JUSTIFICATION OF THE POSSIBILITY FOR EXTENDING THE SERVICE LIFE OF CAST PARTS OF A THREE-AXLE BOGIE BASED ON RESULTS OF THE RUNNING STRENGTH TESTS TO DETERMINE THEIR LOADING

Rustam Rahimov*, Diyor Zafarov

Faculty of Railway Transport Engineering, Tashkent State Transport University, Tashkent, Republic of Uzbekistan

*E-mail of corresponding author: rakhimovrv@yandex.ru

Rustam Rahimov 0000-0002-5652-2604, Diyor Zafarov 0000-0003-0100-4815

Resume

The article presents the results of research aimed at assessing the residual life and the possibility of extending the service life of cast parts of a UVZ-9M three-axle bogie used in six-axle scale test wagons. The tests have shown that the maximum stresses in the most stressed areas of the side frame, spring and pivot beams are within acceptable values, which indicates the presence of a residual life. The analysis of safety margin coefficients confirmed that the bogie elements have a significant reserve of operational characteristics. Calculations of the full service life of cast parts, performed based on the experimental data, demonstrated a sufficient residual life to prolong their use. It has been scientifically and experimentally proven that the cast parts of the UVZ-9M three-axle bogie can be safely operated for 5 years.

Available online: https://doi.org/10.26552/com.C.2025.035

Article info

Received 20 January 2025

Accepted 22 March 2025

Online 16 April 2025

Keywords:

scale test wagon

three-axle bogie

cast parts

stress

residual life

running strength test

safety margin

ISSN 1335-4205 (print version)

ISSN 2585-7878 (online version)

1 Introduction

Extending the service life of railway wagons and their assemblies in modern conditions is an important element of optimizing the operation of transport infrastructure, which contributes to the effective management of their resources while ensuring the continuity and uninterrupted transportation process. It contributes to a significant reduction in capital costs associated with the acquisition of the new rolling stock, and leads to an optimization of the cost of maintaining a serviceable fleet. At the same time, it also has significant disadvantages associated with increased repair and maintenance costs, a decrease in the repair interval and, in some cases, a deterioration in the operational characteristics of wagons, which directly affects the efficiency of their use. A number of scientists and research centers around the world are working on the issues of determining the remaining resource and the possibility of extending the service life of rolling stock and their components.

The authors of [1] proposed modelling and analysis of the remaining service life of railway wagons in the Swedish mining company LKAB. To achieve this goal, the behavior of critical subsystems in the case of failures was analyzed. Then, taking into account effective operational factors, proportional hazard model (PHM) was applied to calculate reliability functions. Within the framework of this concept, it was possible to obtain and analyze the remaining life of wagons with different initial service life.

Work [2] presents a methodology for predicting the remaining service life of both wheels and freight wagons by combining the data from three types of sensors, including wheel shock sensors, machine vision systems and optical geometry sensors. Many new functions are being created based on the normalization of objects, signal characteristics, and summary statistics for previous periods. Missing data is processed in the missForest environment, using a nonparametric algorithm for calculating missing values. Several data mining methods have been implemented and compared to predict the wheel and truck wear on the Class I railroad network in the United States. Numerical tests have shown that the proposed technique makes it possible to accurately predict the wear of railway carriage components, especially in the medium term.

In [3], a method was proposed for assessing the fatigue of axles subject to scratches, which can be used for maintenance and evaluation of damaged axles of high-speed railways. Geometric parameters and the type of load were taken into account to assess the safety of operation of axes subject to scratches. The fatigue limit curve of axes prone to scratches was calculated using the Murakami equation. The results of the study show that when the critical scratch depth is exceeded, the fatigue strength decreases with increasing groove depth. Otherwise, the groove depth has no noticeable effect on the fatigue characteristics of EA4T steel. This means that a critical roughness value can be achieved for high-speed axles made of EA4T steel, which can be very important in the production and maintenance of high-speed railway axles.

The authors of [4] have previously proposed a phased fatigue assessment system for a wheelset with internal axle boxes, which includes a safe service life as the first level and damage resistance as the second level. The estimated load range was used to estimate the remaining service life of the damaged axle made of EA4T steel. The calculation results show that the critical safety zone has been moved to the center of the axis, unlike classical axes, where the probability of a 1.0 mm deep crack spreading, which is the limit of control, is lower. In addition, the wheelset with internal axle boxes shows a lower stress value. The analysis, based on the well-known Kitagawa-Takahashi diagram, indicates a safety risk when using only the rated stress method.

Separately, it is worth noting the work [5], which defines the remaining life of the load-bearing structures of platform wagons with a service life of 25 years. The authors conducted the full-scale tests of the technical condition of the load-bearing structures of the platform wagons on the basis of the Southern Railway depot of "Ukrzaliznytsia" JSC. The model 13-401 platform wagon was chosen as the object of the study. It has been established that the estimated service life of the load-bearing structures of the studied platform wagons, taking into account the extension of their service life, is at least 18 years. The strength of the load-bearing structure of the platform wagon was calculated using the finite element method in the environment of the SolidWorks Simulation (COSMOSWorks) software. In the course of the work, the authors found that the maximum equivalent stresses occurring in the area of interaction of the support beam with the pin are 337.5 MPa, which ensures the strength of the load-bearing structure of the platform wagons. Additionally, an assessment of the progress of the platform wagons has been determined, in the MathCad software environment, using the Runge-Kutta method. The calculations performed show that the wagon's rating is "excellent". Thus, the results of the study contribute to improving the efficiency of combined transportation in international traffic.

There is a well-known study [6] in which, to confirm the service life of freight wagons, the authors evaluated and compared the results of durability and running dynamic strength tests of analog wagons, as well as digital modelling in the "Universal Mechanism" software package. As a result of the testing of this technique, the service life of the hopper wagon models 19-1272-01 and 19-1298, manufactured by JSC "Ruzkhimmash", which is 32 years, was confirmed.

2 The status of the issue, goals and objectives of the work

Summarizing the introductory part of the work, the following conclusions can be drawn:

- methods for assessing the residual life of the railway rolling stock and its components are constantly being improved using modern engineering programs and experimental techniques. However, most research focuses on high-speed rolling stock and general-purpose rolling stock (freight and passenger wagons);
- a number of studies have been conducted on the running gear of the rolling stock, where the object of research is often a two-axle three-element bogie due to its widespread use;
- despite the growing demand for three-axle bogies, their cast bearing components (side frame, springboard and pivot beam) have not been subjected to fatigue strength tests. The regulatory framework for three-axle bogies is poorly developed, mainly attention is paid to two-axle bogies of freight wagons.

It is worth noting that many studies have been conducted in world practice [7-11] aimed at determining the load capacity, residual resource, reliability and fatigue resistance of parts and assemblies in mechanical engineering, in particular the railway rolling stock. The main focus of the research was on high-speed rolling stock, general-purpose wagons and their components. In this regard, the ways of solving issues related to the study of the loading of cast parts of three-axle bogies to determine their residual life, have not been sufficiently investigated nor fully formulated. Taking into account the above, the purpose of this work is to scientifically substantiate the possibility of extending the service life of three-axle bogies of the UVZ-9M models to increase the efficiency of using their resource by experimentally examining the loading of cast parts (side frame, springboard and pivot beam) of this bogie and comparing the results obtained experimentally to calculated and normative data. Thus, the object of research in this work is a three-axle bogie model UVZ-9M, manufactured in 1965 and operated under the scale test wagons of type 640-VPV, and the subject of the study is the loading of cast parts of this bogie.

3 The methodology of the experiment

For an experimental study of the loading of cast parts of a three-axle bogie of the UVZ-9M model, the determination of which makes it possible to assess the residual life of these parts and justify the possibility of extending their service life, a Methodology was developed [12] for conducting the running strength tests of a six-axle scale test wagon of type 640-VPV using the strain gauge method. During the tests, the coefficients of dynamic addition of sprang and non-sprang parts of the wagon bogie were also determined [13].

