Analysis of the Operational Performance and Structural Integrity of Undersized Railway Wheels in BCG Electric Locomotive Applications

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**Abstract.** This article presents the design methodology, assessment criteria, and testing protocols for railway wheels intended for BCG electric locomotives. Manufactured from high-strength carbon or alloy steels, these wheels are critical to the safety and efficiency of rail operations. Designed for a maximum speed of 120 km/h and a static axle load of 245.4 kN, the wheels have a standard minimum tread diameter of 1150 mm. The study outlines a comprehensive framework for evaluating the feasibility of operating wheels with reduced rim diameters, incorporating technical inspections, load analysis, and static and fatigue strength assessments under both laboratory and field conditions. Finite element modeling was used to analyze stress–strain responses under operational loads, demonstrating that the minimum safety factor for static strength remains above permissible limits even with reduced diameters. Fatigue testing of a 1140 mm diameter wheel under cyclic loading up to five million cycles showed no signs of failure. Findings support the operational viability of wheels with diameters as low as 1142 mm, with preliminary data suggesting the possibility of safe use down to 1135 mm. The results confirm the structural integrity and operational reliability of reduced-diameter wheels for continued use in rail service.

**Keywords:** Railway wheels, BCG electric locomotives, high-strength steel, static axle load, finite element modeling, fatigue testing, reduced rim diameter, safety factor, stress-strain analysis, operational reliability

# INTRODUCTION

Railway wheels are a vital component of railway transport systems. They are used in the wheelsets of bogies for freight and passenger cars with locomotive traction, all types of locomotives and electric locomotives, motorized and non-motorized wheelsets of electric and diesel train cars, as well as in the wheelsets of specialized railway rolling stock. Railway wheels are manufactured from a single metal billet through rolling and forging processes. The primary materials used for their production are high-quality carbon or alloy steels, selected for their exceptional strength and wear resistance [1, 5, 7]. The wheel structure comprises a rim, disc, and hub, which are integrated into a single unit.

Railway wheels are characterized by high strength and resistance to mechanical damage. The homogeneous material structure ensures a long service life. Their robustness is critical for ensuring the safe and efficient operation of trains, while also reducing operating costs due to their reliability and durability [2, 3, 6].

Railway wheel consists of a rim, a disc, and a hub, which are integrated into a single unit. The railway wheels under consideration are intended for BCG electric locomotives, designed for an operating speed of 120 km/h and a nominal static axle load of 245.4 kN on the rails. The nominal tread diameter of new wheels is 1254 mm, with a minimum allowable diameter of 1150 mm for worn wheels. The wheels are manufactured from steel 2 [4].

# THE PROCEDURE FOR THE ANALYTICAL AND EXPERIMENTAL ASSESSMENT OF THE LOAD-BEARING CAPACITY OF A RAILWAY WHEEL

The evaluation of the feasibility of commissioning wheelsets with wheels having a critically worn rim diameter involves the implementation of the following stages:

1 Review of Technical Documentation. Study the technical specifications, operational requirements, and past performance data of the wheels under consideration.

2 Analysis of Operational Loads and Simulation. Analyze the loads experienced during operation, develop computational models, and simulate real-world operating conditions.

3 Evaluation of Static Strength. Assess the static strength of the wheel, considering the gradual reduction in wheel diameter.

4 Assessment of Fatigue Resistance. Evaluate the wheel's resistance to fatigue, taking into account the progressive decrease in its diameter.

5 Fatigue Testing on Test Benches. Conducting bench fatigue tests on the railway wheel with the minimum calculated diameter.

6 Field Testing. Perform field trials to observe and analyze wheel performance under actual operational conditions.

7 Decision-Making on Commissioning. Making a decision on approval or rejection for operation based on the computational and experimental assessment.

# ANALYSIS OF OPERATIONAL LOADINGS

The Railway Transport Testing Center of BelSUT conducted an assessment of the impact of the BCG electric locomotive on the track infrastructure. The analysis of data obtained during the tests allowed for the determination of the maximum forces occurring in the wheel-rail interaction zone [8-11].

