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Theory and Practice of the Innovative Spring Suspension Design for Locomotive to Improve its Traction and Dynamic Characteristics

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Abstract

This paper deals with the methods and techniques of the locomotive dynamic characteristics improvement, decrease in force impact on the track, minimizing tire and rail wear by secondary suspension improvement. Based on the calculations carried out using the created mathematical models and experimental research, there are proposed series of construction solutions of the supporting and returning devices with rational characteristics, which allow improving traction characteristics of the locomotive and reducing its dynamic impact on the track in vertical as well as in horizontal planes, on the straight track as well as on the curved track. Moreover, the proposed solution can provide the locomotive body with the centering function relative to the bogie. The proposed body to bogie connection was tested using a special test stand and in operating conditions. According to the test results, the proposed construction of body to bogie connection can ensure the required rigidity and damping characteristics due to the design optimization.

KEY WORDS: *secondary suspension, static deflection, rubber-metal parts, bogie swivel angle*

1. Introduction

Analysis of the research relevance has shown that the most expensive and problematic is creation and technical implementation of the locomotive undercarriage, which largely determines its technical and economic efficiency as a traction vehicle. At the same time, evaluation of this efficiency is contradictory, caused by complex and ambiguous dependencies of traction and coupling, dynamic, ergonomic and other characteristics of the locomotive [1-3]. The change in characteristics of the supporting and returning devices makes it possible to provide: an increase in traction characteristics of the locomotive; a decrease in the maximum dynamic impact on the track in vertical as well as in horizontal planes, on the straight track as well as on the curved track; centering the locomotive body relative to the bogie, etc [4]. Due to this, research of the characteristics of the body to bogie connection and further improvement of its design, aimed at improving the dynamic characteristics of the locomotive and, as a result, reducing force impact on the track and wear of tires and rails, is a topical task [5, 7, 8].

The supporting and returning devices of most locomotives are a combination of a rolling support and a block of the rubber-metal parts (RMP). The support simultaneously ensures the bogie swivel, lateral motion and vertical oscillations of the body relative to the bogies. Roller supporting and returning devices are mounted on the frame of the bogie in such a way that the relative motion of the bogies and the body in the horizontal and lateral direction takes place due to the elastic rubber-metal parts. The bogie swivel relative to the body is provided by deforming the RMP and rolling the rollers along the inclined surfaces.

As studies of diesel locomotives of the 2TE116 and TE121 series have shown, such a spring suspension does not ensure centering the body relative to the bogies with its lateral motion in the pivot gap, motion of the body from the middle position causes a one-sided overload of the wheel sets, which in its turn causes an increase in the slip of its axles when the traction force is realized, the body's non-centering results in a shift of the point of the traction force transfer from the bogie to the body from the central position, which causes yaw moment between them, and as a result, the bogie skew in the rail track, thereby increasing the lateral slip of the wheel sets [6]. The body's non-centering is obviously a consequence of the lack of lateral rigidity of the body to bogie connection.

2. Fluidic Muscle Parameters Research

To determine the parameters of effective operation of the supporting and returning devices, a technique for determining the characteristics of the shift of the rubber-metal parts has been developed.

In the locomotive body supports, the blocks of rubber-metal parts perceive the vertical load Q_o and the lateral horizontal force P_{lh} (Fig. 1). The support plates of the end RMP remain parallel to each other, regardless of the relative lateral motions of the body and the bogie. Taking into account this fact, the existing methods for calculating the elastic characteristics of a rubber shock absorber are unreasonably used to calculate the characteristics of blocks of several shock absorbers installed on each other [9]. At the same time, it is assumed that the remaining plates of the rubber-metal parts remain parallel to the support surfaces, regardless of the relative shift of the bogies under the body.