According to the Methodology [12], the running strength tests were carried out on a track of a length of more than 5 km, without precipitation, under climatic conditions from +9 to +15 ° C using a traction locomotive. At the same time, measuring instruments were placed in conditions that ensure their operation within the passport data. Prior to the start of the tests, strain gauges of the BBF200-10AA-A(11)-BX30 type were

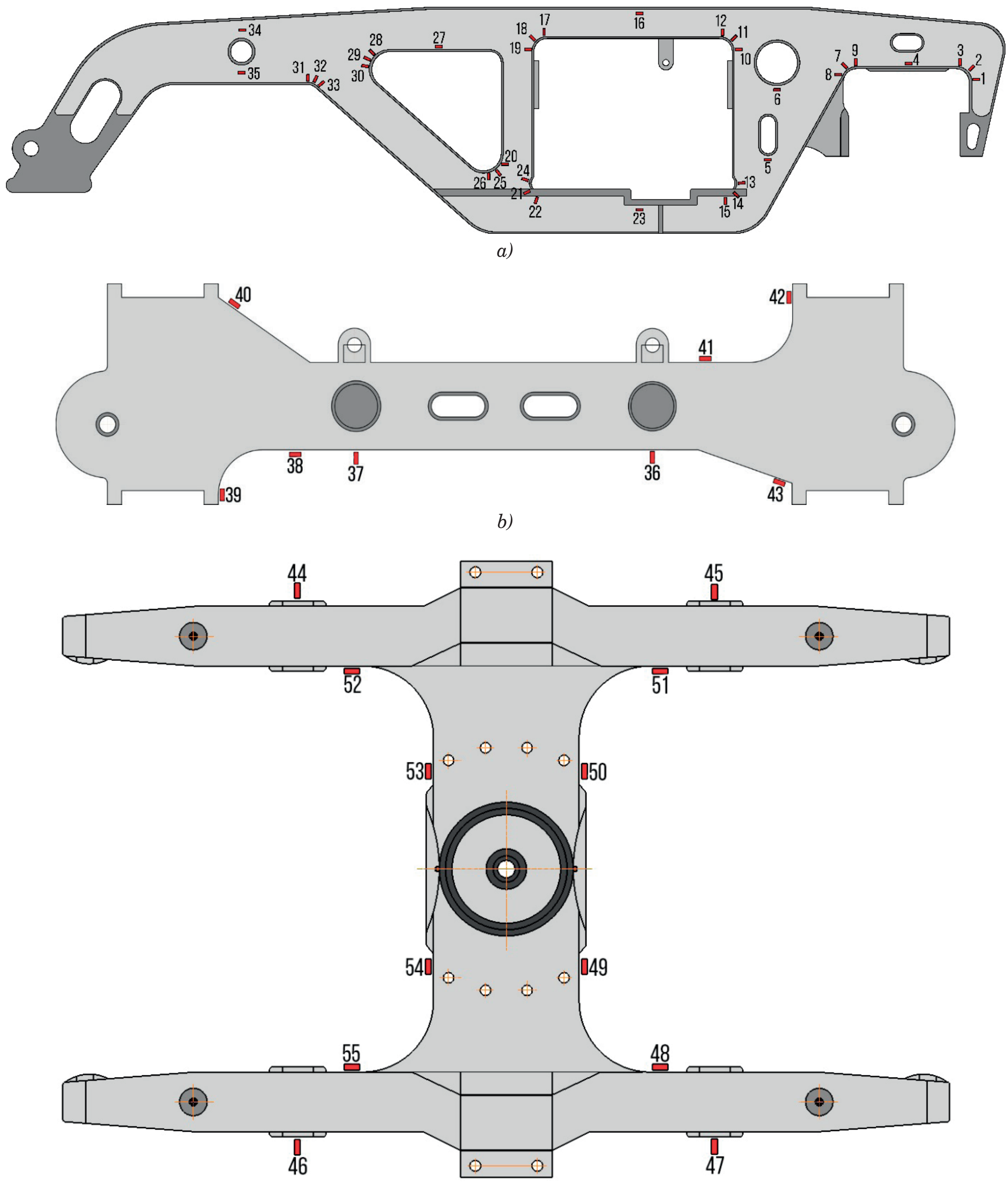
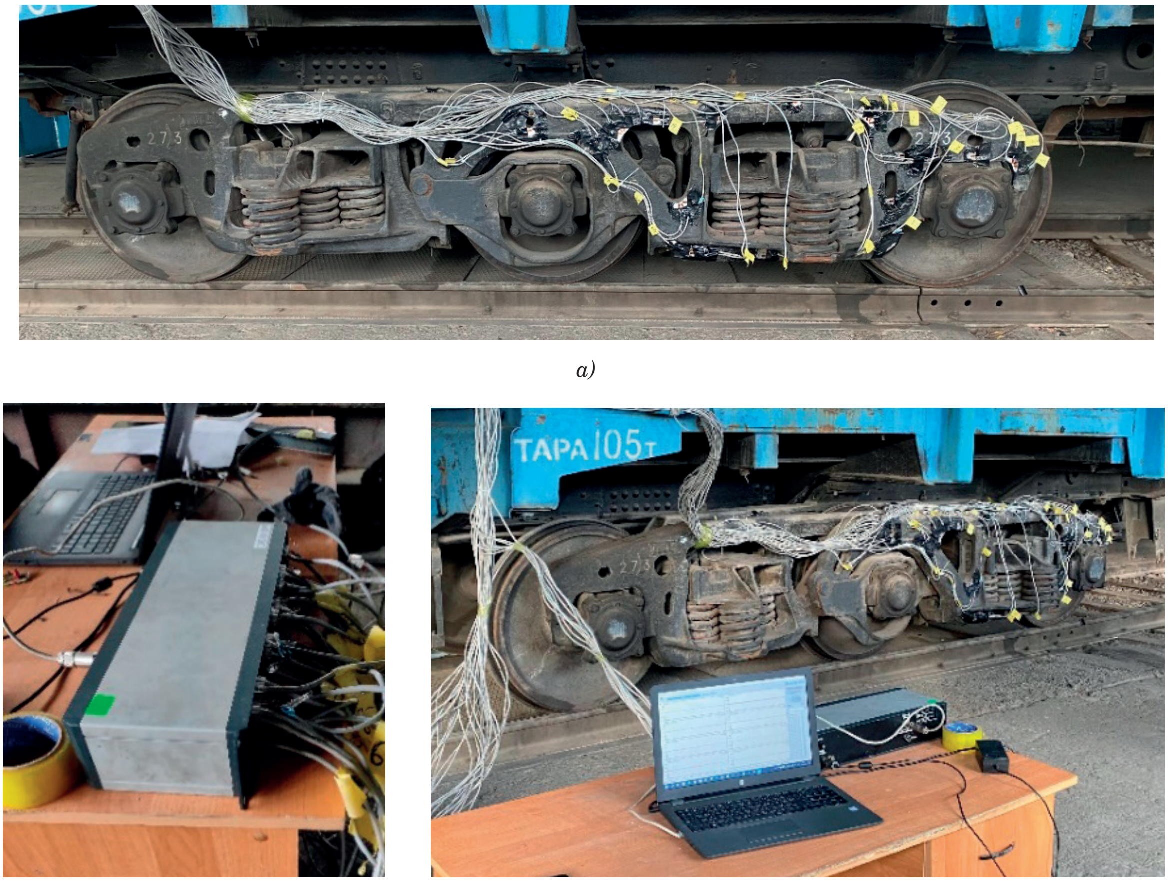


Figure 1 *Scheme of the installation of strain gages on the side frame (a), spring (b) and pivot (c) beam of the bogie model UVZ-9M of six-axle scale test wagon type 640-VPV*



a)

b) c)

Figure 2 *Installation of strain gauges (a), combining them into channels (b) and connecting to a multi-channel strain measuring system type MIC-185 and a computer (c)*

glued to the control zones of the cast parts of the three-axle bogie according to the scheme recommended in the Methodology (Figure 1). The scheme of installation and connection of strain gauges to determine the coefficient of dynamic addition of sprangunsprang parts on the side frame of the bogie was carried out in accordance with State Standard 33788-2016 [14].

After installing the strain gauges on the elements of the bogie and combining them into working channels, they were connected to a multi-channel strain measuring system of the MIC-185 type, which, in turn, was connected to a computer with the Recorder program installed to receive measuring signals (Figure 2).

The constant calibration coefficients of the strain gauge scheme, necessary to measure the coefficients of dynamic addition of sprang and non-sprang parts of the bogie, were determined by gradually raising and lowering the body of the scale test wagon using jacks.

4 Conducting the running strength tests

To carry out the running strength tests, an experimental trailer was formed (Figure 3), consisting of a scale test wagon and a locomotive (Figure 4).