The maximum vertical force was recorded when the BCG electric locomotive was negotiating a curve with a radius of 610 meters at a speed of 40 km/h, reaching 186.2 kN. The maximum lateral (horizontal) force of 92.5 kN occurred when navigating the same curve at a speed of 5 km/h. During movement through switch tracks, the maximum forces observed were as follows: vertical force – 189.1 kN, and horizontal force – 89.1 kN. On a straight track segment, the maximum vertical force reached 168.5 kN.

The presented force values are characteristic of the studied rolling stock and are used as reference inputs for further calculations and simulations.

# EVALUATION OF STATIC STRENGTH

The stress-strain analysis was performed using a software package and a 3D finite element model of the railway wheel developed in the SolidWorks environment [12]. The computational 3D finite element model of the wheel is shown in   
Figure 1. The developed model enables consideration of various levels of wheel wear and allows for the application of different load combinations.



**FIGURE 1.** Model of a railway wheel with a rim diameter of 1140 mm

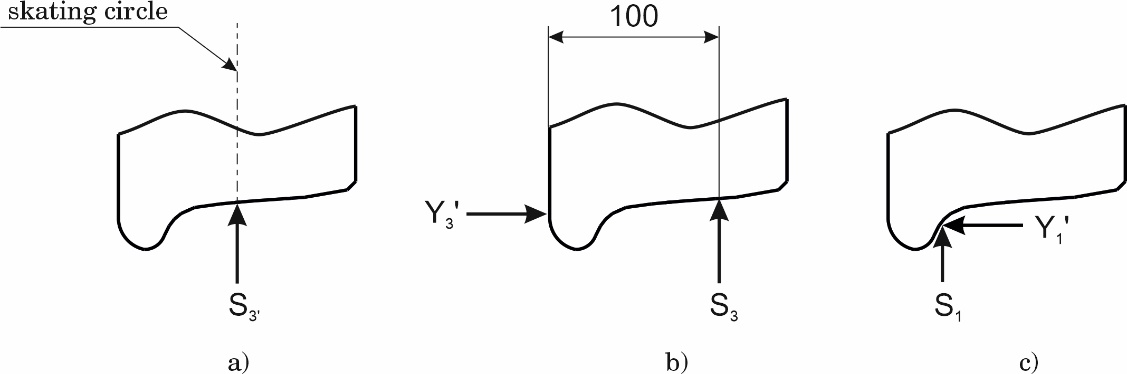
The creation of the finite element model of a railway wheel involves examining the influence of the element size and the number of elements in the model on the calculation results. Convergence of results is achieved at the refinement step where the maximum von Mises equivalent stress changes by less than 3.5 MPa with further mesh refinement. According to Saint-Venant's principle, the length of the segment along the axis on both sides is equal to the wheel's diameter [5, 13].

It was determined that the optimal mesh has an element edge size in the range of 0.15-4.0 mm. The model of the worn railway wheel with a rim diameter of 1150 mm consists of 3,538,200 elements and 4,977,521 nodes (Figure 2).



**FIGURE 2.** Example of a railway wheel region with a generated mesh

The fitting surfaces of the wheel hub and the axle's hub seat are designed as ideal, i.e., without permissible values of taper or ovality, as discussed in [6, 14]. The study considered the simultaneous impact of external mechanical forces on a full-scale solid-rolled wheel in accordance with the loading schemes shown in Figure 3.



**FIGURE 3.** Diagram of the application of external mechanical forces on a rolling railway wheel: a – movement on a straight track segment; b – passage through a railway switch; c – movement through a curve

In the analysis of the stress-strain state of the railway wheel, the maximum vertical and lateral forces determined experimentally were used. The boundary conditions were adopted in accordance with the scheme presented in [7].

