerical criteria for forces of interaction between wheels and rails were calculated from the amplitudes and accelerations of the sprung part of the bogies and body, reduced to their gravitational acceleration in fractions of g, as well as from the dynamic coefficients of the sprung parts K_d, depending on the translational speed of various types of locomotives [6].

Solving the difficult problems of improving the dynamics of traction drives of diesel locomotives, A. I. Belyaev [7] drew the attention of the scientific community to the different vibration state of the axlebox units of wheelsets, with the axial support suspension of traction drives. In the process of carefully prepared and performed experiments, he established that the measured unit of vibration acceleration of the axlebox in fraction g (from the side of the gear reducer) corresponded each time to an uncertain (random) value of vertical amplitudes of disturbances coming from the rail track, in comparison with the opposite axlebox.

By mathematical simulation modelling of vibrations of diesel locomotive components (for TE10L, TE10V, TE116, TEM7 series), in comparison with statistical and probabilistic experimental data, A. I. Belyaev established the existence of dependences of vibration amplitudes of axle box units on conservative forces determined by the unsprung masses of various types of drives. However, these dependencies, due to insufficient analytical argumentation, have made experts distrust them for a long time. At the same time, most of the known models, with rare exceptions, are built based on approximate linear differential equations of forced sinusoidal vibrations of bogie frames and bodies. The mathematical essence of such forecasting reflects an insufficient understanding of the practical laws of harmonic oscillations and the dynamics of the WMU system, in particular, of the existing kinematic and dynamic factors in the contact areas of wheels with rails, when the point of the wheel T (point of contact with the rail) is forced to move along a given fixed surface of the rail of an unpredictable physical condition.

Based on the definition of dynamics, it has only one characteristic point that is the speed. However, to this day, researchers have got yet insufficient understanding of the nature of the relationships between the mechanism of rolling and the mathematical essence of the convergence of equations (in a particular case) of the kinematics of translational-rotational motion of a wheel: of translational, circumferential and angular velocity; tangential, normal and angular accelerations with uniform motion of the locomotive and uniform rotation of the wheel [3].

This is mainly because the authors of modern textbooks on theoretical mechanics and of monographs offer a few contradictory interpretations of the laws of dynamics and theorems of plane-parallel motion of the poles of driving wheels, in particular, the points of their contact with rails. For example, the rolling of a wheel on a straight rail is considered only as translational one at the speed of the centre of the wheel. Thus, complex movement of points – poles of the sections of the rolling circles of wheels – is taken to be identical to the translational motion of the locomotive, in which all its points move in the same way as arbitrarily chosen poles – the centres of wheels [8; 9].

The works [10–12] proposed for the first time adapted methods and algorithms that make it possible to objectively solve problems of the dynamics of non-free, plane-parallel and translational-rotational motion of a wheel pole, when a point is forced to move along a given fixed surface or curve. The technique makes it possible to determine: a) the law of motion of points of the circle of the section of the profile of railway wheels corresponds to the hodograph of the cycloid, preserving the relationships and ratios of the diameters of the wheels of one wheelset with the translational speed of the diesel locomotive; b) the resulting speed V_A of point A (belonging to the tread circle of the wheel) on any section of the transcendental trajectory of the cycloid (from 0 to π), taking into account the diameter of driving wheels, the position of the wheelset in the rail track and time; c) the speed of interaction of wheels with rails V_I, depending on the translational speed V_0 of the diesel locomotive; d) angular speed ω_I of interaction of wheels with rails; e) angular centripetal acceleration ε_C at the contact areas of wheels with rails.

Determination of angular acceleration in contact of a wheel with a rail

One of a set of reasons for a certain underdevelopment of the theory of «wheel-rail» interaction [13] is that the non-free movement of locomotive wheels belongs to little-studied sections of theoretical and applied mechanics [9]. The basis of contradictions, in particular, is dominated by the lack of an adapted practical methodology and algorithm that makes it possible to determine the numerical values of the angular (centripetal) acceleration of the point of the centre of the mass of the driving wheel, which is its pole and point of contact with the rail.

The objective of the work is to update and describe mathematical equations of angular acceleration and develop a mathematical algorithm for solving problems, with high validity of estimates of acceleration criteria in the «wheel-rail» contact point, based on cycloid theory, instantaneous angular velocity of the point of the tread circle of each individual wheel of the wheelset in contact with the rail, considering the design and technical parameters of WMU.