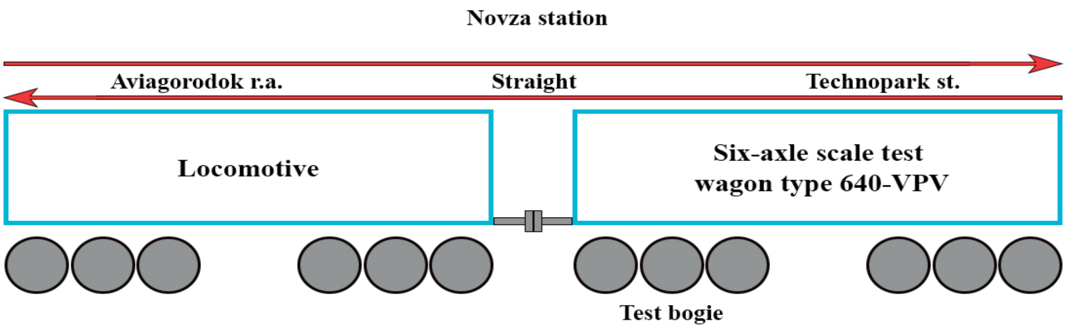


Figure 3 *Experimental trailer scheme*

Figure 4 *Scale test wagon and a locomotive*

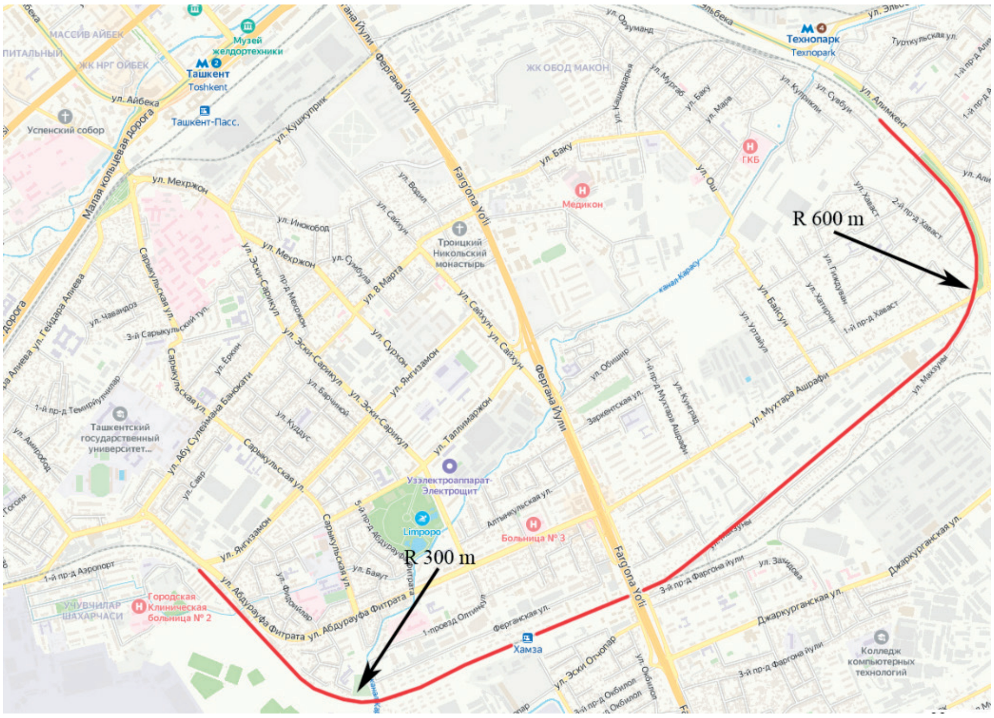


Figure 5 *Diagram of the test section of the railway track*

Table 1 *Conditions for passing the straight and curved sections of railway track during running strength tests*

Track	Speed, km·h^{-1}							
A straight section of the track	10	20	30	40	50	60	70	80
A curved section of the track:								
R = 300 m	10	20	30	40	50	×	×	×
R = 600 m	10	20	30	40	50	60	×	×

The test section of the railway track included curved sections with a radius of R=300 m, R=600 m and a straight section of the railway track according to [12] (Figure 5).

The conditions for passing straight and curved sections of railway track during the running strength tests of cast bogie parts of the UVZ-9M model of six-axle scale test wagons of type 640-VPV are shown in Table 1.

The collection of the necessary and sufficient array of experimental data during the passage of straight and curved sections of the track in each speed range was carried out in three passes according to State Standard 33788-2016 [14]. The average values of the obtained experimental data were selected for subsequent processing and analysis. The results were processed using the WinPOS software.

For the strain gauges installed in orthogonal *x, y* directions and at an angle of 45° to them, measuring relative deformations, ε_x, ε_y, ε_{45}, the corresponding main relative deformations ε_1, ε_2 were determined by the formulas [14]:

$$\varepsilon_1 = \frac{1}{2}\Big(\varepsilon_x + \varepsilon_y + \frac{\varepsilon_x - \varepsilon_y}{\cos 2a}\Big),$$

$$\varepsilon_2 = \frac{1}{2}\Big(\varepsilon_x + \varepsilon_y + \frac{\varepsilon_x - \varepsilon_y}{\cos 2a}\Big), \qquad (1)$$

$$tg2a = \frac{2\varepsilon_{45} - (\varepsilon_x - \varepsilon_y)}{\varepsilon_x - \varepsilon_y},$$

where ε_x, ε_y, ε_{45} are the relative deformations for the strain gages installed in orthogonal x, y directions and at an angle of 45° to them.

The equivalent stress, MPa, was determined by the formula:

$$\sigma_e = \sqrt{\sigma_1^2 + \sigma_2^2 - \sigma_1\sigma_2}, \qquad (2)$$

where σ_1, σ_2 are the corresponding stresses at the measured relative strain ε.

Table 2 *The results of running strength tests on a straight section (side frame, MPa)*

Strain gauge	Zone	Speed (km·h^{-1})							
		10	20	30	40	50	60	70	80
1, 2, 3	The outer corner of the axle box opening	20.0	24.2	29.3	35.5	42.9	51.9	62.8	73.5
4	The edge of the upper belt above the axle box opening	17.7	21.5	26.0	31.4	38.0	46.0	55.7	67.4
5	The edges of the technical holes	11.3	13.6	16.5	19.9	24.1	29.2	35.3	42.8
6		12.2	14.8	17.9	21.7	26.2	31.7	38.4	46.4
7, 8, 9	The inner corner of the axle box opening	15.1	18.2	22.1	26.7	32.3	39.1	47.3	57.2
10, 11, 12	Upper outer right corner of the spring opening	14.1	17.1	20.6	25.0	30.2	36.5	44.2	53.5
13, 14, 15	Lower outer right corner of the spring opening	17.3	21.0	25.4	30.7	37.1	44.9	54.4	65.8
16	Upper belt above the spring opening	16.4	19.9	24.1	29.1	35.3	42.7	51.6	62.5
17, 18, 19	Upper outer left corner of the spring opening	14.1	17.1	20.7	25.0	30.2	36.6	44.3	53.6
20	The lower edge of the technical hole	16.8	20.3	24.6	29.8	36.0	43.6	52.7	63.8
21	Lower outer left corner of the spring opening	19.2	23.3	28.2	34.1	41.2	49.9	60.4	73.0
22		19.7	23.9	28.9	34.9	42.3	51.1	61.9	72.9
23	Lower belt above the spring opening	20.4	24.6	29.8	36.1	43.6	52.8	63.9	73.1
24	Lower outer left corner of the spring opening	20.1	24.3	29.5	35.6	43.1	52.2	63.1	72.4
25	The lower edge of the technical hole	14.5	17.5	21.2	25.6	31.0	37.5	45.4	54.9
26		14.0	17.0	20.5	24.8	30.1	36.4	44.0	53.2
27	Upper belt above the technical hole	13.4	16.2	19.6	23.7	28.7	34.7	42.0	50.8
28, 29, 30	The edges of the technical holes on the trunk side	14.1	17.1	20.6	25.0	30.2	36.5	44.2	53.5
31, 32, 33	Transitions from the lower surface of the trunk to the inclined belt	16.9	20.5	24.8	30.0	36.3	43.9	53.1	64.3
34	The edges of the technical holes	14.2	17.2	20.8	25.1	30.4	36.8	44.5	53.8
35		13.7	16.6	20.0	24.2	29.3	35.5	42.9	51.9

The results of running strength tests, obtained according to the above formulas, and readings of strain gauges installed in the studied areas, are shown in Tables 2-10, and Figures 6-8 graphically show the stresses occurring in the most stressed areas of the side frame, spring and pivot beams.