The static strength of the railway wheel, according to [8, 15], is evaluated using the following formula:

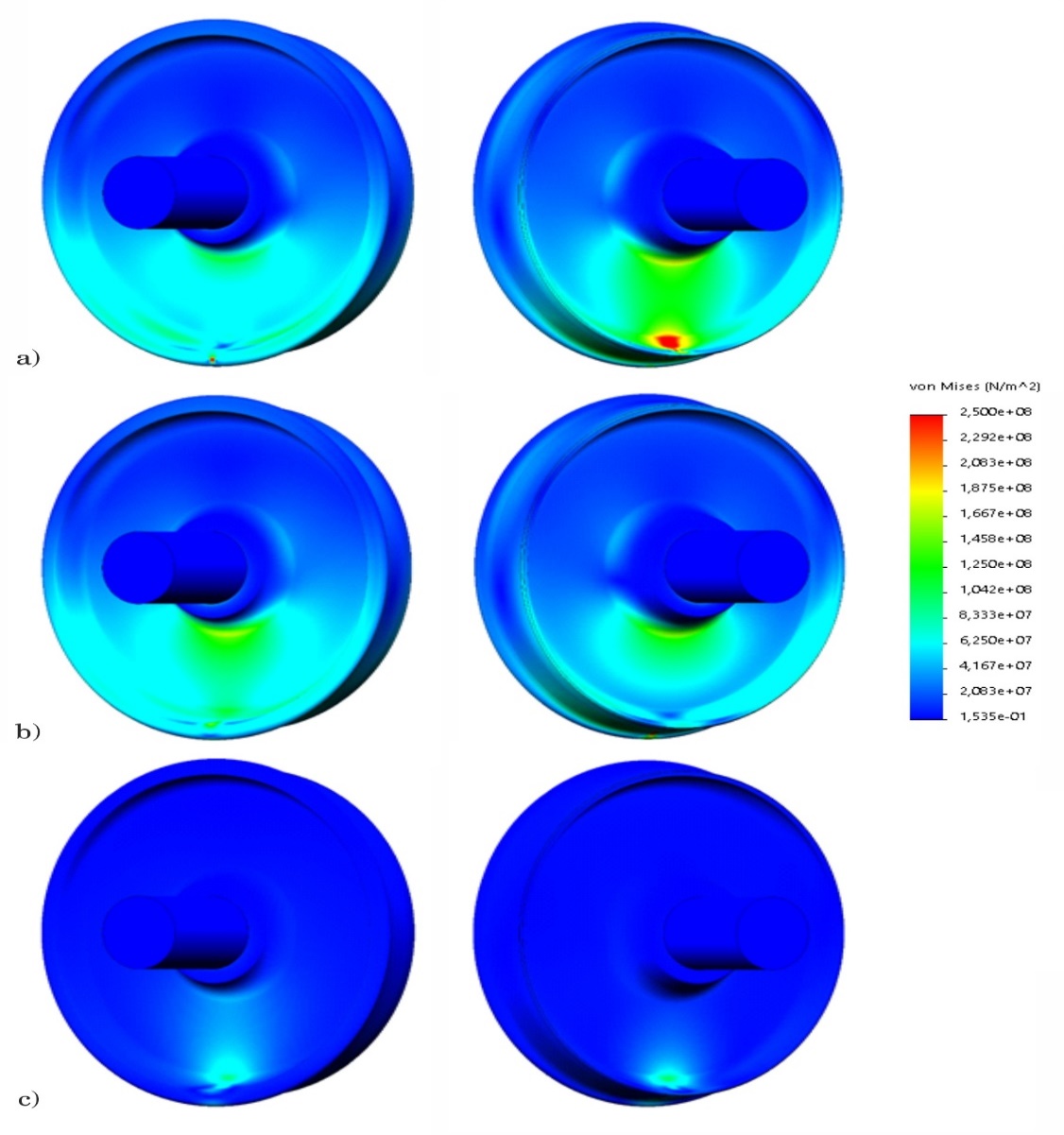
(1)

where σ*t* – yield strength of the material of the railway wheel, for grade 2 steel according to [8 and 9] σ*t* = 400 MPa; σ*emax* – maximum total equivalent stresses occurring during the operation of the railway wheel; [*nk*] – allowable static strength safety factor of the railway wheel disc, ranging from 1.0 to 1.2 according to [8].