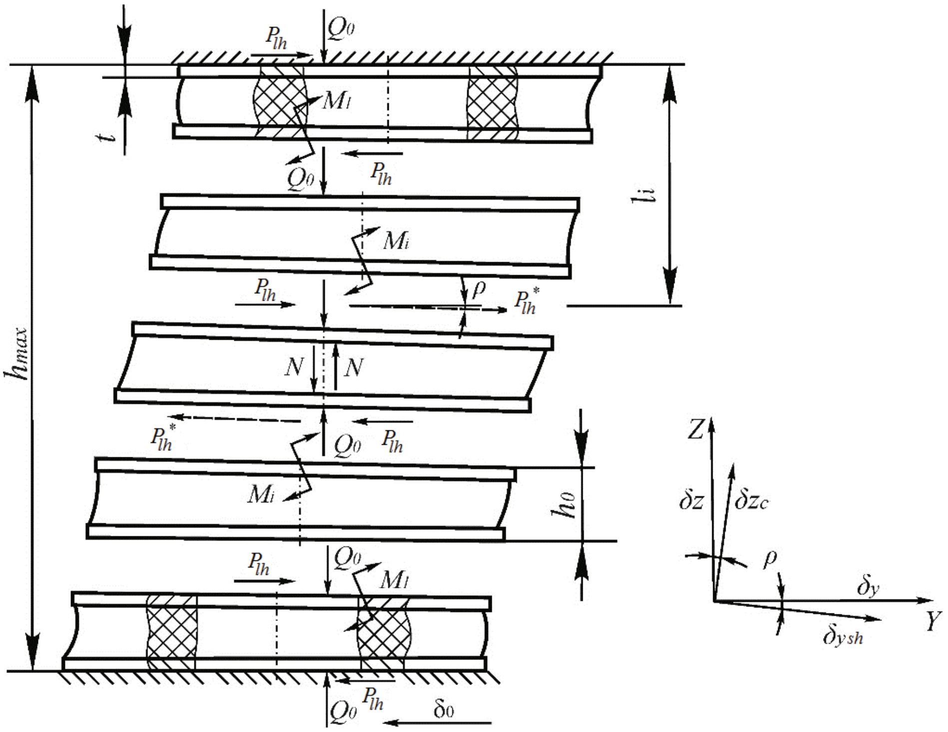

Fig. 1 The design model of the support block consisting of the rubber-metal parts

More precise ways of solving the problems of theory of elasticity with reference to one rubber part lie in establishing the value of stresses and motions that satisfy the equilibrium conditions and the boundary conditions, and in case of solving the system of equations they satisfy the compatibility conditions of deformations. The calculation method presented in the work [9, 10] is based on the application of the Ritz energy method, in which the expressions for motions corresponding to the conditions of the problem are given. They satisfy the condition of constancy of the volume. The deformation components and invariants are calculated based on motions; the deformation energy is calculated by integrating the expression of the specific energy in the whole volume; the potential of external forces is calculated and the expression of the total energy of the system is made; the coefficients are determined by the conditions of the energy minimum; the directions and values of the main deformations are determined; the main stresses in the sites of interest are determined.

The work presents a technique for calculating the compression characteristics of a column of flat rubber disks placed on the top of each other, vulcanized to steel plates. In this case, each of the rubber parts of the whole block is subjected to the same loads and deformations.

As experiments have shown, under real conditions, under the action of the returning force P_{lh} and the vertical load Q_o along with the lateral and vertical relative motions of the steel plates different in position in the *RMP* block the relative turn of the plates around the longitudinal horizontal axis is observed, which is explained by the different additional moments of forces M_l. Thus, while determining the elastic characteristics of the block of the rubber-metal parts, not only characteristics of one *RMP* and its quantity in the block should be taken into account, but also the vertical and horizontal loads creating bending moments of forces, differing in value, affecting each *RMP* block, i.e. their angular motions.

The solution of the problem of determining one of the elastic characteristics of the block of rubber-metal parts – rigidity on the lateral shear – is advisable to begin with the statement that the returning force P_{lh} is known, and then to find the value of the lateral motion of the support surfaces δ_o. Particular interest is in determination of the horizontal and vertical deformations of an average rubber-metal part when the support surfaces of the *RMP* block are laterally shifted to δ_o, taking into account the turn to the angle ρ (Fig. 1).

