

New Bogie for Flat Wagons Designed for High-Speed Container Transportation by Ukrainian Railways

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Summary

The paper is devoted to scientific and technical issues related to the development of a new generation bogie for the equipment of specialized flat wagons designed for high-speed transportation of containers. Based on the analysis of previous research results and main technical requirements, a technical solution for a bogie with an all-welded frame and axle-box spring suspension, provisionally named TFT, has been proposed. According to the estimated strength of the welded frame of the bogie, satisfactory compliance of the stress-strain state of the frame with regulatory requirements was established. By means of computer modeling, the dynamic performance indicators of the container flat wagon with TFT type bogies were determined in comparison with the case of equipping the flat wagon with three-piece bogies of the model 18-100. The corresponding mathematical models were built according to the calculation schemes of wagons as spatial multibody mechanical systems, taking into account the action of dry friction forces in the spring suspension and in the body supports on the bogies. The results of the study indicate significant advantages in terms of both cargo vibration protection and movement safety of the variant of equipping the flat wagon with TFT bogies. A significantly lower level of force action on the track of the flat wagon with TFT bogies was also noted.

Keywords: flat wagon, TFT type bogie, frame strength evaluation, model 18-100 bogie, calculations of dynamic indicators

1. Introduction

World experience convincingly proves that container railway transportation is becoming a necessary element of the transport system and an important indicator of its development [12, 13]. The prospects for the development of railway transport equipment and technologies are primarily associated with the introduction of high-speed container cargo transportation as a component of combined transport, which will ensure compliance with international standards, the main criteria of which are: the route speed (not less than 1000 km per day), the route schedule accuracy and the cargo safety.

As is known, the running qualities of rolling stock significantly depend on the characteristics of the running gears. Container flat wagons of the existing UZ wagon fleet are equipped with bogies of a three-piece structure. These are mainly model 18-100 bogies, which have certain limitations in terms of speed and vibration-proof characteristics [5]. According to the technical documentation, bogies of this type should ensure the speed of wagons up to and including 120 km/h, while in practice the permissible speed

of freight trains does not exceed 70–80 km/h. At the same time, there is an increased dynamic effect of freight wagons on the track, which leads to an accelerated breakdown of the track structure.

Repeated attempts to improve the dynamic properties of freight wagons by certain modernization of three-piece bogies did not allow solving the problem of achieving the speed of freight trains up to 120–140 km/h. Therefore, in order to realize the high-speed movement of freight trains, primarily container trains, qualitatively new approaches to the development of new type bogies are needed with an emphasis on ensuring the guaranteed safety of technical operation and minimal impact of freight wagons on the track.

In recent years, a technical solution for a high-speed bogie of domestic development has been proposed. The peculiarity of the structural scheme of the new bogie is the use of an all-welded frame and axle-box spring suspension. The main projected advantages of using this type of bogie are as follows:

- significant reduction in the mass of unsprung parts of the bogie, which has a positive effect on the run-

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ning characteristics of the wagon and its impact on the track and, as a result, reduces the cost of maintaining the railway infrastructure;

- significant reduction in the level of vibration accelerations of wagon bodies, which eliminates the danger of damage to cargoes sensitive to vibrations and shocks;
- no restrictions on the speed indicators of freight wagons, both in terms of dynamic indicators of motion safety, and from the point of view of braking characteristics.

2. General characteristics and technical solution of a new generation bogie

According to the technical requirements, the structural scheme of the new bogie should include: an all-welded frame; axle-box spring suspension; wheelsets with axle-box assemblies; braking equipment [17]. Design characteristics of the bogie: weight, not more than 5000 kg; base, not more than 1850 mm; design speed of the wagon, depending on the bogie modification – 120–160 km/h; calculated static load from the wheelset on the rails, depending on the bogie modification – 180–220 kN; transverse base along the axes of the spring sets – 2036 mm; static deflection of the suspension of a loaded wagon, not less than 70 mm; static deflection of the suspension of an empty wagon, not less than 20 mm.

Taking into account the many years of scientific and technical development regarding wagon running gears with axle-box spring suspension, the following requirements are proposed for the component parts of the new generation bogie.

The bogie frame must perform satisfactorily under operating conditions without the occurrence of such defects as static failure, residual deformation and fatigue cracks. Procedures for acceptance of the bogie frame should include the following stages: carrying out calculations; static tests; fatigue tests; operational tests.