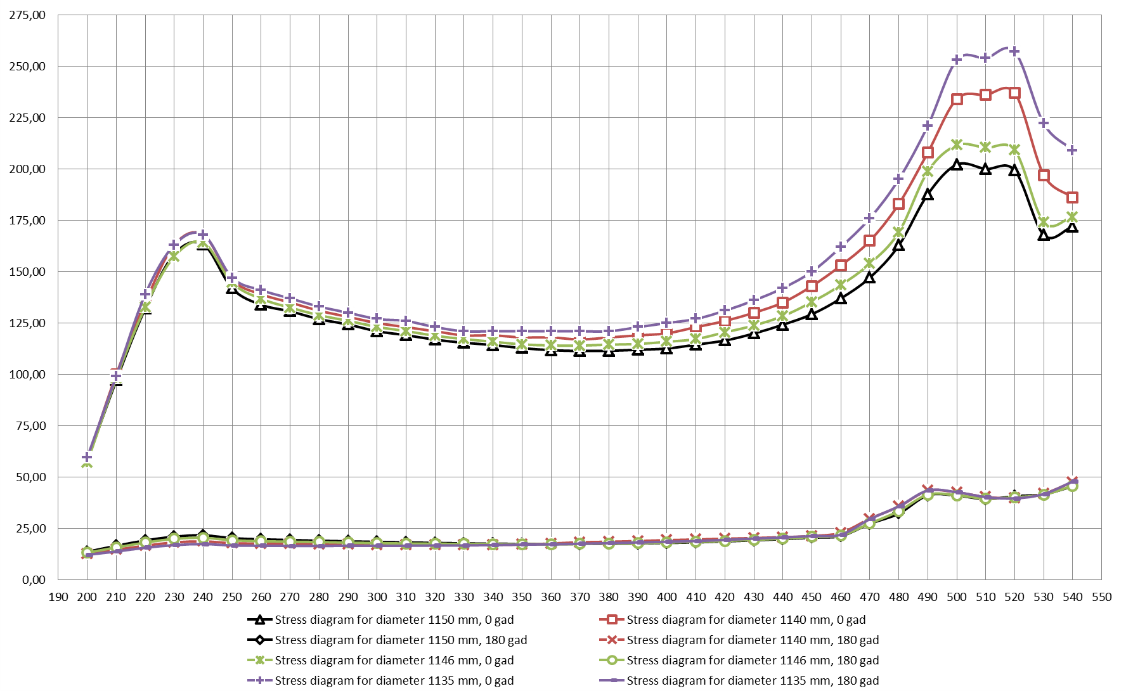
The calculation was performed according to the loading conditions characteristic of railway wheel movement through a railway switch, in curves, and on straight track segments. Figure 4 shows the distribution of equivalent stresses in the disc of the railway wheel under the aforementioned loading conditions, for a wheel with a rim diameter of 1135 mm.

Figure 5 presents the generalized results of the distribution of equivalent stresses in the rim of the railway wheel with wear diameters of 1150 mm, 1146 mm, 1142 mm, and 1135 mm along the outer side of the wheel during passage through a railway switch.

The analysis of the obtained data revealed that the maximum equivalent stresses are as follows: 202.1 MPa (for a diameter of 1150 mm), 211.5 MPa (for a diameter of 1146 mm), 228.2 MPa (for a diameter of 1142 mm), and 257.0 MPa (for a diameter of 1135 mm). Therefore, the minimum static strength safety factor for a wheel with a diameter of 1150 mm is 1.98, for a diameter of 1146 mm it is 1.89, for a diameter of 1142 mm it is 1.75, and for a diameter of 1135 mm it is 1.56, with the minimum allowable value being 1.0 [16, 19].