Let us assume that the vertical force Q_0 and the horizontal force P_{lh} are applied to the middle rubber-metal part. Parallelism of these plates indicates that the rubber packing does not perceive any bending moments. Then the resultant of the forces Q_0 and P_{lh} can be replaced by the normal pressure N and the shear force P_{lh}*:

$$N = Q_0 \cdot \cos\rho - P_{lh} \cdot \sin\rho\,; \tag{1}$$

$$P_{lh}^{*} = P_{lh} \cdot \cos\rho + Q_0 \sin\rho\,. \tag{2}$$

With an increase in the angle of inclination ρ of the rubber-metal part, the compression force decreases by the value ΔQ_0:

$$\Delta Q_0 = Q_0 - Q_0 \cdot \cos\rho + P \cdot \sin\rho . \qquad (3)$$

Respectively, deformation of the rubber part thickness will decrease by the value:

$$\delta^*_{z\,c} = \frac{\Delta Q_0}{S_c} , \qquad (4)$$

where S_c is rigidity of the rubber part compression, the value of which is determined as:

$$S_c = \frac{\pi\left(R^2 - r^2\right)E_c}{h_0} , \qquad (5)$$

where R - the radius of the rubber part; h_0 - thickness of the rubber part; k - the coefficient of the rubber part shape; E_c - elasticity module on compression of the rubber part, the value of which can be determined by the formula [10]:

$$E_c = 6 \cdot G\left(1 + k^2\right) , \qquad (6)$$

where G is the modulus of elasticity on the shear of the rubber part.

For the rubber part that is a hollow packing with the internal diameter d, the form coefficient k will be [11]:

$$k = \frac{D - d}{4h} . \qquad (7)$$

At the same time, the shear deformation along the plate becomes equal to:

$$\delta^*_{y\,sh} = \frac{P^*_{lh}}{S_{sh}} ; \qquad (8)$$

$$S_{sh} = \frac{\pi\left(R^2 - r^2\right)G}{h_r} ; \qquad (9)$$

$$h_r = h_0\left(1 - \frac{Q_0}{S_{sh}}\right) , \qquad (10)$$

where S_{sh} is the shear rigidity of the rubber part; G - the modulus of elasticity on the shift of the rubber part; h_r – thickness of the rubber part under the load.

The total vertical deformation of the inclined rubber part is equal to:

$$\delta_z = -\delta^*_{z\,c} \cdot \cos\rho + \delta^*_{y\,sh} \cdot \sin\rho . \qquad (11)$$

The horizontal deformation of the inclined rubber part is:

$$\delta_y = -\delta^*_{z\,c} \cdot \sin\rho + \delta^*_{y\,sh} \cdot \cos\rho . \qquad (12)$$

The value of the lateral motion of other rubber-metal parts in the support block can be determined with sufficient accuracy according to the angle of inclination of the steel plates of this *RMP*:

$$\delta_{yi} = -\delta^*_{z\,c} \cdot \sin\rho_i + \delta^*_{y\,sh} \cdot \cos\rho_i \qquad (13)$$

$$\rho_i = \frac{\rho^*_{i-1} + \rho^*_i}{2} \qquad (14)$$

where ρ^*_{i-1} - the angle of inclination of the outer (respectively to the block center) plate of the *i*-th *RMP*; ρ^*_i - the angle of inclination of the inner plate of the *i*-th *RMP*.

To find the angle of inclination of the RMP, we will consider the rubber packing as a deformed rod, which is under the action of the lateral force P_{lh} and the moment of the forces M_i under conditions of rigid mounting to the fixed surface at one end. According to the formulas of small deformations, it follows from Hooke's law that the calculated value of the angle of inclination of one steel plate regarding the other one can be determined by the formula:

$$\rho_i^* = \frac{P_{lh} h_r^2}{2EI_x} + \frac{M_i h_r}{EI_x} = \frac{h_r}{EI_x}\left(\frac{P_{lh} h_r}{2} + M_i\right), \tag{15}$$

where I_x - the moment of inertia of the rubber packing regarding the axis OY passing through its geometric center; M_i - the moment of force affecting the rubber-metal part and depending on its location in the rubber column, the value of which can be determined by the formula:

$$M_i = P_{lh} l_i + Q_0 \frac{\delta_0 \cdot l_i}{h_{max}} = \left(P_{lh} + Q_0 \frac{\delta_0}{h_{max}}\right) \cdot \left(h_r + 2t\right) \cdot i\,; \tag{16}$$

$$h_{max} = \left(h_r + 2t\right) \cdot n\,, \tag{17}$$

where n-amount of the *RMP* in the block; t - thickness of the steel plate; i-amount of the *RMP* from the center of the block.