The spring suspension of the bogie with spring sets and vibration dampers should provide elastic perception and damping of vertical, longitudinal and transverse dynamic actions on the over-spring part of the wagon. The force characteristic of the spring suspension of the bogie should be bilinear (two-mode) due to the use of springs of different heights or non-linear (rigid) when other elastic elements are used. Rigid and dissipative characteristics of the spring suspension should be chosen based on the condition of ensuring the stability of the wagon against hunting self-oscillations and normative values of dynamic indicators.

The balancer-type axle-box unit must contain a cassette-type roller bearing with a common outer

ring and built-in seals or a double bearing. The design of the axle-box assembly must allow turning of the wheelset behind the rolling circle of the wheels without dismantling the fastening.

Depending on the modification of the bogie, it is allowed to use both double-sided shoe brakes and disc brakes. At the same time, the maximum design speed of a wagon on bogies with a shoe brake should be at least 120 km/h, and with a disc and anti-slip device (140–160 km/h). For shoe brakes, composite two-section shoes should be used and anti-slip devices should be provided. The design of the brake should ensure the stability of the brake pressure and the uniform distribution of the braking forces on the wheelsets. The design of the bogie should allow the installation of automode.

The connection of the bogie elements, as well as the connection of the bogies with the wagon body, must be made in such a way that it is possible to lift the wagon together with the bogie. In order to facilitate the replacement of bogies, it is necessary to simplify the disconnection of the pivots of the bogies and the brake rods with the help of quick coupling mechanisms. Bogies must be equipped with safety devices that prevent bogie parts from falling onto the track. The design of bogies should provide for the location of nodes and parts to ensure convenient inspection and repair. It is recommended to make bogie elements with natural wear and tear-resistant materials.

Bogies must have indicators of reliability and maintainability in accordance with current regulations. When designing bogies, it is necessary to calculate the strength and fatigue life of its components, in particular, axles of wheelsets, elastic elements of spring suspension, vibration dampers, bearings, etc.

In accordance with the technical requirements, the design of the 1520 mm track freight (4) wagon bogie with the given technical characteristics was developed to its technical characteristics, this bogie belongs to the family of bogies, which have received the conditional name “track friendly trucks – TFT”. A number of bogie modifications are provided, depending on the design speed, including those designed to replace Y25 bogies on wagon rearrangement points and with gauge change wheelsets.

Figure 1 shows the general view of the TFT type basic bogie. A bogie of this type consists of two wheelsets with axle boxes (1), *H*-shaped frame of welded construction (2), axle-box spring suspension with vibration dampers (3), body support devices (4), and elements of the braking system (5).

The body of the axle-box has lugs for the installation of the axle-box springs and the support welded in the upper part for the installation of the overbox spring. In the empty mode, this spring is free and is included in the operation in the loaded mode. In this

way, a two-mode spring suspension with a bilinear force characteristic is realized. Inside the axle-box springs there is a spindle-type friction damper.

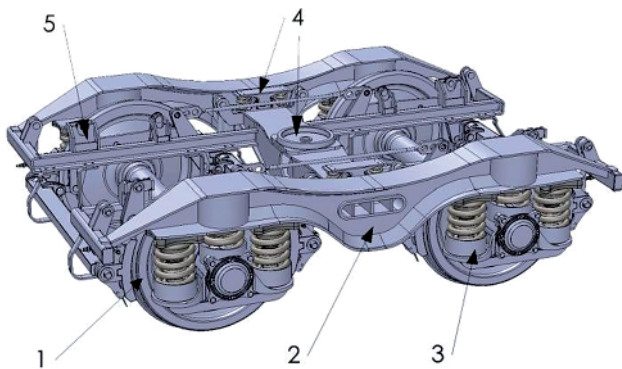


Fig. 1. Bogie type TFT

The body rests on the bogie frames through center plate assemblies and elastic side bearings. In turn, the bogie frame rests on the axle boxes of the wheelsets through cylindrical springs mounted on balancers. In the loaded mode, the axle-box springs are included in the operation. Damping of vertical vibrations is carried out by friction dampers, the friction forces in which depend on the spring suspension deflection. The schemes of the spring's position in the empty and loaded modes are shown in Figure 2.