**FIGURE 4.** Distribution of equivalent stresses (MPa) in the disc of a railway wheel with a diameter of 1135 mm:   
a – during passage through a railway switch; b – during movement through a curve; c – during movement on a straight track segment



**FIGURE 5.** Diagrams of the distribution of equivalent stresses (MPa – Y-axis) along the outer side of the disc of a railway wheel (mm – X-axis) with different rim diameters

# FATIGUE RESISTANCE ASSESSMENT

The fatigue resistance safety factor of the railway wheel is evaluated using the formula [7, 8]:

(2)

where σ*aD* – endurance limit of the railway wheel, obtained from the results of its bench tests under asymmetric loading cycles (considering the effects of assembly and residual stresses σ*aD* = 150 MPa in accordance with [10, 11]); σ*ai* – maximum value of the stress amplitude from dynamic loads at the selected point on the railway wheel; *k2* – coefficient accounting for the dependence of fatigue resistance on the value of the total mean stress of the cycle σ*m2* during operation; *k1* – coefficient accounting for the dependence of fatigue resistance on the value of the total mean stress of the cycle σ*m1* during bench tests (taken as 0.895 according to [7]); *nyk* – fatigue resistance safety factor of the railway wheel;[*nyk*] – allowable fatigue resistance safety factor of the railway wheel, [*nyk*] = 0.7 in accordance with [7, 17].

The coefficients *k1* and *k2* are determined using the formula

(3)

where σ*mi* – total mean stress of the cycle (including assembly, residual, and operational stresses); σ*t* – yield strength of the material of the railway wheel, for steel 2.

The amplitude of the operational stress intensity σ*ai* is determined as the half-difference of the stress intensities at the position of the calculation section of the railway wheel relative to the contact point with the rail during rotation at angles of 0° and 180°, over one full rotation of the railway wheel.

(4)

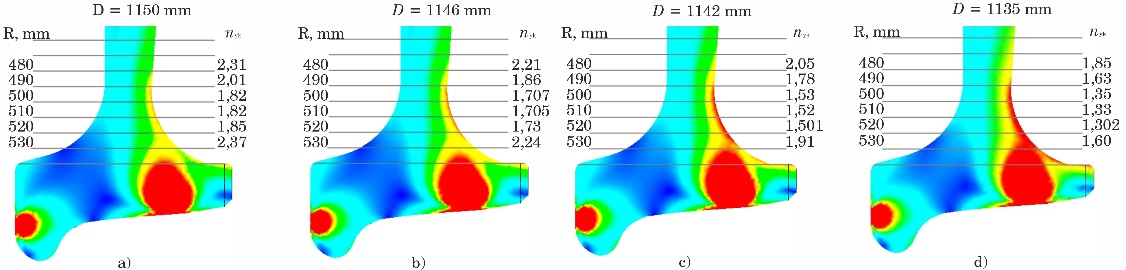
The average stress intensities are as follows:

(5)

The allowable safety factor for the fatigue resistance of a railway wheel, in accordance with [7], is defined as follows: at least 1.7 if preliminary strength calculations are available; at least 1.5 if strength calculations are supplemented with the results of bench fatigue tests on railway wheels; at least 1.3 if strength calculations are supplemented with the results of both bench fatigue tests and field tests on railway wheels.

In accordance with formulas (4) and (5), the calculation of the amplitude and average stresses, distributed along the contour of the railway wheel (both outer and inner sides), has been carried out.

An analysis of the stress-strain state of the railway wheel identified the most loaded zones with the maximum stress range at positions 0° and 180°. For these zones, calculations of the mean and amplitude stress values, as well as correction factors, were performed. Figure 6 visually demonstrates the distribution (along the height) of the fatigue strength safety factor in the most critical zone of the railway wheel's disc during the modeling of its passage through a railway switch.

