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REVIEW OF RESEARCH ON LOADING, FATIGUE DAMAGE, REMAINING SERVICE LIFE, AND TECHNICAL DIAGNOSTICS OF ELECTRIC LOCOMOTIVE AND ELECTRIC MULTIPLE-UNIT BOGIE FRAMES

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Abstract. This article reviews existing research on loading conditions, fatigue damage, remaining service life, and technical diagnostics of bogie frames used in electric locomotives and electric multiple units (EMUs). Particular attention is paid to the effects of static and dynamic loads, cyclic stresses, vibration, and operational conditions on the structural integrity and fatigue resistance of bogie frames. The review examines commonly used approaches to stress analysis, fatigue life assessment, structural reliability evaluation, and residual service life prediction, including analytical calculations, finite element analysis, experimental testing, and numerical simulation. It also considers modern technical diagnostic methods, such as non-destructive testing, strain and vibration measurements, and condition monitoring, which support the detection of cracks, material degradation, and other structural defects.

Keywords: electric locomotives, electric multiple units, bogie frames, loading conditions, fatigue damage, fatigue life assessment, remaining service life, structural integrity, technical diagnostics.

In railway rolling stock, the bogie frame is one of the principal welded load-bearing structures that withstands vertical loads transmitted from the carbody, lateral and impact forces arising from wheel–rail interaction, and longitudinal forces generated during traction and braking. Consequently, its technical condition is determined not only by the static strength margin but also by multiaxial cyclic loading, local stress concentrations, fatigue properties of welded joints, the spectrum of in-service loads, and the rate of development of existing defects. Fatigue cracks in bogie frames are usually associated with abrupt changes in structural cross-section, welded joints, connections between side and transverse beams, and local zones where load paths are redistributed. Therefore, modern diagnostics should not be limited to the question of whether a crack is present in the frame; rather, the primary task is to identify, using computational and operational data, the zones in which defects are most likely to occur [7–10, 12–15].

The scope of this literature review is defined strictly in accordance with the dissertation subject: specifically, the bogie frames of electric locomotives, locomotives, and electric multiple units; their stress–strain state; fatigue damage; remaining service life; non-destructive testing; and crack monitoring in bogie frames. Studies devoted to electric locomotive electrical equipment, traction

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converters, bearings, wheelsets, or onboard diagnostics that do not directly assess the technical condition of the frame structure were excluded from Section 1.1. This restriction allows the literature sources to be linked directly to the task of identifying hazardous sections of the O‘Z-Y electric locomotive bogie frame and subsequently organizing targeted non-destructive testing (NDT) specifically at these locations.

Research by Uzbek Scientists on Bogie Frame Strength and Remaining Service Life

In Uzbekistan, research on the assessment of locomotive bogie frame service life and stress state has developed in several stages. N.S. Zayniddinov’s work on estimating the remaining service life of locomotive bogie frames represents one of the important methodological foundations of this area. The author considered the modelling of the stress–strain state of a locomotive bogie frame, calculation of stresses in welded sections, assessment of loading cycles, and determination of the remaining service life of the supporting structure within a unified framework [6]. Although this work introduced a computational and experimental approach to extending the service life of locomotives operating on Uzbekistan’s railways, the research primarily aimed to justify the overall remaining service life of locomotive frames approaching the end of their designated service life. The planned O‘Z-Y study differs in that it first identifies a map of consistently critical zones using finite element analysis (FEM) before assessing remaining service life at the level of the overall structure, and directs diagnostic inspection specifically to these zones.

In 2023, A.M. Yusufov, O.R. Khamidov, N.S. Zayniddinov, and Sh.X. Abdurasulov investigated the prediction of the stress–strain state and assessment of the remaining service life of shunting locomotive bogie frames used on Uzbekistan’s railways by means of the finite element method in SolidWorks [5]. A strength of this study is that it connects a load-bearing structure that has undergone actual service with a three-dimensional model, applied loads, and the concept of remaining service life. However, the automatic selection of NDT locations during maintenance from FEM results, the consolidation of detected defects with mileage and loading data in a common database, and the development of risk-based inspection intervals were not its primary objectives. Thus, this study provides a methodological analogue for the 3D model and remaining-life calculation in the O‘Z-Y research, but not a complete analogue for the ultimate diagnostic algorithm.