The bogie frame structurally consists of two side beams and a pivot beam. In the middle part, it has a window for a welded connection with a pivot beam. On the consoles of the side beams, pads are welded for the installation of spindles. Hollow cups are welded in the side beams for the placement of the overbox springs. The upper part of the cup is used to support the base of the overbox spring under load in the loaded mode. A centre plate and side spring-loaded bearings are installed on the pivot beam. Rolled sheet steel 09G2 is used for the manufacture of the bogie frame.

The braking equipment of the bogie involves two-sided pressing of the brake shoes to the rolling sur-

faces of the wheels and consists of a system of levers, traverses with shoes and pads, additional beams for placing the brackets of the support points of the levers, and safety brackets for the suspension of the traverses. For bogie variants with design speeds of 140–160 km/h, the bogie is expected to be equipped with a disc brake and an anti-slip device.

Compared to three-piece bogies with cast side frames and bolsters, a bogie with a frame made by welding technology has a number of advantages, in particular:

- significant energy savings during the manufacture of the main load-bearing elements of the bogie;
- easier diagnosis of possible defects of the welded frame that occur in real operation conditions;
- in the case of cracks in the welded frame, their development is less intense from the moment of initiation to the complete loss of the load-bearing capacity of the structure, than in cast parts of a three-piece bogie.

3. Evaluation of the strength of the bogie frame of the welded structure

A number of scientific works are devoted to the analysis of the strength of bogie frames [2, 3, 14, 15]. Depending on the modifications of the bogies, different calculation schemes and load conditions are considered. The relevant calculations were carried out in accordance with the regulatory documents in force on railways of 1435 mm track gauge.

With regard to three-piece bogies by scientists of the Institute of Electric Welding named after Ye. O. Paton of the National Academy of Sciences of Ukraine proposed the development of side frames and bolsters of welded construction. In the work [9], the expediency of using all-welded load-bearing elements of a freight wagon bogie under the condition of ensuring their operational reliability is substantiated.

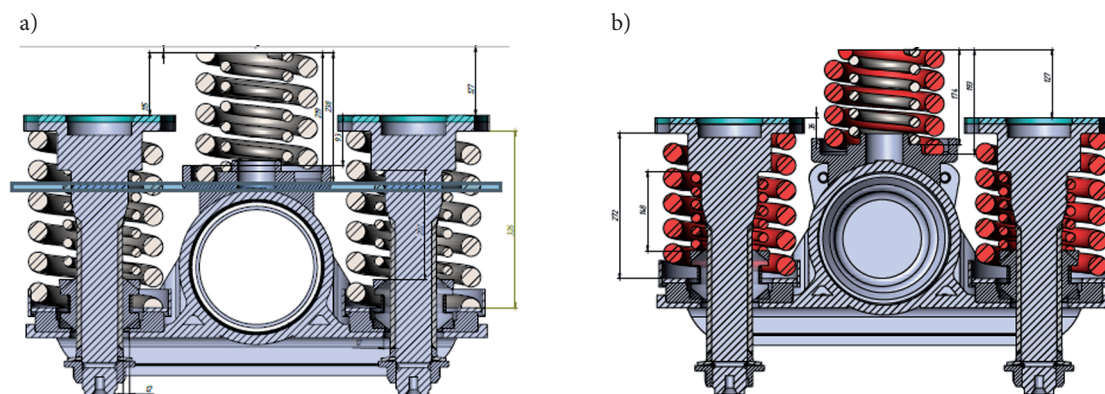


Fig. 2. Spring suspension of a TFT type bogie: a) wagon in the empty state, b) wagon in the loaded state

In accordance with the regulatory requirements [7], calculations of the strength of the frame of the TFT type bogie were performed according to the allowable stresses in the main design modes (I and III). The calculation model of the bogie frame is a system of two-dimensional finite elements. A standard grid is used for finite element calculations. The number of elements is 95,512 with a size of 26.4926 mm. The Solidworks Simulation application was used for calculations.

The values and combination of loads acting on the bogie frame are given in the Table 1. In the calculations according to the third mode, the maximum value of the coefficient of vertical dynamics $k_{dv} = 0.6$ is accepted.

In Figures 3 and 4 show pictures of the distribution of equivalent stresses on the bogie frame. From the results obtained for the first mode, the shock load case was selected as the most stressful.