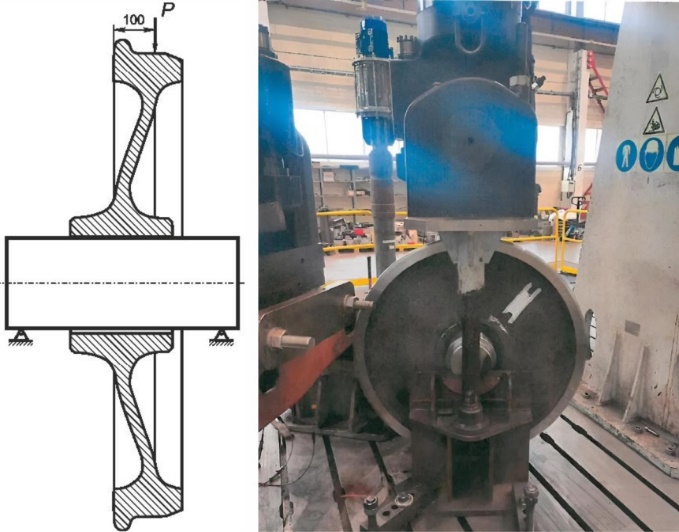


**FIGURE 6.** The distribution of the fatigue safety factor in the most critical zone of the solid-rolled wheel disc:   
a – 1150 mm; b – 1146 mm; c – 1142 mm; d – 1135 mm

# FATIGUE TESTING

The tests were conducted at the laboratories of Tikhvin Railway Transport Testing Center. The tests involved radial cyclic loading of a 1140 mm diameter wheel. The tests aimed to determine the absence of failure (crack formation) in the wheel under an axial load of up to 245.0 kN, with a design speed of up to 200 km/h, under radial cyclic loading with an asymmetry coefficient of 0.1 (loading cycle parameters: Pmax = 450 kN, Pmin = 45 kN, sample loading frequency 7 Hz) over five million cycles, in accordance with [4].

The testing scheme, which most effectively loads the area of the wheel where, according to the calculation results, the minimum fatigue strength safety factor was obtained, is presented in Figure 7. The wheel is mounted vertically, and a steel axle, 1-2 mm smaller in diameter than the hub hole, is passed through the hub opening. The axle rests on two fixed profile supports of the testing equipment. Cyclic loading is applied in the radial direction to the rim of the railway wheel [18, 20].



**FIGURE 7.** Loading scheme and fatigue testing process of the forged railway wheel

The values and stability of the cyclic load during testing are monitored using load-measuring devices. The number of loading cycles is recorded using a counter. The accuracy of force measurement was ±2 %, and the number of loading cycles was ±1 %. The absence of cracks in the wheel is monitored visually every 1×10⁶ cycles, with the use of color penetrant testing if necessary. Testing was conducted on one sample, at one section. The tests were conducted on a single sample and within a single section. Testing within one section of the wheel continues until either the base number of load cycles (5×10⁶ cycles) is reached or a fatigue crack of 20 mm or more appears in any part of the wheel, whichever occurs first. As a result of radial cyclic loading tests on a wheel with a diameter of 1140 mm, performed using the described methodology and up to 5×10⁶ cycles, no cracks were detected. The presented scope of computational and experimental assessment of the permissible operating diameter of the BСG electric locomotive wheels ensures, in accordance with [7], the establishment of a fatigue resistance safety factor of no less than 1.5. This criterion (see Figure 6) corresponds to a wheel with a maximum worn diameter of 1142 mm.

# CONCLUSION

1. A procedure for the computational and experimental assessment of the feasibility of commissioning railway wheels of BCG locomotive wheelsets with diameters below the maximum wear limit specified in the design documentation has been developed.

2. An analysis of the research results on the impact of the BCG locomotive on the track has been conducted. Forces acting on the wheel during the locomotive's movement on a straight track section, in a curve, and through a turnout have been obtained and analyzed.

3. The static strength of wheels with diameters ranging from 1150 mm to 1135 mm was evaluated. The minimum static strength safety factor was determined to be 1.56, exceeding the minimum allowable value of 1.0 for a diameter of 1135 mm.

4. Computational methods were used to calculate the minimum fatigue strength safety factors in the disk of railway wheels with different tread diameters. The minimum fatigue strength safety factors were 1.705 for a diameter of 1146 mm, 1.501 for 1142 mm, and 1.302 for 1135 mm.

5. A methodology for conducting fatigue testing was developed, and fatigue tests were carried out on a wheel with a diameter of 1140 mm. The tested wheel successfully completed the entire test cycle without failure.

Based on the results of this research, it can be concluded that the BCG locomotive wheel can be safely operated down to a diameter of 1142 mm. If additional fatigue testing of railway wheels and a series of field tests are conducted, the wheel diameter could potentially be reduced to 1135 mm, subject to positive test results.

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