The research school most closely related to electric locomotive bogie frames in Uzbekistan has developed through the work of G.A. Khromova and D.O. Radjibayev. The monograph by Khromova, Radjibayev, and S.A. Khromov systematically addresses dynamic-strength calculations for locomotive frame structures of complex configuration, their vibrations, and service-life extension [2]. D.O. Radjibayev’s 2024 DSc research considers operational failures, dynamic loads, hazardous sections, modernization, and service-life tests of VL80 and 3VL80s electric locomotive bogie frames within a single study [1]. These studies are especially significant because they demonstrate in practice that operating data from Uzbekistan’s railways can be linked to computational results.

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Radjibayev's dissertation abstract presents data from the "O'zbekiston" locomotive depot for VL80 and 3VL80s electric locomotives during 2017–2022. Bogie frames accounted for 35% of the overall failure distribution. The same source reports a total of 153 failures associated with fatigue cracks in mechanical components from 2 February 2017 to 11 October 2022, of which 54.71% were attributable to bogie frames; within bogie-frame failures, the pivot beam zone accounted for 18.86%, the longitudinal beam for 24.53%, and cracks along the frame contour for 11.32% [1]. These figures lead to an important conclusion: distinguishing zones repeatedly damaged in service may enable more rational use of diagnostic resources than inspecting the entire frame surface with equal intensity. Nevertheless, these zones identified for the VL80 cannot be transferred directly to the O'Z-Y frame; a separate FEM analysis is required for the O'Z-Y's own geometry, load-transfer arrangement, and operating conditions.

In 2022, Khromova and Radjibayev proposed a mathematical model and algorithm for calculating the durability indicators of VL80s electric locomotive bogie components. The authors developed the concept of calculating durability indicators from instrumental and non-destructive testing results [3]. This approach provides an important theoretical basis for the dissertation's chain "NDT result → technical condition/service-life assessment." However, the study did not address selecting NDT locations from an FEM load map specific to the O'Z-Y, separately classifying critical zones that remain consistent under different loading regimes, or subsequently deriving a probabilistic risk indicator.

In their 2025 study, Khromova, Radjibayev, and A. Mavlyanov compared analytical–numerical calculations of the dynamic strength of VL80s electric locomotive frame structures with finite element modelling results and substantiated modernization methods using results from full-scale dynamic tests [4]. The study is methodologically relevant to the O'Z-Y because it takes actual loading into account and combines quasi-static and dynamic calculations. At the same time, its main objective is to reinforce the existing VL80 structure and extend its service life. The planned O'Z-Y research, by contrast, aims not so much to design reinforcement as to develop a new diagnostic framework: calculating critical zones in advance, inspecting those specific zones with portable NDT, and converting inspection results into risk estimates.

Patent No. IAP 06795 of the Republic of Uzbekistan deserves particular attention as a practical result of the local research school. The test stand proposed by G.A. Khromova, S.A. Khromov, and D.O. Radjibayev is intended for testing the dynamic strength and fatigue performance of bogie frames of locomotives with electric power transmission to the wheelsets. The patented solution seeks to reproduce conditions close to actual operation by controlling load amplitude, mean load level, and frequency, or by reproducing operating load cycles [20]. This invention is of considerable significance for service-life testing but does not resolve the task of rapidly inspecting critical sections of every in-service O'Z-Y locomotive using portable NDT in a depot. Accordingly, the O'Z-Y research does not

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duplicate test-stand experiments; it links the computational question "where should inspections be performed?" with the operational question "when and how should inspections be performed?"