In the first case (Fig. 3), the highest calculated stresses reached 250 MPa, in the second (Fig. 4) – 221 MPa. The permissible stress for the material from which it is recommended to make the frame of

the bogie (rolled steel sheet 09G2) is 274.5 MPa. Thus, the regulatory requirements regarding the strength indicators of the bogie frame are satisfied.

4. Modelling the flat wagon dynamics

The structural scheme of a flat wagon with TFT bogies is similar to the structural scheme of a freight wagon with Y25 bogies [16]. That is, it is a system of seven rigid bodies: body, 2 bogie frames, and 4 wheelsets.

The moment of friction forces during bogie frame turns relative to the flat wagon frame in the horizontal plane M_f is determined as the sum of the friction forces moments in the center plate assembly and in the side bearings. The value of M_f determines the resistance index of the bogie to turn X [13]: $X = M_f / (2a \cdot 2Q_0)$, where $2a$ is the bogie base, $2Q_0$ is the axial load. The X values should not exceed 0.16 for an empty wagon and 0.1 for a loaded one.

Taking into account the movement of the wagon along the elastic-viscous-inertial track, the calcula-

Design loads of the bogie frame of the TFT type

Table 1

Load mode	Load, kN		
	Vertical	Longitudinal	Lateral
Mode I (impact, jerk)	586,9	170,9	–
Mode I (quasi-statics)	586,9	–	153,7
Mode I (static + 100% dynamic additive)	757,6	–	–
Mode III ($k_{dv} = 0.6$)	666,0	488,1	312,1

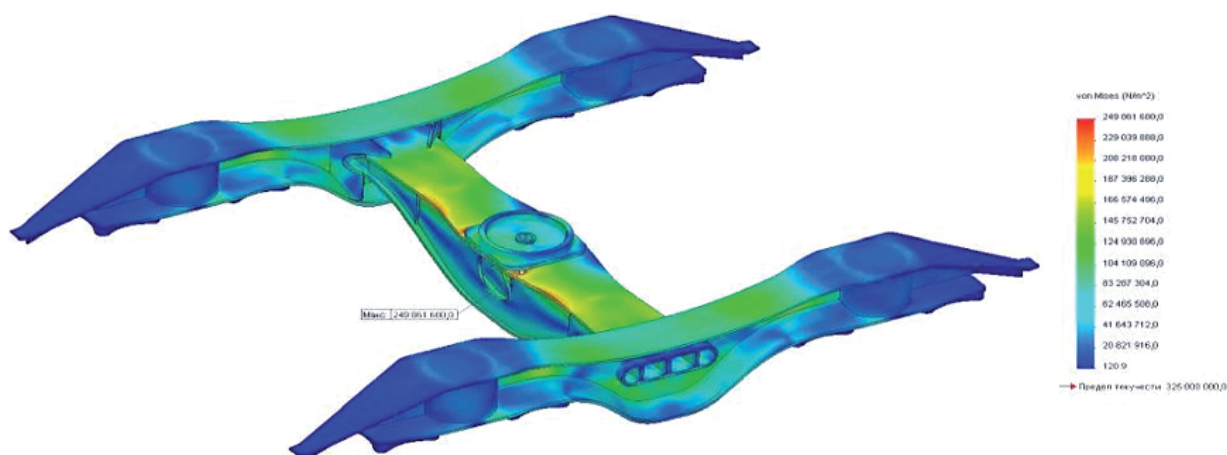


Fig. 3. The stress-strain state of the bogie frame when loaded according to mode I (impact, jerk)

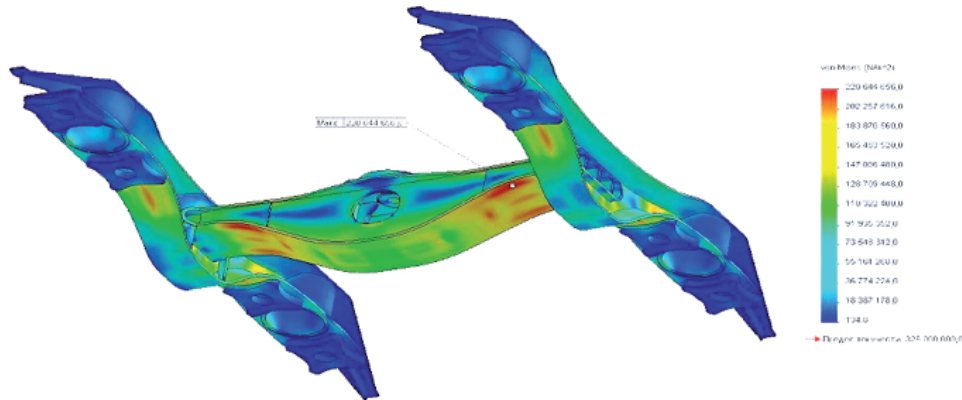


Fig. 4. The stress-strain state of the bogie frame when loaded according to mode III