Then the relative angular motion of the steel plates of one *RMP* is:

$$\rho_i = \frac{h_r}{EI_x}\left[\frac{P_{lh} h_r}{2} + \left(P_{lh} + Q_0 \frac{\delta_0}{h_{max}}\right)\left(h_r + 2t\right) \cdot i\right]. \tag{18}$$

It should also be taken into account that deformation of the rubber column increases in the lateral direction by a value equal to:

$$\delta_i^* = \frac{P_{lh} h_r^3}{3EI_x} + \frac{M_i h_r^2}{2EI_x} = \frac{h_r^2}{2EI_x}\left[\frac{2P_{lh} h_r}{3} + \left(P_{lh} + Q_0 \frac{\delta_0}{h_{max}}\right)\left(h_r + 2t\right) i\right]. \tag{19}$$

The value of the total lateral motion of the supporting surfaces, caused by the forces P_{lh} and Q_0 affecting one body support, consists of angles of turn and lateral motion of all the rubber-metal parts of the block. So, as for the support, the total lateral motion of the supporting surfaces is determined by the formula:

$$\delta_0 = \sum_{i=1}^{n} \delta_{yi} + \sum_{i=1}^{n} \delta_i^*\,. \tag{20}$$

The shear rigidity of the RMP block is determined as the result of dividing the value of the returning lateral force P_{lh} by the lateral motion of its support surfaces:

$$S_{shs} = \frac{P_{lh}}{\delta_0} \tag{21}$$

In the same way, the formulas were obtained for calculating rigidity for the blocks consisting of different amount of the *RMP*. Comparing the values of the elastic characteristics of the *RMP* block obtained by the proposed method with the values obtained by the existing technique [10, 12], when $S_{shsn} = S_{sh}/n$, where n is the amount of the *RMP* in the block, we determine that the difference among the values of the shear rigidity of the *RMP* block can reach 10%-40%. At the same time, with an increase in the horizontal force P_{lh}, the values of the static deflection may differ by 19%, in case of absence of the horizontal force this difference practically does not exist. With an increase in the vertical load on the support Q_o, the difference in the values of S_{shs} obtained by both techniques increases, in case of absence of the vertical load, this difference practically does not exist. Thus, the shear rigidity of the block of the rubber-metal parts, determined by the existing technique, differs from the proposed one as it does not take into account the differences in the conditions of deformations of the individual *RMP*, then, as experimental research shows, it introduces a significant error in the results obtained. Thus calculation of the shear rigidity of the block of seven *RMP* according to the developed technique allows increasing the accuracy of the calculation by 9 ... 10 times in comparison with the existing technique, that is, the difference between the calculated and experimental values of S_{shs7} decreases from 17 ... 40% to 1.65 ... 4%.

The advantage of the developed technique for calculating rigidity of the support shear with the *RMP* block is that its usage makes it possible to more accurately determine the elastic characteristics of the block with any predetermined number of the *RMP* and the value of the vertical load on the support.

According to the calculations performed, with an increase in the vertical load on the support and the number of the *RMP* in the block, the returning force in connection of the body to the locomotive bogies is expected to decrease as well as the stability of the body on the bogies. Thus, when designing the undercarriage, attention should be paid to the fact that to increase the dynamic qualities it is necessary to increase the static deflection, but at the same time to ensure stability of the supports by optimizing rigidity, thereby ensuring high traction and safe entry into the curved sections of the track.

3. Experiment

Experiments to determine elastic deformations of the *RMP* supports of various configurations in the horizontal plane; the choice of the rational design of the body side support on the bogie was carried out at the test stand of OJSC Holding Company “Luhaskteplovoz” [9].

The test stand allows simulating the real operating conditions of the locomotive returning devices. Fig. 2 shows the appearance of the test stand and the layout of the test stand (side view).