Identification of Critical Zones in International Studies Using FEM and In-Service Load Spectra

In international literature, methods for evaluating bogie-frame fatigue life have been systematically reviewed by R. Xiu, M. Spiryagin, Q. Wu, S. Yang, and Y. Liu [7]. The authors grouped these methods according to whether they rely on design loads prescribed by standards, measured in-service load spectra, or simulated load spectra. Their review indicates that standard loads can produce conservative results in design and remaining-life assessments, whereas measured spectra better reproduce operating scenarios, although acquiring them is expensive and time-consuming. An important research gap identified is the insufficient representation of traction and braking forces in certain simulated load spectra [7]. This conclusion is particularly important for electric locomotives, including the O'Z-Y: constructing a bogie-frame loading map using only vertical static loads may lead to incorrect assessment of hazardous sections. Therefore, in Stage 2 of the dissertation, vertical, lateral, traction, and braking load cases need to be developed both separately and in combination.

Y. Wang, J. Xue, X. Zhang, and L. Chen evaluated a passenger-locomotive bogie frame for static strength, modal behaviour, and reliability using ANSYS and a three-dimensional solid model [8]. This work presents a typical sequence for transferring a 3D model into an FEM model, obtaining the stress field under loading, and calculating reliability. However, unless such a conventional FEM assessment is linked to inspection locations used in maintenance, it remains at the design-verification level. The principal distinguishing feature of the O'Z-Y study should be the next step: identifying zones that repeatedly experience high stress under different operating regimes as "consistently critical zones" and converting them into an NDT inspection route.

Y. Lu, Z. Feng, T. Chen, J. Zeng, and P. Wu developed shell and solid finite element models for evaluating the multiaxial fatigue state of a bogie frame, defined load cases according to UIC 615-4 and other railway standards, and assessed fatigue strength using the Goodman criterion [9]. Their study demonstrates the similarity of results from shell and solid models and the need to reduce multiaxial stress states to a scalar assessment criterion. For the O'Z-Y dissertation, the methodological implication is that the complexity of the 3D model is not itself a scientific result; the model must predict stresses in critical zones with adequate accuracy and distinguish recurring "hot spots" across multiple loading regimes.

C. Ji, S. Sun, Q. Li, Z. Ren, and G. Yang evaluated fatigue-critical locations in a high-speed electric-train bogie frame using field measurements of actual loads by strain gauges, static calibration, and a load–strain response matrix [10]. On the basis of actual loading histories, they formed a load spectrum using the principle of damage consistency and demonstrated that it represents in-service fatigue damage more accurately than a standard test spectrum. In 2025, Y. Yin and co-authors extended this line of research by proposing a spectrum that accounts not only for load amplitude but

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also for correlations in frequency, phase, and load sequence [11]. These studies substantiate the "standard loads + actual operating loads" principle for the O'Z-Y project. However, their primary goal was to improve test load spectra, while portable NDT inspection routes in depots and conversion of defect databases into risk-based decisions remained secondary or separate issues.

The failure analysis conducted by S. Qu, J. Wang, D. Zhang, D. Li, and L. Wei clearly demonstrates the role of operating dynamics in the development of critical zones [12]. The authors detected premature fatigue cracks in 27 bogie frames during maintenance and combined field tests, dismantled-frame inspection, and dynamic simulation. According to the source, these frames developed cracks after approximately 3 million km of operation, compared with an expected design service distance of 15 million km. The analysis linked cracks at the junction of side and transverse beams to hunting instability [12]. This example demonstrates that the simplistic assumption "the point of maximum static stress equals the actual zone of an in-service crack" is not always valid. Consequently, the critical-zone map for the O'Z-Y must be generated from the combined results of several load cases and subsequently verified using NDT data.