tion scheme is supplemented with eight track masses reduced to each wheel. These masses have the ability to move in the vertical and transverse horizontal directions. The reduced masses are supported by springs and viscous friction dampers that model the elastic-dissipative properties of the rails and the sub-rail base.

Following the classical approach to the development of mathematical models of the dynamics of rail vehicles, founded by academician V.A. Lazaryan [8], the equations of motion of the wagon are written in the form of Lagrange equations of the second order. In this way, a system of 42 non-linear differential second order equations has been created, which describes the spatial vibrations of the wagon with TFT type bogies. The simulation of wagon forced vibrations due to movement on a track with irregularities is carried out by generating external disturbances in the form of random stationary processes with a Gaussian distribution in amplitude and spectral density that has a monotonically decreasing character. The recommendations of UIC Leaflet 518 on track roughness data used in modelling for the acceptance procedure were taken into account [1].

On the basis of the compiled mathematical model, an algorithm and computer software has been developed to evaluate the dynamic performance of the wagon with TFT type bogies. The dynamic performance was evaluated by analysing the results of numerical integration of nonlinear differential equations describing the vibrational motion of the studied wagon using the Adams-Bashforth method.

To obtain the dynamic performance of a flat wagon with 18-100 model bogies, a model similar to that presented in the monograph [6] was used. In this case, we are dealing with a design scheme in the form of a spatial system of 11 solids, which was modified to take into account the technical characteristics of the track.

5. Simulation results

According to DSTU 7598:2014, the assessment of the dynamic qualities of freight wagons is carried out according to the following indicators [7]:

- acceleration of the body in the areas of the center plate in the horizontal and vertical directions – $\dot{j}_h$ and $\dot{j}_v$;
- vertical dynamics coefficient k_{dv} as the ratio of the dynamic component of vertical forces to the static load;
- horizontal dynamics coefficient k_{dh} , which is numerically equal to the value of the frame force H_f (the horizontal lateral force acting from the side of a separate wheelset on the bogie frame) in the shares of the axial load P_a , i.e. H_f / P_a ;
- safety factor of the wheelset against derailment provided that the wheel flange does not roll onto the rail head k_{ds} .

Table 2 shows the standard values of dynamic indicators. The coefficient of stability margin of the wheelset against derailment in the case of rolling of the wheel flange on the head of the rail k_{ds} is a standardised indicator used to assess the dynamic behaviour of rolling stock in terms of motion safety on railways with a track gauge of 1520 mm. The value of this coefficient, when the vehicle moves at maximum speed on a straight track of satisfactory condition with a combination of deviations in the plan, distortions and permissible drawdowns, is calculated by the formula [7]:

$$k_{ds} = \frac{\text{tg}\beta - \mu}{1 + \mu \cdot \text{tg}\beta} \cdot \frac{P_v}{P_h} \geq [k_{ds}] \quad (1)$$

Where:

β – is the angle of inclination to the horizon of the generative cone-shaped surface of the wheel flange;

Table 2

Standard values of indicators of dynamic qualities of freight wagons

Motion assessment	Vertical dynamics coefficient k_{dv}		Horizontal dynamics coefficient k_{dh}		Vertical accelerations j_v in fractions g		Horizontal accelerations j_h in fractions g	
	loaded	empty	loaded	empty	loaded	empty	loaded	empty
Excellent	0.20	0.50	0.20	0.25	0.20	0.50	0.10	0.20
Good	0.35	0.60	0.25	0.30	0.35	0.60	0.15	0.25
Satisfactory	0.40	0.70	0.30	0.38	0.45	0.70	0.30	0.40
Allowable	0.65	0.75	0.38	0.40	0.65	0.75	0.45	0.55

μ – is the coefficient of friction of the sliding surfaces of the interacting wheels and rails;

P_v – is the vertical component of the forces acting from the wheels on the rails;

P_h – is the horizontal component of the forces of interaction between the wheel and the rail, which acts simultaneously with the force P_v .