The coefficients of vertical dynamics of the sprang and unsprang parts of the bogie were also determined according to [15]. These coefficients are necessary to understand the behavior of sprang and non-sprang parts and allow accurate assessment of their load capacity and service life, which is important for planning the maintenance and repair. The coefficients of vertical dynamics obtained during the running strength tests of a six-axle scale test wagon type 640-VPV are shown in Figure 9.

As can be seen, the coefficient of vertical dynamics of the sprang parts of the bogie, at a maximum speed of 80 km·h^{-1}, is 0.28, which does not exceed the maximum allowable value of 0.65 for the sprang parts, while this coefficient for the non-sprang parts is 0.39, which also does not exceed the maximum allowable 0.9 for the non-sprang parts according to [15].

The analysis and evaluation of the results of running dynamic load tests of cast bogie parts of the UVZ-9M model of six-axle scale test wagons of type 640-VPV

***Table 3** The results of running strength tests on a section with R = 300 m (side frame, MPa)*

Strain gauge	Zone	Speed (km·h^{-1})				
		10	20	30	40	50
1, 2, 3	The outer corner of the axle box opening	20.7	26.3	33.3	42.3	53.7
4	The edge of the upper belt above the axle box opening	19.2	24.4	31.0	39.3	49.8
5	The edges of the technical holes	17.7	22.5	28.5	36.2	46.0
6		17.0	21.5	27.3	34.7	44.0
7, 8, 9	The inner corner of the axle box opening	17.3	22.0	27.9	35.4	44.9
10, 11, 12	Upper outer right corner of the spring opening	15.5	19.6	24.9	31.6	40.1
13, 14, 15	Lower outer right corner of the spring opening	18.7	23.7	30.1	38.2	48.5
16	Upper belt above the spring opening	19.2	24.4	30.9	39.2	49.8
17, 18, 19	Upper outer left corner of the spring opening	17.3	22.0	27.9	35.4	44.9
20	The lower edge of the technical hole	18.6	23.6	30.0	38.1	48.3
21	Lower outer left corner of the spring opening	23.8	30.2	38.3	48.6	61.7
22		25.0	31.7	40.2	51.0	64.7
23	Lower belt above the spring opening	23.4	29.7	37.6	47.8	60.6
24	Lower outer left corner of the spring opening	22.2	28.2	35.8	45.4	57.6
25	The lower edge of the technical hole	16.1	20.5	26.0	33.0	41.9
26		17.1	21.7	27.5	34.9	44.3
27	Upper belt above the technical hole	18.6	23.6	30.0	38.0	48.2
28, 29, 30	The edges of the technical holes on the trunk side	15.5	19.6	24.9	31.6	40.1
31, 32, 33	Transitions from the lower surface of the trunk to the inclined belt	19.7	24.9	31.6	40.2	51.0
34	The edges of the technical holes	16.5	20.9	26.5	33.7	42.7
35		17.0	21.5	27.3	34.7	44.0

Table 4 *The results of running strength tests on a section with R = 600 m (side frame, MPa)*

Strain gauge	Zone	Speed (km·h^{-1})					
		10	20	30	40	50	60
1 2 3	The outer corner of the axle box opening	21.2	26.2	32.6	40.4	44.2	50.2
4	The edge of the upper belt above the axle box opening	19.2	23.9	29.6	36.8	40.3	45.7
5	The edges of the technical holes	15.1	18.8	23.4	29.2	32.0	36.5
6		15.2	18.9	23.5	29.3	32.1	36.6
7 8 9	The inner corner of the axle box opening	16.8	20.9	26.0	32.3	35.3	40.2
10 11 12	Upper outer right corner of the spring opening	15.3	19.0	23.6	29.4	32.1	36.5
13 14 15	Lower outer right corner of the spring opening	18.7	23.2	28.8	35.8	39.2	44.5
16	Upper belt above the spring opening	18.6	23.0	28.6	35.6	38.9	44.3
17 18 19	Upper outer left corner of the spring opening	16.3	20.2	25.2	31.3	34.2	39.0
20	The lower edge of the technical hole	18.4	22.9	28.4	35.3	38.6	43.9
21	Lower outer left corner of the spring opening	22.4	27.8	34.6	43.0	47.1	51.6
22		23.3	28.9	35.9	44.7	48.9	51.7
23	Lower belt above the spring opening	22.8	28.3	35.1	43.6	47.7	52.3
24	Lower outer left corner of the spring opening	22.0	27.3	33.9	42.2	46.1	52.4
25	The lower edge of the technical hole	15.9	19.8	24.5	30.5	33.4	37.9
26		16.2	20.1	25.0	31.1	34.0	38.7
27	Upper belt above the technical hole	16.6	20.7	25.8	32.1	35.1	40.0
28 29 30	The edges of the technical holes on the trunk side	15.3	19.0	23.6	29.4	32.1	36.5
31 32 33	Transitions from the lower surface of the trunk to the inclined belt	19.0	23.6	29.3	36.4	39.9	45.3
34	The edges of the technical holes	16.0	19.8	24.6	30.6	33.5	38.1
35		16.0	19.8	24.7	30.7	33.6	38.2

Table 5 *The results of running strength tests on a straight section (spring beam, MPa)*

Strain gauge	Zone	Speed (km·h^{-1})							
		10	20	30	40	50	60	70	80
36	The central belt of the spring beam	14.2	17.2	20.8	25.2	30.4	36.8	44.6	53.9
37		13.5	16.4	19.8	24.0	29.0	35.1	42.5	51.4
38	The transition from the central belt to the ends of the beam	12.3	14.8	17.9	21.7	26.3	31.8	38.5	46.6
39		11.3	13.7	16.6	20.1	24.3	29.4	35.6	43.0
40	Corner belt at the end of the beam	12.8	15.5	18.7	22.6	27.4	33.1	40.1	48.5
41	The transition from the central belt to the ends of the beam	11.3	13.7	16.6	20.1	24.3	29.4	35.6	43.1
42		12.6	15.3	18.5	22.3	27.0	32.7	39.6	47.9
43	Corner belt at the end of the beam	10.1	12.3	14.8	17.9	21.7	26.3	31.8	38.5

Table 6 The results of running strength tests on a section with R = 300 m (spring beam, MPa)

Strain gauge	Zone	Speed (km·h⁻¹)				
		10	20	30	40	50
36	The central belt of the spring beam	17.4	22.0	27.9	35.5	45.0
37		17.0	21.6	27.4	34.8	44.1
38	The transition from the central belt to the ends of the beam	14.2	18.0	22.8	28.9	36.7
39		14.9	18.9	24.0	30.4	38.6
40	Corner belt at the end of the beam	14.5	18.4	23.4	29.6	37.6
41	The transition from the central belt to the ends of the beam	13.6	17.3	21.9	27.9	35.3
42		15.0	19.0	24.1	30.6	38.8
43	Corner belt at the end of the beam	13.9	17.6	22.4	28.4	36.0

Table 7 The results of running strength tests on a section with R = 600 m (spring beam, MPa)

Strain gauge	Zone	Speed (km·h⁻¹)					
		10	20	30	40	50	60
36	The central belt of the spring beam	16.4	20.4	25.4	31.5	34.5	39.3
37		15.9	19.8	24.6	30.6	33.5	38.1
38	The transition from the central belt to the ends of the beam	13.7	17.1	21.2	26.4	28.8	32.8
39		13.6	17.0	21.1	26.3	28.8	32.7
40	Corner belt at the end of the beam	14.2	17.6	21.9	27.2	29.8	33.8
41	The transition from the central belt to the ends of the beam	13.0	16.1	20.1	25.0	27.3	31.1
42		14.4	17.8	22.1	27.5	30.1	34.3
43	Corner belt at the end of the beam	12.5	15.6	19.4	24.1	26.4	30.1

Table 8 The results of running strength tests on a straight section (pivot beam, MPa)