METHODOLOGY, RESULTS, DISCUSSION

Methodological approaches to solving problems of estimating angular accelerations, in a particular case, require clarification and justification of features of the theoretical provisions of the kinematics and dynamics of the constrained, complex, translational-rotational movement of locomotive wheels. For example, the rotation of wheels (wheelset) pressed onto an axle. The law of rotational motion of the wheel is expressed by the equation:

$$\varphi = f(t). \tag{1}$$

The angle φ is always measured in radians. The main kinematic characteristics of rotational motion of the wheel are its angular speed ω and angular acceleration ε. The angular speed at a given time t is expressed by the equation:

$$\omega = d\varphi/dt. \tag{2}$$

If the angular speed of the wheel remains constant (ω = const), then the rotation of the wheel is called uniform:

$$\omega = \varphi/t. \tag{3}$$

In technology, the speed of uniform rotation is often determined by the number of revolutions per minute, denoting this value by n, rpm. Relationship between n, *rpm* and ω – 1/*sec*. With one revolution the wheel rotates through an angle of 2π, and with n revolutions for an angle 2πn, this rotation is made in time t = 1 *min* = 60 *sec*. Based on this it follows that:

$$\omega = \pi n/30 \approx 0{,}1\ \text{n}. \tag{4}$$

It should be especially emphasised that the dimension of n is not the angle, but the angular speed. Then the angular acceleration at a given time will be numerically equal to the first derivative of the angular speed with respect to time:

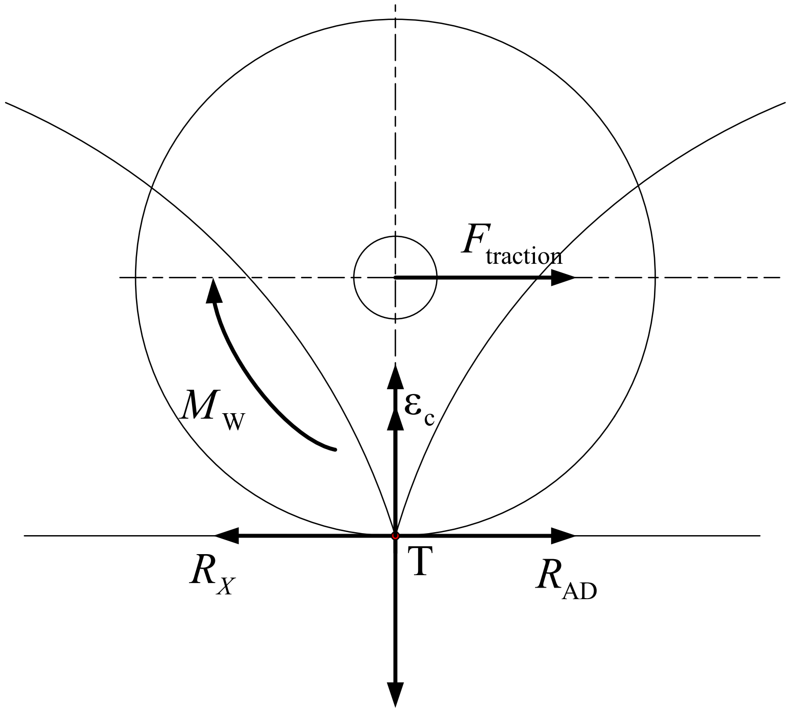
$$\varepsilon = d\omega/dt. \tag{5}$$

The unit of measurement is usually $1/\text{sec}^2$.

Having established the characteristics of the angular speed of the wheel's tread circle as a whole, it is necessary to move on to explaining movement of its individual points [10; 14]. To forestall contradictions and discussions, it is necessary to recall that the law of motion of the conditional point of the circle of cross-section of the driving wheel has a mathematical description of an ordinary cycloid. With a wheel (tread circle with radius r) motion, the conditional point A will describe a cycloid, the plane of which is perpendicular to the axis of rotation, but the centre of rotation will be at point T, at the pole on the fixed surface of the centroid (surface of the rail head).

It should be noted that the angular speed of rolling of the cross-sectional circle of the rim differs from the linear or circumferential speed of point A [10; 14].

The mathematical law of uniform, plane-parallel movement of wheel cross-section points without slipping at the poles, is represented by a mathematical transcendental function – a cycloid, which preserves the relationships and ratios of acceleration vectors at the wheel pole. This law is determined by the equations of kinematics of translational, resultant and angular



Pic. 1. Trajectory of movement of point A of the wheel cross-section (cycloid lines), vectors of angular acceleration ε_C, moment M_W in contact of the wheel with the rail, vectors: $F_{traction}$ – traction forces, R_x – rail reactions, R_{AD} – force reflecting adhesion in a state of equilibrium (identical to Rx), K_0 – impulse of resultant forces [performed by the authors].

speeds for uniform motion of the wheelset and by angular acceleration at the conditional cusps of an ordinary cycloid, and the theorems of N. E. Zhukovsky, D'Alembert [15].