In formula (1), the ratio of the vertical and horizontal components of the forces acting from the wheels on the rails is determined as follows:

$$\frac{P_v}{P_h} = \frac{P_{aj} \left[\frac{2(b-a_2)}{l} - k_{dv}^* \frac{(2b-a_2)}{l} + k_{dv}^{**} \frac{a_2}{l} \right] + q \frac{b-a_2}{l} + \frac{r}{l} H_f}{\mu \left[\frac{2(b-a_1)}{l} + k_{dv}^* \frac{a_1}{l} - k_{dv}^{**} \frac{(2b-a_1)}{l} \right] + \mu q \frac{b-a_1}{l} + (1 - \frac{r}{l} \mu) H_f}, \quad (2)$$

Where:

P_{aj} – is the static load on the axle journal;

H_f – is the frame force;

q – is the weight of unsprung parts;

$2b$ – is the distance between axle journals of the wheelset ($2b = 2.036$ m);

a_1, a_2 – is a projection on the axis of distances between point of contact of rails and leading and driven wheels and midpoint of journals ($a_1 = 0.25$ m, $a_2 = 0.22$ m);

r – is the radius of rolling circumference of moderately worn wheel ($r = 0.45$ m);

l – is an average distance between points of contact of wheels and rails ($l = 1.58$ m);

k_{dv} – is the coefficient of vertical dynamics for the in-running (k_{dv}^*) and non-in-running (k_{dv}^{**}) wheels.

For freight wagons, the permissible value of the safety factor of the wheelset against derailments is taken to be $[k_{ds}] = 1.3$ [11].

In the analysis of the results of calculations to determine the dynamic indicators of a loaded flat wagon, the main attention is paid to the indicators of

vibration loading of the body, namely, the frame acceleration in the areas of the center plate assemblies in the horizontal and vertical directions – j_h and j_v . In addition, we consider traffic safety indicators, i.e., horizontal dynamics coefficients k_{dh} and safety factors of a wheelset against derailment provided that the wheel flange does not roll onto the rail head k_{ds} .

Table 3 shows the extreme values of the dynamic indicators of the flat wagon in the loaded state. Here, the numerator is the value of the indicators obtained in the case of using TFT bogies, and the denominator is the value of the indicators obtained in the case of using 18-100 bogies.

Table 3

Values of dynamic indicators of the flat wagon in the loaded state

V, km/h	j_h , m/s ²	j_v , m/s ²	k_{dh}	k_{ds}
60	0.94/1.72	0.57/2.07	0.05/0.28	3.10/1.42
80	0.89/1.77	0.69/2.05	0.05/0.28	3.06/1.48
100	0.85/1.89	0.70/2.45	0.05/0.27	3.08/1.45
120	0.91/2.46	0.82/2.42	0.06/0.30	2.98/1.47
140	0.93/3.58	0.97/1.94	0.06/0.29	2.95/1.48
160	0.93/8.07	1.13/1.99	0.07/0.85	2.81/0.80

The tabular data indicate that the level of flat wagon horizontal accelerations with TFT bogies does not depend much on the motion speed and is significantly lower compared to the case of the flat wagon with 18-100 model bogies. This difference increases with increasing speed. Thus, if at $V = 60$ km/h the ratio of accelerations in question is 1:1.8, then at $V = 120$ km/h this ratio is 1:2.7. At $V = 160$ km/h, the accelerations obtained for the flat wagon with 18-100 model bogies reach 8.1 m/s², which is significantly higher than the maximum permissible value of 0.45 g.

The level of vertical accelerations of the flat wagon with TFT bogies increases gradually with the increase

in the speed of movement. The dependence on the speed of vertical accelerations obtained for the platform on model 18-100 bogies is variable, remaining above the level of accelerations determined for the platform on TFT bogies.

The values of the horizontal dynamics coefficient k_{dh} obtained for the wagon with TFT bogies are not very sensitive to changes in speed. Up to a speed of 140 km/h, the k_{dh} values for the wagon with TFT bogies are at least 4.5 times lower than those obtained for the wagon with 18-100 bogies. At $V = 160$ km/h, the k_{dh} value for this wagon is more than twice the maximum permissible value of 0.4.