Strain gauge	Zone	Speed (km·h⁻¹)							
		10	20	30	40	50	60	70	80
44	Pivot beam	12.2	14.8	17.9	21.7	26.2	31.7	38.4	46.5
45		12.2	14.7	17.8	21.6	26.1	31.6	38.2	46.2
46		11.5	13.9	16.8	20.3	24.6	29.8	36.0	43.6
47		11.9	14.4	17.4	21.0	25.4	30.8	37.3	45.1
48		13.2	16.0	19.4	23.4	28.4	34.3	41.5	50.2
49		12.8	15.4	18.7	22.6	27.4	33.1	40.0	48.5
50		11.7	14.1	17.1	20.7	25.0	30.3	36.7	44.4
51		12.0	14.6	17.6	21.3	25.8	31.2	37.8	45.7
52		12.8	15.5	18.8	22.7	27.5	33.3	40.3	48.8
53		13.2	16.0	19.3	23.4	28.3	34.2	41.4	50.1
54		14.1	17.1	20.7	25.0	30.2	36.6	44.3	58.9
55		13.1	15.8	19.1	23.2	28.0	33.9	41.0	49.6

were carried out by examining their technical condition and comparing the maximum stresses obtained to the permissible values, according to [15]. Thus, the test results show that the most stressed zones are the lower belt of the spring opening of the side frame, in which the highest stresses are formed, amounting to 73.5 MPa in straight sections of the track, 64.7 MPa in curved sections with a radius of curvature R 300 and 52.4 MPa in curved sections with a radius of curvature R 600.

According to the calculations, the coefficient of safety margin of the side frame was 2, for the spring beam - 2.7 and the pivot beam - 2.5, which is higher than the minimum permissible 1.6 according to [15].

Thus, the stresses obtained in the cast parts of the UVZ-9M three-axle bogie during the running strength tests of the 640-VPV six-axle scale test wagon do not exceed the permissible value of 145 MPa according to [15], which fully meets the established requirements. Therefore, it can be concluded that there is a safety margin (residual life) and the possibility of extending the service life of a three-axle bogie model UVZ-9M six-axle scale test wagon type 640-VPV.

***Table 9** The results of running strength tests on a section with R = 300 m (pivot beam, MPa)*

Strain gauge	Zone	Speed (km·h^{-1})				
		10	20	30	40	50
44	Pivot beam	13.7	17.3	22.0	27.9	35.4
45		14.5	18.4	23.4	29.7	37.7
46		13.8	17.5	22.2	28.2	35.8
47		13.6	17.2	21.8	27.7	35.1
48		16.4	20.8	26.4	33.6	42.6
49		14.8	18.8	23.9	30.3	38.5
50		13.6	17.2	21.9	27.8	35.2
51		14.0	17.8	22.6	28.7	36.4
52		15.3	19.4	24.7	31.3	39.7
53		16.3	20.6	26.2	33.2	42.2
54		17.7	22.4	28.5	36.1	45.8
55		16.9	21.5	27.3	34.6	43.9

***Table 10** The results of running strength tests on a section with R = 600 m (pivot beam, MPa)*

Strain gauge	Zone	Speed (km·h^{-1})					
		10	20	30	40	50	60
44	Pivot beam	13.5	16.7	20.8	25.8	28.2	32.1
45		13.9	17.3	21.4	26.7	29.2	33.2
46		13.1	16.3	20.3	25.2	27.6	31.4
47		13.2	16.4	20.4	25.4	27.7	31.5
48		15.4	19.2	23.8	29.7	32.5	36.9
49		14.4	17.8	22.2	27.5	30.1	34.3
50		13.2	16.3	20.3	25.2	27.6	31.4
51		13.6	16.8	20.9	26.0	28.5	32.4
52		14.7	18.2	22.6	28.1	30.8	35.0
53		15.3	19.1	23.7	29.5	32.2	36.7
54		16.5	20.6	25.6	31.8	34.8	39.6
55		15.6	19.4	24.2	30.1	32.9	37.4

5 Calculation of the remaining service life of cast parts of the UVZ-9M bogie

The determination of the possibility of extending the service life of the cast parts of the UVZ-9M bogie by the residual life was carried out based on the condition of the absence of visible damage to the cast elements (cracks in welds or base metal, violation of geometry, loss of stability of structural elements), as well as stress values in the control zones obtained after the implementation of all modes of running strength tests that should not exceed the values specified in [15].

Thus, based on the results of experimental studies, the service life (residual life) for each cast part was calculated according to [15] using the formula:

$$T_k = \frac{\left(\frac{\sigma_{a,N}}{[n]}\right)^m \cdot N_0}{B \cdot \mu f \sum_{j=1}^{n} K_{yzj} \sum P_{vi} \sum \sigma_{ai}^m P_{\sigma i}}, \tag{3}$$

where: $\sigma_{a,N}$ is the endurance limit (in amplitude) for the control zone with a symmetrical cycle and steady-state loading mode with a base number of cycles $N_0 = 10^7$,

N_0 is the base number of cycles; m is the exponent in the equation of the fatigue curve in amplitudes,

μ is the coefficient obtained from the results of modelling the dynamics of wagons, taking into account the impact of degradation during operation of the wagon structure (friction and corrosion wear),

B is the conversion coefficient of the estimated calendar service life of the beam in years during continuous movement in seconds, s·year^{-1},

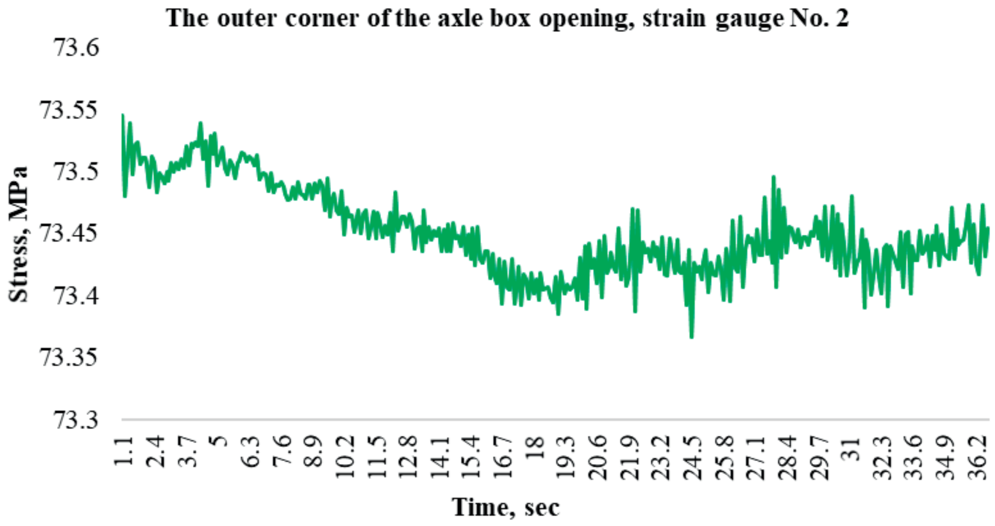
f is the frequency of changes in the dynamic additive coefficient,

K_{yzj} is the average fraction of the length of the track sections,

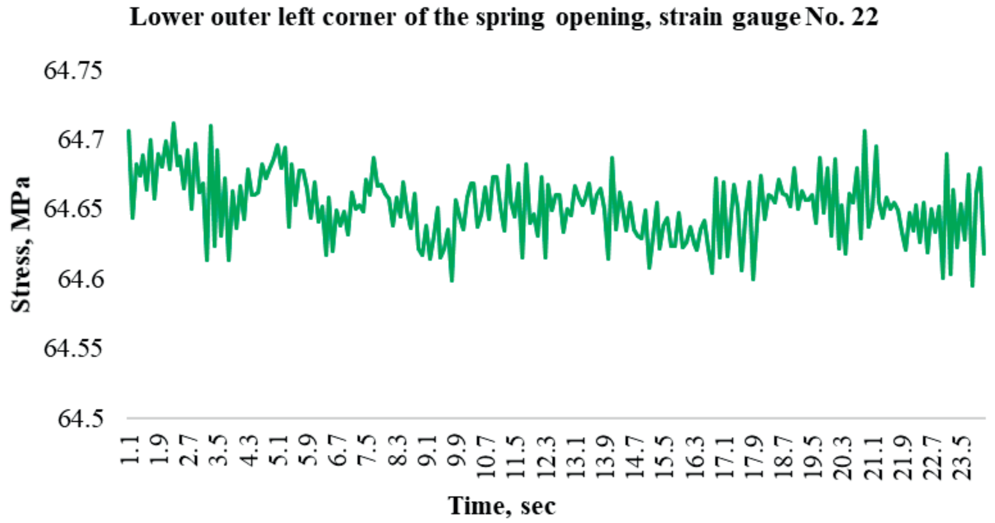
$P_{\sigma i}$ is the probability of occurrence of an amplitude with the level σ_{ai} in the i-th range of carriage speeds,