Approaches to Fatigue Crack Propagation and Remaining Service-Life Assessment

In 2024, J.-W. Seo, H.-M. Hur, S.-J. Kwon, and K.-H. Moon evaluated crack propagation in bogie frames in relation to operating dynamic stresses [13]. They used FEM to identify critical zones and the stress intensity factor, then analysed crack-growth characteristics. An important aspect of the study is that it directly links FEM results with the concept of crack propagation. However, the objective proposed for our dissertation is not limited to calculating a crack-growth law: the hazardous zone identified by FEM should be inspected in practice during maintenance, and the size and condition of the detected defect should be stored together with mileage and loading information and influence the subsequent inspection decision.

In 2025, Q. Xiao, M. Zhang, C. Chang, and X. Gao proposed a nonlinear cumulative fatigue damage model for bogie frames subject to complex multistage loading [14]. The study indicates that load sequence, interactions between loads, and degradation of material properties during service are not adequately represented by conventional linear Miner-type approaches. This result supports selecting, for Stage 7 of the O'Z-Y dissertation, a probabilistic/risk model updated with loading and defect data rather than a simple deterministic rule of the form "higher mileage means higher risk."

The multiscale study published in 2026 by Z. Zhang, B. Yang, J. Liu, Y. Song, H. Li, J. Yan, S. Xiao, and L. Yang combined full-scale fatigue testing, multiaxial crack-growth experiments, and FEM to investigate the condition of high-speed train bogie-frame materials after long-term service [15]. The authors reported that service-induced damage reduced remaining useful life by up to 70.54% in welded zones and up to 22.31% in base metal. The substantial difference between these two results demonstrates the need for separately tailored inspection intensity for welds and adjacent zones. In the O'Z-Y study, this idea should serve not as a basis for directly transferring material properties from

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another structure, but as a methodological basis for treating "critical zone + weld condition + mileage/loading + defect" as separate factors within the risk model.

A synthesis of international studies on remaining service life reveals three trends: first, classical fatigue assessment based on standardized cycles and S–N curves; second, more accurate quantification of damage accumulation using actually measured load spectra; and third, ongoing updating of remaining useful life by accounting for existing crack length, material degradation, and probabilistic data. For a master's-level study of the O'Z-Y, it is not necessary to convert the entire process into a complex fracture-mechanics model. The most scientifically and practically appropriate approach at the master's level is to identify hazardous zones using FEM, determine actual defect conditions using NDT, and combine mileage and operational loading to develop a risk index associated with defect initiation or progression.

Non-Destructive Testing and Portable Diagnostic Tools for Bogie Frames

Visual and dimensional inspection, magnetic particle testing (MT/MPI), penetrant testing (PT), and ultrasonic testing (UT) are the principal NDT methods used in the technical diagnostics of bogie frames. In a review of railway vehicle maintenance and NDT, K. Makino reported that inspection levels for Shinkansen and conventional rolling stock are determined according to time or mileage, with periodic inspections primarily using magnetic particle testing for surface defects in bogie-frame welds and ultrasonic testing for internal weld defects [17]. This approach provides an important methodological basis for relating the O'Z-Y inspection interval not only to calendar time but also to mileage and risk indicators.

J.S. Kim and N. Kim evaluated a bogie frame through combined static, fatigue, and non-destructive testing [19]. Fatigue testing continued up to 10×10^6 cycles, with magnetic particle and penetrant inspections performed at 6×10^6 and 10×10^6 cycles. The study shows that test cycles can be linked to NDT. However, this was an inspection conducted under full-scale test-stand conditions, whereas the O'Z-Y dissertation aims to develop a portable inspection scheme suitable for maintenance of an in-service electric locomotive, enabling rapid inspection of a limited number of pre-calculated critical zones.

M. Miki and M. Ogata developed phased-array ultrasonic testing schemes for welds in bogie frames and showed that conventional UT requires several measurement passes to detect defects in different orientations and that internal obstructions increase inspection time [16]. They optimized inspection by placing an array probe on the outside of the side beam and using direct and double-skip sound paths. In 2024, K. Makino applied phased-array ultrasonic testing (PAUT) to an actual bogie frame and evaluated its ability to detect and visualize inclined surface defects, as well as the effect of paint thickness on the signal [18]. These studies show that if ultrasonic testing is selected for the O'Z-Y, a generic recommendation that "UT is available" is insufficient; a probe configuration matched to the precise geometry of the critical zone, weld orientation, and surface condition is needed.