The data on safety factors of a wheelset against derailment k_{ds} presented in the table indicate a small margin of stability of the flat wagon with bogies 18-100. In this case, at $V = 160$ km/h, the value of k_{ds} is 1.6 times lower than the maximum permissible value of 1.3, while the lowest value of this coefficient obtained for the wagon with TFT bogies is more than twice the permissible value.

The dynamics of wagons in the empty state is the subject of numerous studies, which is explained by the tendency of empty wagons to lose stability in the rail track. As noted in [6], the actual speed of a train with empty wagons is limited to 70 km/h, which is significantly lower than the design speed specified in the technical characteristics of the wagons – 120 km/h. The obtained extreme values of the flat wagon's dynamic performance in the empty state are shown in Table 4.

Table 4

Values of dynamic indicators of the flat wagon in the empty state

$V, \text{ km/h}$	$j_h, \text{ m/s}^2$	$j_v, \text{ m/s}^2$	k_{dh}	k_{ds}
60	2.17/2.12	1.69/2.08	0.10/0.33	2.47/1.44
80	2.92/2.20	1.83/2.25	0.13/0.34	2.31/1.42
100	3.43/2.43	2.75/2.78	0.16/0.35	2.22/1.42
120	3.99/3.09	4.19/3.06	0.20/0.41	2.18/1.40
140	3.89/4.82	4.27/2.96	0.19/0.44	2.09/1.30
160	4.16/ –	4.48/ –	0.18/ –	2.07/ –

From the comparison of the calculated acceleration values in both the horizontal and vertical directions, it can be stated that the levels of these accelerations are close and meet the regulatory requirements. The results of the analysis of the obtained values of the horizontal dynamics coefficient k_{dh} show that at $V = 120$ km/h, the k_{dh} value for the flat wagon with 18-100 bogies exceeds the maximum permissible value, while for the flat wagon with TFT bogies this indicator is two times lower.

Regarding the k_{ds} indicator it can be noted that the safety margin in the rail track of the flat wagon with TFT bogies at $V = 120$ km/h is 1.5 times higher than that established for the flat wagon with 18-100 bogies. The calculations show that at $V = 140$ km/h the k_{ds} value for the flat wagon with 18-100 bogies reaches the permissible limit, and at $V = 160$ km/h the flat wagon loses stability in the rail track.

The results of calculations of the vertical dynamics of the wagon in the loaded state show that the k_{dv} values obtained for a wagon with TFT type bogies at speeds up to 140 km/h inclusive are at least two times lower than for a wagon with bogies of the 18-100 model and do not exceed 0.10. In the case of an empty mode, the values of this indicator in both variants of the use of running gear are close and meet the excellent rating.

Important indicators of the dynamic running qualities of freight wagons also include the forces of interaction between wheels and rails. It is important to note that the stability of the rail track against transverse displacement depends on the level of lateral forces. According to the calculated data, the level of dynamic track loading by lateral forces from the flat wagon with TFT bogies is significantly lower than the impact on the track of the flat wagon with 18-100 bogies. In particular, in the loaded mode at $V = 120$ km/h, the ratio of lateral forces is 1:7.5, and in the empty mode – 1:8.4, which confirms the “track friendliness” of the TFT type bogies.

6. Conclusions

Based on the results of the analysis of previous studies and taking into account the experience of wagon building for 1435 mm track gauge railways, the feasibility of designing a bogie for 1520 mm track gauge railways with an all-welded frame and axle-box spring suspension for freight wagons of high-speed container trains has been proved. The basic design of the “track friendly” bogie with a conditional name TFT was developed according to the existing technical requirements.

According to the estimated strength of the welded frame of the TFT type bogie, satisfactory compliance of the stress-strain state of the frame with regulatory requirements was established.

The results of the dynamic properties study of the flat wagon for the transport of containers in two variants of equipment with running gears – TFT type bogies and 18-100 model bogies – indicate significant advantages of the first variant both in terms of cargo vibration protection and motion safety. A significantly lower level of lateral impact on the track of the flat wagon with TFT bogies was noted.

The obtained simulation results are of an evaluative nature, but they convincingly prove the prospects of the project for the development of high-speed bogies with all-welded frames and axle-box spring suspension.

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