P_{Vi} is the fraction of time spent on operation in the i-th speed range,

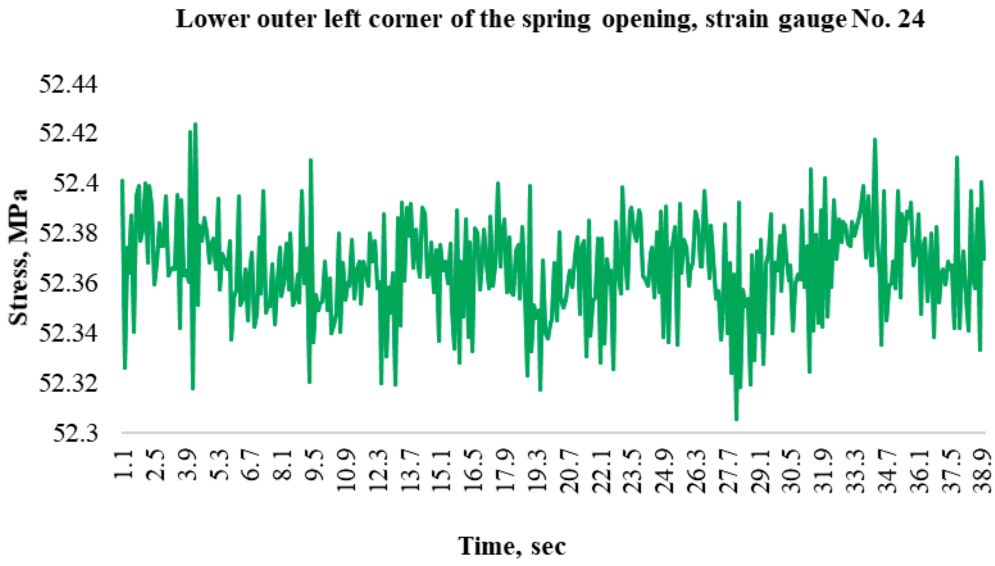
σ_{ai} is the level of stress amplitudes from the action of vertical dynamic forces in the interval i, reduced to an equivalent symmetrical cycle.



a)

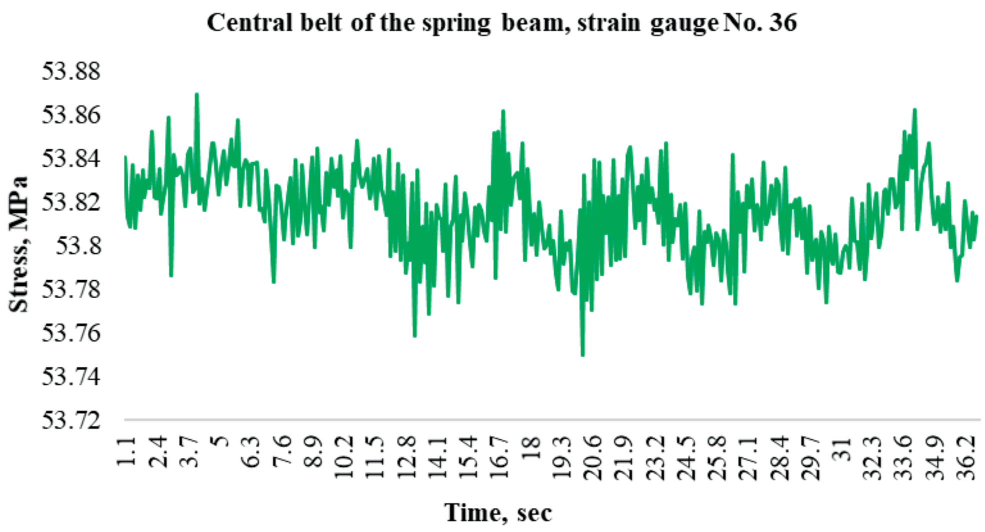


b)

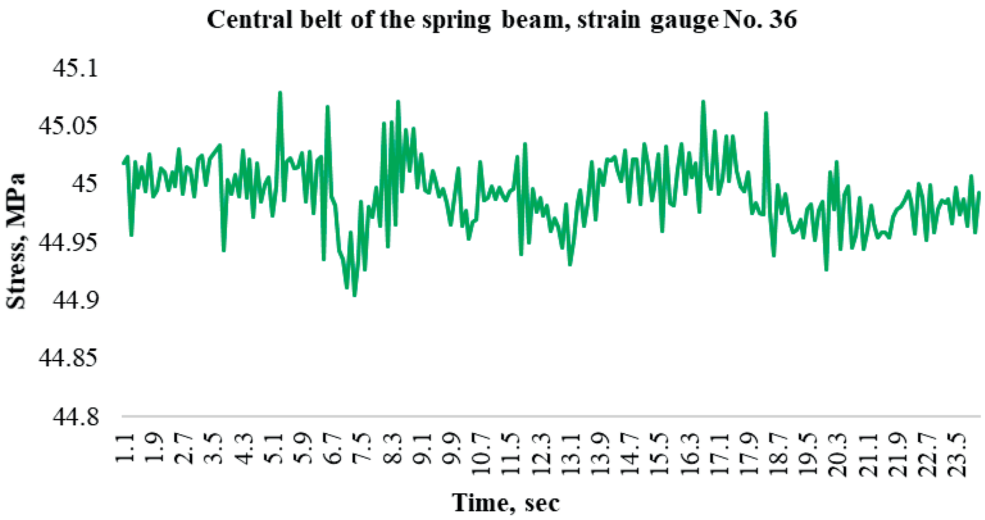


c)

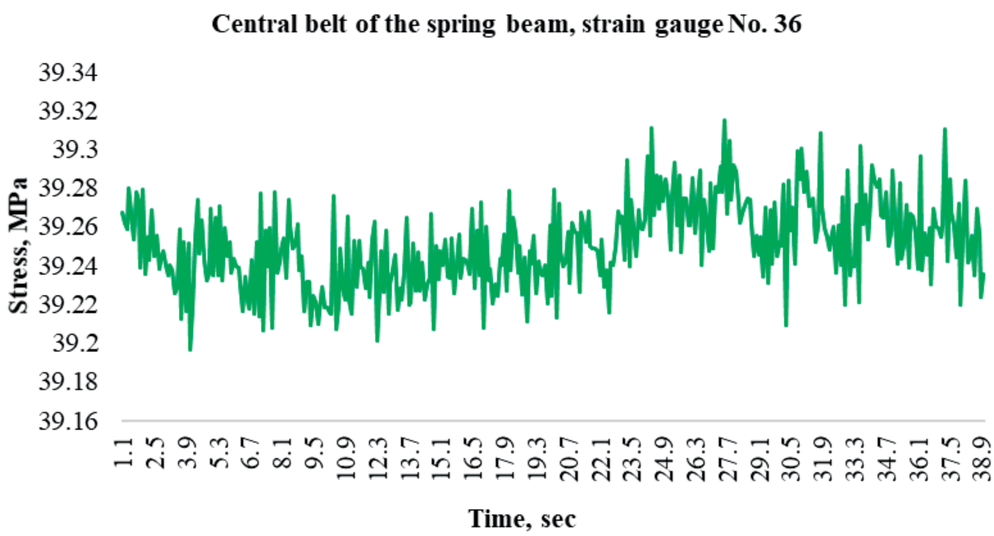
Figure 6 *Stresses obtained on the side frame of the UVZ-9M bogie during the running strength tests of a six-axle scale test wagon type 640-VPV on a straight section of track at a speed of 80 km·h*$^{-1}$ *(a), on a curved section of track with a radius of R = 300m at a speed of 50 km·h*$^{-1}$ *(b) and on a curved section paths with a radius of R = 600m at a speed of 60 km·h*$^{-1}$ *(c)*



a)