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J. Yan, H. Jin, H. Sun, and X. Qing developed an active monitoring system for fatigue cracks in bogie-frame weld zones based on ultrasonic guided waves [24]. The system comprises a permanently installed network of piezoelectric sensors, portable diagnostic hardware, and signal-processing software; laboratory experiments demonstrated detection of a 2 mm crack. This result confirms the technical feasibility of detecting localized frame damage using portable equipment. However, installing permanent sensor networks on all O‘Z-Y frames would require a separate capital and operational project. In a master’s study, taking a portable instrument to FEM-selected zones instead of installing permanent sensors could be investigated as a simpler solution in economic and organizational terms.

A methodological distinction must be drawn here. Conventional NDT procedures are generally based on periodic inspection of previously specified welds and structural zones. In the proposed O‘Z-Y approach, however, inspection locations are chosen not on the basis of structural convention or past failures alone, but at the intersection of three types of evidence: (1) high and recurring stresses in FEM; (2) geometric stress-concentration characteristics of the weld or section; and (3) defects or signal trends in the operational NDT history. In this way, portable NDT becomes not a tool for “inspecting everything,” but a means of prioritizing inspections according to risk.

Table 1.1. Comparative Analysis of Major Bogie-Frame Studies in Relation to the O‘Z-Y Dissertation

No.	Author and subject	Principal method and finding	Difference from the O‘Z-Y dissertation
1	D.O. Radjibayev, 2024; VL80/3VL80s electric locomotives [1]	Operational failure statistics, dynamic strength, hazardous sections, experiments, and modernization.	Focused on reinforcement and extending VL80 service life; FEM–NDT–risk integration for O‘Z-Y was not developed.
2	G. Khromova, D. Radjibaev, 2022; VL80s bogie components [3]	Model for calculating durability indicators using instrumental and NDT data.	Does not address selecting NDT points from an O‘Z-Y-specific critical-zone map or managing inspection risk.
3	A. Yusufov et al., 2023; shunting locomotive [5]	SolidWorks/FEM; prediction of stress state and remaining service life.	A methodological analogue for a locomotive frame; not linked to O‘Z-Y geometry or targeted portable NDT.
4	R. Xiu et al., 2020 [7]	Systematic review of bogie-	Identifies the need to fully

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No.	Author and subject	Principal method and finding	Difference from the O‘Z-Y dissertation
		frame fatigue-life assessment methods: standard, measured, and simulated load spectra.	account for traction/braking loads; supports broader O‘Z-Y load-case definition.
5	Y. Wang et al., 2019; passenger locomotive [8]	3D model, ANSYS, static and modal analysis, reliability assessment.	No mechanism developed for converting FEM results into an operational NDT route.
6	Y. Lu et al., 2014 [9]	Shell and solid FEM; multiaxial fatigue; Goodman assessment.	Strong modelling and fatigue assessment, but not linked to real defect databases or risk-based inspection.
7	C. Ji et al., 2020 [10]	Field strain-gauge measurements and actual load spectra; fatigue-critical points.	Strong representation of operating loads; depot NDT and a portable inspection algorithm were not primary subjects.
8	S. Qu et al., 2021 [12]	Premature cracks in 27 frames; field tests, dismantled inspection, and dynamic simulation.	Identifies the effect of dynamic hunting; no preventive FEM–NDT–risk monitoring chain established.
9	J.-W. Seo et al., 2024 [13]	FEM critical zones, stress intensity factors, and in-service crack growth.	Assesses crack propagation but provides no depot decision algorithm based on mileage/loading/defect data.
10	K. Makino, 2024 [18]	Detection and visualization of welded defects in actual bogie frames using PAUT.	Advanced NDT technology, but inspection priority is not determined using an FEM risk map.