With this approach, the law of motion of a material point along the surface of the rail is equal to:

$$V_0 = \frac{dS}{dt}, \qquad (6)$$

where V_0 is translational speed of the wheel.

Provided that the wheel rotates uniformly, we can determine the linear speed of point *A*, which is located on the tread circle of the wheel rim:

$$V_A = V_0 = \frac{dS}{dt} = (r\varphi) = r\frac{d\varphi}{dt} = r\omega. \qquad (7)$$

According to the properties of the cycloid [10–12; 14], we obtain the equation for the linear resulting speed vector:

$$V_A = 2\,V_0 \bullet \cos\alpha. \qquad (8)$$

From the condition that the contact pole of the wheel *T* with the rail does not slide along the rail, then the vector of the linear resulting speed of the wheel point V_A, which is directed at an angle $\cos 45^0$ to the translational speed of the wheel center V_O, which corresponds to $\frac{\sqrt{2}}{2}$, we find:

$$V_A = 2V_0\frac{\sqrt{2}}{2} = V_0\sqrt{2}. \qquad (9)$$

Consequently, identity (9) excludes the doubts of Professor M. F. Verigo [3] and allows determining the instantaneous angular speed of interaction of the tread circle of each wheel of the wheelset with the rail:

$$\omega_T = \frac{V_A}{r}. \qquad (10)$$

Formula (10) shows that V_A represents the instantaneous speed of interaction of the wheel cross-section with the rail at the *T* pole. This speed is mathematically justified by a parametric relationship with the diameter of the tread circle. Along with this, the vector of the resulting speed V_A, tangent to the cycloid, always passes through the upper point of the diameter of the tread circle. And the normal to the tangent always passes through the pole *T* [10–12; 14]. In accordance with the transcendence of the cycloid, each hodograph has its own constant *k*:

$$k = \sqrt{\frac{1}{2r}}. \qquad (11)$$

According to condition (10), when we know the module of the average algebraic translational speed V_0, the numerical value of the gear ratio μ of the traction gear reducer of the wheel-motor unit, the diameter of the tread circles of the wheels, we determine the angular speed of interaction of the wheel with the rail for any section of the profile of one wheelset. In this case, the linear speed V_0 must be expressed in radians per second, then:

$$V_0 = \frac{\pi n}{30} r \ , \tag{12}$$

$$\omega_T = V_T = V_0\sqrt{2} \ , \tag{13}$$

$$\omega_T = \frac{\pi n}{30} r\sqrt{2} \ . \tag{14}$$

If the angular speed is a constant value ω = const, then the vector of normal angular acceleration of the pole T will be directed as normal to the transcendental hodographs of the moving centroid's point[1]. Consequently, acceleration of the material point of the wheel corresponds in absolute value to the centripetal acceleration ε_C, the vector of which is always directed from point T to the centre of the axis of the circle O of the section of the complex profile of the wheel (Pic. 1):

$$\varepsilon_C = \frac{\pi^2 n^2}{900} r\sqrt{2} \ . \tag{15}$$

RESULTS

Thus, development of a methodology for determining the category of speed of complex translational and rotational motion of a locomotive wheel makes it possible to solve the Newton's first and second law problems and determine the reactions of superimposed relationships. The basic law of dynamics for non-free movement of a wheel point will take the form:

$$\sum m_W \varepsilon_C = \sum F^a + N \ , \tag{16}$$

where F^a are active constant and variable forces acting on the T pole;

N – reaction of a flat surface of a stationary centroid (rail) to the influence of a wheel pole, considering the convergence of active forces and speed.

REFERENCES

1. Gapanovich, V. A., Popov Yu. I. On the interaction of the dynamically loaded mechanical part of electric locomotives and infrastructure [*O vzaimodeistvii dinamicheski nagruzhennoi mekhanicheskoi chasti elektrovozov i infrastruktury*]. *Locomotive*, 2021, Iss. 5 (774), pp. 2–5. EDN: UMAZYL.

2. Valinsky, O. S. Locomotive traction: present situation and challenges for the future [*Lokomotivnaya tyaga: nastoyashchee i zadachi na budushchee*]. *Locomotive,* 2017, Iss. 12 (732), pp. 2–6. EDN: ZVRVEV.