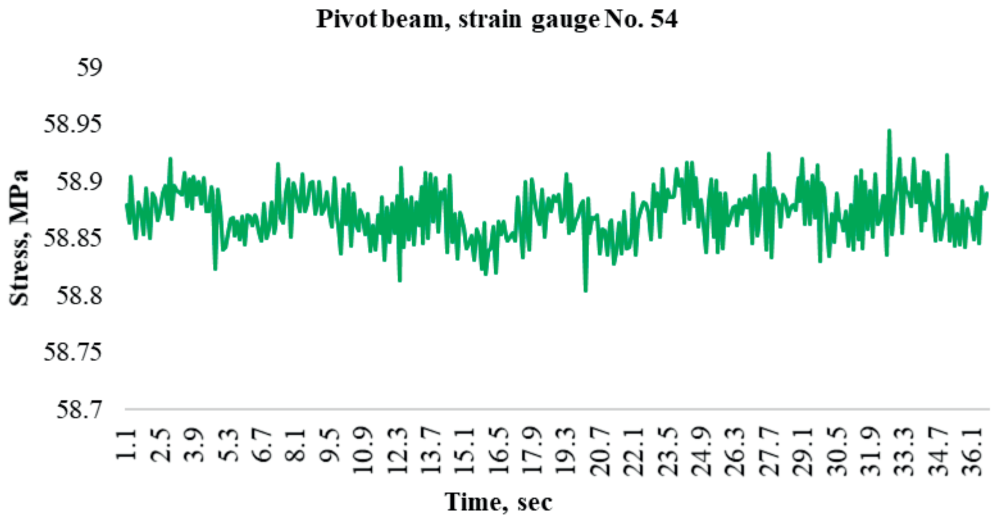


b)

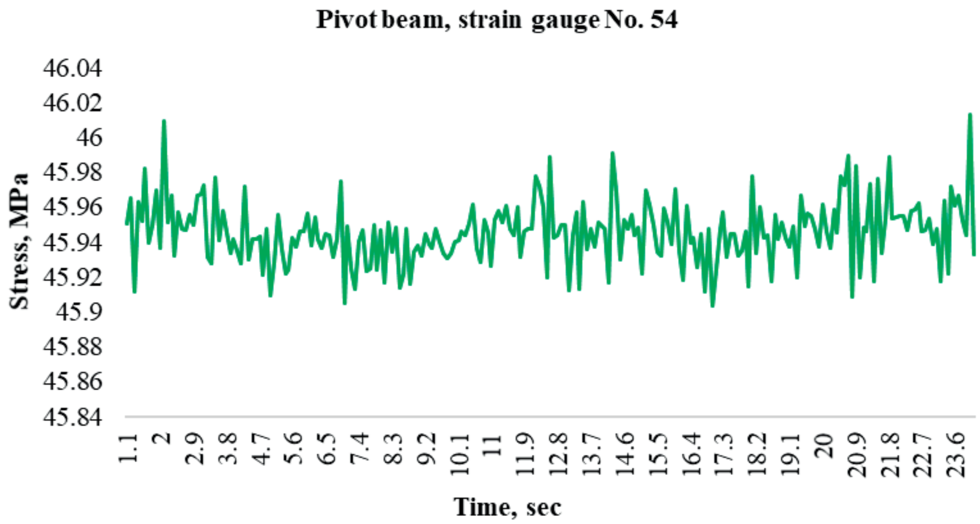


c)

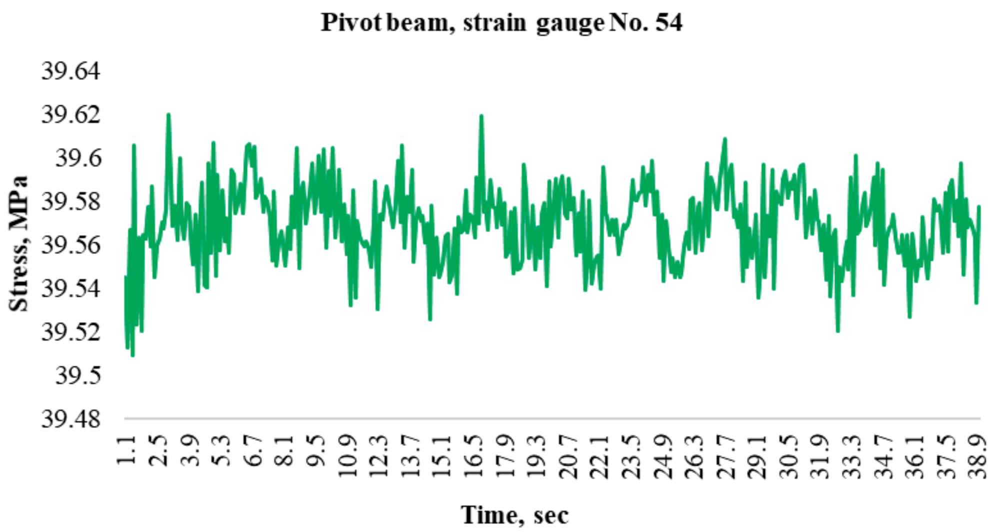
Figure 7 *Stresses obtained on the spring beam of the UVZ-9M bogie during the running strength tests of a six-axle scale test wagon type 640-VPV on a straight section of track at a speed of 80 km·h^{-1} (a), on a curved section of track with a radius of R = 300 m at a speed of 50 km·h^{-1} (b) and on a curved section paths with a radius of R = 600 m at a speed of 60 km·h^{-1} (c)*



a)



b)



c)

Figure 8 *Stresses obtained on the pivot beam of the UVZ-9M bogie during the running strength tests of a six-axle scale test wagon type 640-VPV on a straight section of track at a speed of 80 km·h*$^{-1}$ *(a), on a curved section of track with a radius of R = 300 m at a speed of 50 km·h*$^{-1}$ *(b) and on a curved section paths with a radius of R = 600 m at a speed of 60 km·h*$^{-1}$ *(c)*

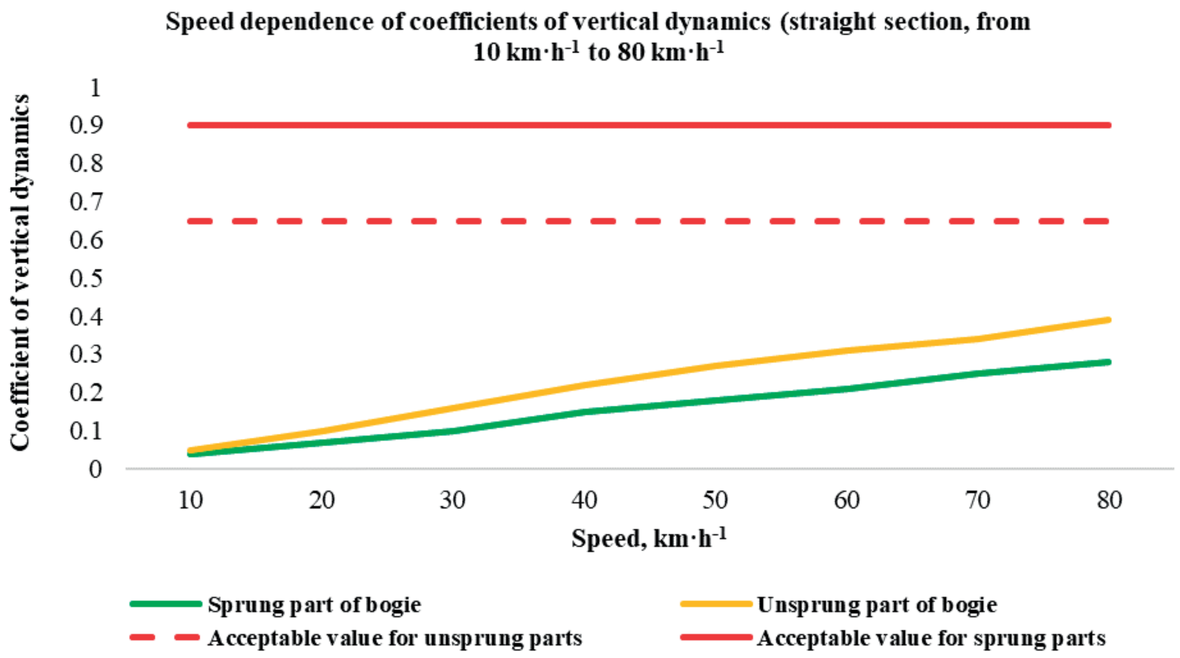


Figure 9 *Coefficients of vertical dynamics of sprang and unsprang parts of the UVZ-9M bogie, obtained during the running strength tests of a six-axle scale test wagon type 640-VPV depending on the speed of movement on a straight section of track*

The calculation results were:

- for the side frame - 64.3 years;
- for the spring beam - 67.8 years;
- for the pivot beam - 66.1 years.