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No.	Author and subject	Principal method and finding	Difference from the O‘Z-Y dissertation
11	Z. Zhang et al., 2026 [15]	Full-scale testing + FEM + multiaxial crack growth; remaining-life degradation.	In-depth material-level analysis, not a simplified portable maintenance inspection algorithm.

Analysis of Patented Solutions Related to Bogie Frame Diagnostics

Unlike scientific articles, patent literature shows which technical means can be used to implement diagnostic procedures. Therefore, the criteria used to analyse patents were the principle of detecting bogie-frame defects, whether monitoring is continuous or periodic, the need for permanent sensors, the need to modify the structure, and the feasibility of retrofitting the solution to the O‘Z-Y.

Uzbekistan Patent IAP 06795 concerns testing the dynamic strength and fatigue performance of bogie frames under test-stand conditions [20]. Its advantage is the ability to reproduce loading close to real operating cycles. Its limitation is that it is intended for service-life testing rather than rapid inspection of an existing frame in a depot. Thus, the patent is useful for substantiating the O‘Z-Y computational load cases and subsequent experimental validation, but it is not a direct prototype for portable diagnostics.

Patent KR20090069471A, developed by the Korea Railroad Research Institute, proposes installing accelerometers on bogie components, processing their vibration characteristics in the frequency domain, and monitoring signs of fatigue or imbalance using a microcontroller [21]. The main advantage of the solution is continuous monitoring of bogie condition while the vehicle is moving. However, such a system requires permanent sensors, signal-processing hardware, and integration with onboard systems. Because the O‘Z-Y master’s research envisages inspecting selected zones using portable NDT during maintenance, it may require substantially less capital equipment.

Patent JP2011255754A (subsequently JP5357835B2) of the Railway Technical Research Institute (Japan) proposes supplying gas pressure to selected sealed compartments of a welded bogie frame and detecting cracks through changes in internal pressure when a crack forms. The inventors are Shota Yamamoto, Takeshi Yagi, and Tokuzo Miyaji; the solution uses a specially sealed chamber of an air-spring bogie structure [22]. This principle enables rapid crack detection, but it cannot simply be added to an existing frame as a routine maintenance device: integration with the frame structure and pneumatic system is required. For the O‘Z-Y, external portable NDT equipment is a more practical research subject than such structural modifications.

In Patent EP3783356A1, Guoqiang Cai, Jianqun Wang, and Ming He propose a train-component crack-monitoring system that combines a piezoelectric sensor network, Lamb waves, historical defect data, and Bayesian–MCMC forecasting [23]. The patent identifies the bogie frame as an important load-bearing component of a locomotive or railcar; detected crack-length data are stored on a server,

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and the rate of damage progression is predicted from historical data. This patent is among the closest methodological analogues for Stages 6–7 of the dissertation: a defect database and a probabilistic model. The difference is that the patent relies on a permanent sensor network, whereas the O‘Z-Y study envisages using portable NDT results obtained during maintenance together with mileage/loading indicators as data sources.

Table 1.2. Comparative Analysis of Patented Solutions Related to Bogie Frame Diagnostics

Patent	Inventor / organization	Technical concept	Difference from the O‘Z-Y study
IAP 06795, Uzbekistan, 2022	G.A. Khromova, S.A. Khromov, D.O. Radjibayev	Test-stand testing of locomotive bogie frames under realistic dynamic/fatigue loads.	Designed for service-life testing, not targeted portable NDT of in-service frames.
KR20090069471 A, Korea, 2009	Shin Kyung-ho, Shin Deok-ho, Jeong Ui-jin, Kim Yong-gyu; Korea Railroad Research Institute	Real-time monitoring of bogie condition/fatigue using accelerometers and frequency analysis.	Requires permanent sensors and onboard integration; unlike local NDT during maintenance.
JP2011255754A / JP5357835B2, Japan, 2011/2013	Shota Yamamoto, Takeshi Yagi, Tokuzo Miyaji; Railway Technical Research Institute	Crack detection by pressure changes in a sealed frame compartment.	Requires special structural/pneumatic integration; not a straightforward retrofit for existing O‘Z-Y frames.
EP3783356A1, 2021	Guoqiang Cai, Jianqun Wang, Ming He; Jiangsu Bide Science and Technology Co. Ltd	Lamb-wave sensor network + crack-data database + Bayesian–MCMC forecasting.	Similar data/risk approach, but based on a permanent sensor network; portable NDT is intended for O‘Z-Y.