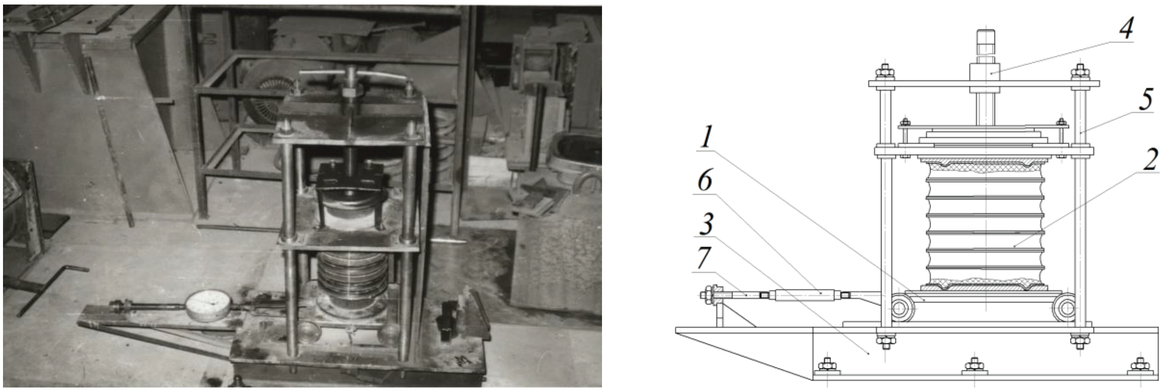

Fig. 2 General view and diagram (side view) of the test stand for static tests of the RMP. *1* - carriage; *2* - RMP; *3* - base; *4* - vertical load screw; *5* - frame post; *6* - dynamometer; *7* - horizontal load screw

The test stand consists of fixed base *3* on which movable carriage 1 simulating the bogie is disposed. On fixed base *1* there is installed frame post *5* with the vertical load screw, and the frame post of the horizontal load screw is fixed. Horizontal load screw *7* is connected with movable carriage 1 by dynamometer *6*. The tested *RMP* of the support is mounted between movable carriage *6* and vertical load unit *4* simulating the bogie and the body.

Prior to the beginning of the tests, all the *RMP* were checked for compliance with the requirements of the drawing. Under the static load of 110 *kN*, the vertical deflection of the RME and the support as a whole were measured.

The test stand works as follows.

In accordance with the test program, RMP set *2* is mounted to movable carriage 1 of the stand, the maximum motion of which is 140 mm. The vertical load was created by screw *4* by means of closed space frame *5* and base *3*. Horizontal motions of the support were carried out by screw *7*, the force measurements were made by dynamometer *6* of Dor 3-5 type.

A middle longitudinal line was drawn on each *RMP* support along its perimeter; for the *RMP* set, a vertical middle line was drawn. The intersections of these lines were used to measure both vertical and horizontal motions.

After loading the support with the static load of 110 *kN*, which was monitored by the deflection of the *RMP*, the horizontal force registered by the dynamometer was applied to the support; obtained horizontal and vertical motions of the *RMP* were measured with a ruler of 150 GOST 427-75.

Before rating the support performance, cyclic load was applied to the *RMP* set in the horizontal direction until stable characteristics were obtained.

The test results show that when combined vertical and horizontal forces are applied the *RMP* of series-produced support are not loaded equally, and the support configuration acquires a curved S-shape, which indicates the uneven stress condition of the support elements and possible loss of its stability. On the test stand, various designs of the supporting and returning devices with the *RMP* holes in different parts of the support were tested. The most effective solution was the support design, successfully implemented on the *TEP150* diesel locomotive [13].

Comparison of the results of weighing wheel by wheel showed that after installation of experimental supports, the centering of the locomotive body on the bogies was improved. Thus, the maximum actual difference in the loads of the wheels of one axis in the initial state reached more than 5%, which exceeds the permissible value of 4%. After re-equipping the section with experimental supports, the difference was 2%.

4. Construction Solution

The purpose of the design is high traction and dynamic, and brake qualities of the high-speed rolling stock, centering the body relative to the bogies during entry into curved sections of the track. The side support consists of eight rubber-metal parts (*RMP*), working on compression in the vertical direction and on twisting around the vertical axis (Fig. 3), the body, the lower support plate of which is connected by pins with the bearer and mounted in the pallet; the upper support with a lock, on which a set of rubber-metal parts is mounted. Each element consists of a rubber shock absorber, vulcanized to the metal plates. The interaction of the guide with the lock as well as the annular corrugations of the plates excludes the lateral shift of the rubber-metal parts in the sets and in the connections with the supports. The height of the set of the rubber-metal parts on the support is regulated by washers. There are two parallel rollers in the body, which are connected by clips. Movable parts of the support, moving in the body parallel to the lateral axis of the bogie, are guided by welded steel bars [Declarative patents for utility model №№ 8060, 50938, 46011, 45011].