Thus, calculations to determine the full technical service life of the cast parts, based on experimental data, indicate the presence of a residual life of 5.3 years for the side frame, for the spring and pivot beams of 8.5 and 7.1 years, respectively.

6 Results and their significance

As can be seen from the calculation results based on experimentally obtained data, the total life of the cast parts of the UVZ-9M three-axle bogie exceeds their service life by 5.3 years at the moment, taking into account the minimum value obtained (side frame). Therefore, based on the data obtained, it is possible to scientifically substantiate the possibility of extending the service life of cast parts by 5 years.

Based on the results of the work, it is possible to single out a key advantage - the possibility of extending the service life of cast parts of bogies without their premature replacement. This makes it possible to significantly reduce the capital costs for the purchase of new bogies, extend the operation of the rolling stock without reducing its reliability, ensure a more rational use of the resources of railway enterprises, and create a scientifically sound basis for assessing the lifetime of similar units in other types of wagons.

An additional advantage is the reduction of the negative impact on the environment. Extending the service life of existing parts reduces the need to manufacture new cast elements, which in turn reduces CO_2 emissions, reduces consumption of natural resources, and reduces waste from decommissioned parts and structures.

From an economic point of view, extending the service life of parts can significantly reduce the costs of replacing them and purchasing new components for foreign currency. The purchase of new bogies requires large investments, while the operation of existing ones, provided they comply with regulatory requirements, is more profitable and helps to reduce operating costs.

It is important to note that the proposed method of running strength tests can be successfully adapted for other types of wagons, such as dump trucks, platforms, tanks and other industrial units using the three-axle trucks of the UVZ-9M model. This expands the scope of its application, going beyond the weighing industry and making the technique a universal tool for assessing the strength and durability of structures.

In conclusion, it should be emphasized that the studies carried out confirm the strength of cast parts, exclude the presence of critical defects and justify the possibility of extending their service life without the risk of structural failures. Thus, the results obtained not only make it possible to increase the service life of trolleys, but make their use safe and economically justified, as well.

7 Conclusion

Experimental studies conducted using the developed methodology [14] for conducting the running strength tests of a six-axle scale test wagon of type 640-VPV made it possible to determine the dependence of the stress-strain state of cast parts of a three-axle bogie of the UVZ-9M model on the speed of movement of a six-axle scale test wagon of type 640-VPV to substantiate the possibility of extending the service life of these parts, taking into account the assessment of their safety margin and the remaining lifetime.

The following main results were obtained during the running strength tests:

- the maximum stresses generated on the side frame of the bogie are concentrated in the area of radius R55, above the axle box opening, the stresses reach 73.5 MPa;
- on the spring beam of the bogie, maximum stresses are observed in the central belt, the value of which does not exceed 53.9 MPa.
- the maximum stresses on the pivot beam are concentrated in the transverse beam with a support arm, where their stresses reach 58.9 MPa.

As can be seen from the results, all the maximum stresses obtained on individual cast parts do not exceed the maximum value of 145 MPa set by [15].

An analysis of calculations, based on the experimental safety margin data, showed that the full service life of cast parts is 64.3 years for the side frame, and for the spring and pivot beams this figure is 8.5 and 7.1 years, respectively. Thus, the scientific and practical research has substantiated the possibility of extending the service life of cast parts by 5 years, taking into account the minimum total service life of the side frame.

Acknowledgements

The authors received no financial support for the research, authorship and/or publication of this article.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] RAHIMDE, M., GHODRATI, B., TAGHIZADEH VAHED, A. Prediction of mining railcar remaining useful life. In: 28th International Symposium on Mine Planning and Equipment Selection MPES 2019: proceedings [online]. 2020. ISBN 978-3-030-33954-8, p. 281-288. Available from: https://doi.org/10.1007/978-3-030-33954-8_35

[2] LI, Z., HE, Q. Prediction of railcar remaining useful life by multiple data source fusion. *IEEE Transactions on Intelligent Transportation Systems* [online]. 2015, **16**(4), p. 2226-2235. eISSN 1558-0016. Available from: https://doi.org/10.1109/TITS.2015.2400424

[3] XU, Z. W., WU, S. C., WANG, X. S. Fatigue evaluation for high-speed railway axles with surface scratch. *International Journal of Fatigue* [online]. 2019, **123**, p. 79-86. ISSN 0142-1123. Available from: https://doi.org/10.1016/j.ijfatigue.2019.02.016

[4] WU, S. C., LIU, Y. X., LI, C. H., KANG, G. Z., LIANG, S. L. On the fatigue performance and residual life of intercity railway axles with inside axle boxes. *Engineering Fracture Mechanics* [online]. 2018, **197**, p. 176-191. ISSN 0013-7944. Available from: https://doi.org/10.1016/j.engfracmech.2018.04.046

[5] FOMIN, O., VATULIA, G., HORBUNOV, M., LOVSKA, A., PISTEK, V., KUCERA, P. Determination of residual resource of flat wagons load-bearing structures with a 25-year service life. *IOP Conference Series: Materials Science and Engineering* [online]. 2021, **1021**(1), ISSN 1757-899X. Available from: https://doi.org/10.1088/1757-899X/1021/1/012005

[6] SYGANSKAYA, L., HAMRAEVA, E., NARKIZOVA, E. Testing the methodology for justifying the service life of freight cars based on the results of analog car testing. *Bulletin of Scientific Research Results* [online]. 2024, **2024**(4), p. 15-23. ISSN 2223-9987. Available from: https://doi.org/10.20295/2223-9987-2024-04-15-23

[7] LUO, Y., LI, C., KANG, X., HU, Y., WU, S. Fatigue limit and residual life evaluation of railway EA4T axles with artificial surface impacts. *Journal of Materials Engineering and Performance* [online]. 2023, **32**, p. 5167-5175. eISSN 1544-1024. Available from: https://doi.org/10.1007/s11665-022-07447-3

[8] REN, X., WU, S., XING, H., FANG, X., AO, N., ZHU, T., LI, Q., KANG, G. Fracture mechanics based residual life prediction of railway heavy coupler with measured load spectrum. *International Journal of Fracture* [online]. 2022, **234**, p. 313-327. eISSN 1573-2673. Available from: https://doi.org/10.1007/s10704-022-00627-1

[9] WANG, C., ZHU, T., YANG, B., XIAO, S., YANG, G. Remaining useful life for heavy-duty railway cast steel knuckles based on crack growth behavior with hypothetical distributions. *Chinese Journal of Mechanical Engineering* [online]. 2024, **37**, 77. ISSN 2192-8258. Available from: https://doi.org/10.1186/s10033-024-01052-2

[10] ORLOVA, A. M., BABANIN, V. S., TURUTIN I. V. Calculation justification of the assigned service life of the finished axle of a freight wagon wheelset. *Railway Technique*. 2023, **1**(61), p. 22-26. ISSN 1998-9318.

[11] ELYAZOV, I. S., YUSIFZADE, E. N., BAKHSHIEV, A. B., HUSEYNOV, I. D. Method for calculating the durability of a car wheelset. *Bulletin of RGUPS*. 2024, **3**(95), p. 109-118. ISSN 0201-727X.

[12] ZAFAROV, D. Development of a methodology for conducting running strength tests to determine the load of cast parts of a three-axle bogie. *Railway Transport: Topical Issues and Innovations*. 2023, **4**, p. 165-171. ISSN 2181-953X.

[13] BORONENKO, Y., RAHIMOV, R. Experimental determination of forces through measurements of strains in the side frame of the bogie. *Transport Problems* [online]. 2021, **16**(3), p. 199-211. ISNN 1896-0596. Available from: https://doi.org/10.21307/tp-2021-053

[14] State standard 33788-2016. Freight and passenger wagons. Strength and dynamic quality testing methods. Standartinform. 2016.

[15] Norms for the calculation and design of wagons, railways of the MPS track gauge 1520 mm (non-self-propelled) with amendments and additions. GosNIIV-VNIIIZHT. Moscow, 1996.