3. Verigo, M. F., Kogan, A. Ya. Interaction of track and rolling stock [*Vzaimodeistvie puti i podvizhnogo sostava*]. Moscow, Transport publ., 1986, 558 p.

4. Petrov, N. P. Wheel pressure on rails of railways, rail strength and track stability [*Davlenie koles na relsy zheleznykh dorog, prochnost relsov i ustoichivost puti*]. Petrograd, Printing shop of the Partnership of Electro-printing house of N. Ya. Stoikov, 1915, 263 p.

5. Karyanin, V. I. Memorial sign to the scientist-innovator [*Pamyatniy znak uchenomu – novatoru*]. *Locomotive,* 2020, Iss. 6 (762), pp. 46–48. EDN: QPLZTR.

6. Korolev, K. P. Bogie underframes of locomotives for increased speeds [*Telezhechnie ekipazhi lokomotivov dlya povyshennykh skorostei dvizheniya*]. *Trudy VNIIZhT*, 1962, Iss. 248, 304 p.

7. Belyaev, A. I. Dynamic properties of traction drives of diesel locomotives and the possibility of their improvement. D.Sc. (Eng) thesis [*Dinamicheskie svoistva tyagovykh privodov teplovozov i vozmozhnosti ikh uluchsheniya. Diss… dokt.tekh.nauk*]. Moscow, MIIT, 1978, 394 p.

8. Garg, V. K., Dukkipati, R. V. Dynamics of railway vehicle systems. [Russian edition title: *Dynamika podvizhnogo sostava*]. Moscow, Transport publ., 1988, 391 p. ISBN 5-277-00226-X (рус.), ISBN 0-12-275950-8 (English).

9. Gura, G. S. Rolling of bodies with friction. Fretting [*Kachenie tel s treniem. Fretting*]. Sochi, Doria Printing Centre LLC, 2009, 295 p. ISBN 978-5-94945-020-8.

10. Novachuk, Ya. A., Nikitin, D. N., Koblov, R. V., Teplyakov, A. N. New paradigm of «wheel-rail» kinematics. *Izvestia Transsiba*, 2014, Iss. 3 (19), pp. 24–31. EDN: SYLZDD.

11. Koblov, R. V., Egorov, P. E., Novachuk, Y. A. New Perusal of Locomotive Traction Force Formation Mechanism. *World of Transport and Transportation,* 2016, Iss. 5 (66), pp. 6–18. DOI: https://doi.org/10.30932/1992-3252-2016-14-5-1.

12. Novachuk, Ia., Koblov, R., Teplyakov, A., Egorov, P. Innovative Method of Determination of Speed of Interaction of Wheels with Rails. 15th International Scientific Conference «Procedia Engineering». St. Petersburg, 2016, Vol. 165, pp. 1503–1511. DOI: 10.1016/j.proeng.2016.11.886.

13. Mitrokhin, A. N. «Wheel-rail»: A more advanced theory is required [*«Koleso-rels»: Trebuetsya bolee sovershennaya teoriya*]. *Zheleznodorozhniy transport*, 1998, Iss. 7, pp. 41–44.

14. Novachuk, Ya. A., Nikitin, D. N., Koblov, R. V. Kinematics of Interaction between the Wheel and the Rail. *World of Transport and Transportation*, 2012, Iss. 4 (42), pp. 16–19. EDN: PFFKJP.

15. Zhukovsky, N. E. Kinematics, statics, dynamics of a point [*Kinematika, statika, dinamika tochki*]. Moscow, Oborongiz publ., 1939, 403 p. ●

---

[1] Bat, M. I., Dzhanelidze, G. Yu., Kelzon, A. S. Theoretical mechanics in examples and problems. In 3 volumes. Volume 1. Statics and kinematics. Moscow, Nauka publ., 1967, 512 p.

Information about the authors:

Egorov, Petr E., *Senior Lecturer at the Department of Railway Transport of Far Eastern State Transport University (FESTU), Khabarovsk, Russia, P. E. Egorov@rambler.ru.*

Koblov, Roman V., *Senior Lecturer at the Department of Railway Transport of Far Eastern State Transport University (FESTU), Khabarovsk, Russia, romashka.one2007@rambler.ru.*

Novachuk, Yaroslav A., *Ph.D. (Eng), Associate Professor at the Department of Railway Transport of Far Eastern State Transport University (FESTU), Khabarovsk, Russia, novachuk@inbox.ru.*

Article received 06.12.2022, updated 07.05.2023, approved 27.08.2023, accepted 29.08.2023.