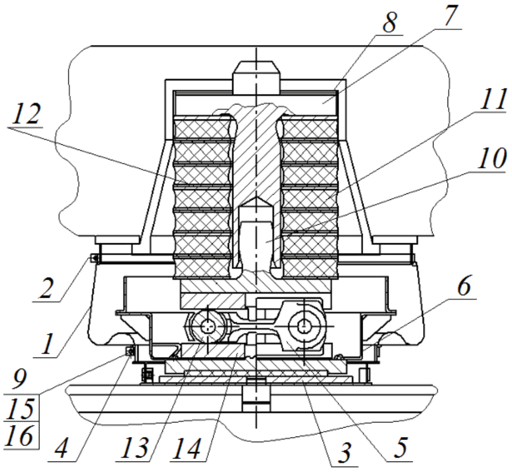

Fig. 3 Diagram of the lateral support of the body on the bogie

When the locomotive moves along the straight section of the track, the rollers occupy the middle position between the inclined surfaces of the supports. When entering the curves, the body shifts relative to the bogies due to motion of the support on the rollers (Fig. 4). In this case, the rollers, rolling on the inclined surfaces of the supports, create horizontal forces that tend to return the body into its initial position. A polymer plate (fluoroplast-4) is mounted on the lower plate of the roller; sliding friction of this plate along the steel plate ensures swiveling the bogies relative to the body in the horizontal plane. The bearer moves along the straight line perpendicular to the radius connecting the center of the support to the pivot.

When the vehicle is moving in the traction and braking mode, the upper part of lock *14* interacts with the lower part of lock *12* on the surface *"A"*, the gap *"B"* is reduced, eliminating compliance of the *RMP* block in the longitudinal direction of the vehicle axis. It helps to ensure parallelism of the upper and lower supporting surfaces of the *RMP*, and, accordingly, to redistribute the vertical load along the axes of the wheel sets, thereby providing better utilization of the adhesive weight, improving the traction and brake characteristics of the locomotive.

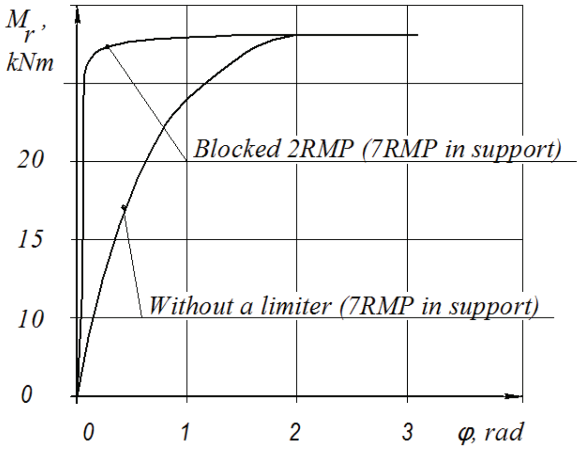

Fig. 4 The dependence of the returning moment M_r of the bogie swivel angle φ

When entering curved sections of the track, the RMP block is blocked, eliminating skewing of the body in the longitudinal direction. A covering is installed in the internal cavity of the support to protect it from dust and moisture. The cavity of the support is filled with oil.

The proposed design can be used for both high-speed rolling stock, and for cargo, shunting.

Full-scale tests of this support have shown that in the straight sections of the track at the speed of 100 km/h for the locomotive in the initial state, the maximum amplitudes of oscillations were 34 mm, for the locomotive with the experimental supports – 19 mm, the maximum swivel angles were respectively $13.2 \cdot 10^{-3}$ rad and $3.6 \cdot 10^{-3}$ rad.

5. Conclusions

In accordance with the purpose of the work, as a result of theoretical and experimental research, recommendations have been developed to improve adhesion of the body with the locomotive bogies. The developed technologies for calculating the shear rigidity of the support with the RMP block allows us to more accurately determine elastic characteristics of the block with any predetermined amount of the RMP and the value of the vertical load on the support. The proposed adhesions of the body with the bogies are tested on the test stand, and some of the proposed versions of the supports on a real locomotive. The developed with the participation of the author design of the side body support on the bogies, which allows providing the required elastic characteristics, was tested and introduced on the diesel locomotive *TEP150*. Installation of the experimental supports allowed improving the body centering of the locomotive on the bogies. The maximum actual load difference of the wheels of one axis in the initial state reached more than 5%, which exceeds the permissible value of 4%. After re-equipping the section with the experimental supports the difference was 2%.

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