Scientific Distinction and Relevance of the Planned O‘Z-Y Study Relative to Existing Research

Considering the reviewed Uzbek and international research as a whole, the scientific problems relating to bogie frames can be classified into five relatively independent areas: structural/FEM strength analysis; fatigue assessment using standard or measured load spectra; crack-growth and

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remaining-life calculations; defect detection through NDT/structural health monitoring (SHM); and probabilistic forecasting using historical damage data. Some major studies integrate two or three of these areas, but most are directed towards certification of new structures, laboratory fatigue testing, permanent-sensor monitoring, or extending the service life of particular older locomotive types [1, 7, 10, 13–15, 23].

Within the scope of this literature search, no openly available scientific publication was identified that implements the following complete sequence as a unified methodology specifically for the O‘Z-Y electric locomotive bogie frame: standard and in-service loading cases → FEM stress–strain field → map of consistently critical zones across different operating regimes → inspection of these zones using portable NDT during maintenance → consolidation of mileage, loading, and defect results in one database → risk/probability-based inspection decision. This statement does not claim that the O‘Z-Y frame has not been studied at all; it refers specifically to the absence of the described integrated diagnostic sequence in the open literature searched.

This distinction determines the relevance of the dissertation. First, local experience with the VL80 has shown that bogie-frame failures account for a substantial share of operational failures and that fatigue cracks concentrate in particular zones [1]. Second, international studies indicate that standard design loads alone do not fully reproduce actual fatigue-damage distributions and that measured load spectra and dynamic instabilities can shift critical zones [7, 10–12]. Third, recent remaining-life studies show that long-term service can substantially reduce resistance to crack growth, particularly in welded zones [15]. Fourth, modern NDT technologies allow visualization and monitoring of small localized defects in frames [16–18, 24]. Thus, the problem is not whether NDT tools exist but how to scientifically substantiate exactly which zone to inspect, at what frequency, and according to which risk criterion.

Accordingly, the proposed scientific approach for the O‘Z-Y electric locomotive should treat “calculation” and “diagnostics” not as separate stages but as a mutually reinforcing closed loop. First, a reliable computational 3D model of the O‘Z-Y bogie frame is established. Next, standard and, to the extent possible, actual operating load cases are defined. FEM calculations then yield fields of equivalent and principal stresses for each operating regime. Rather than relying on a single maximum, zones that repeatedly exhibit high values under different regimes are identified as “consistently critical zones.” These zones become priority locations for portable magnetic particle, penetrant, or ultrasonic testing during maintenance. The NDT result is not limited to “defect present/absent”; it is entered into a database together with defect type, location, size, mileage, inspection date, and operating-load indicators. Once repeated observations accumulate, the probability of defects and the risk index for each critical zone are updated.

Such a methodology does not negate the remaining-life, dynamic-strength, and operational-statistics research undertaken by Uzbek scientists for VL80 and other locomotives; instead, it extends these findings into a diagnostic framework adapted to the O‘Z-Y. International studies provide the

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necessary methodological components relating to measured load spectra, multiaxial fatigue, crack growth, PAUT, and sensor monitoring. The scientific task of the dissertation is not to assemble these components mechanically, but to justify a coherent integration of the most necessary elements into a diagnostic algorithm for the O‘Z-Y bogie frame that can be implemented under depot conditions.

As a result, the review in Section 1.1 establishes the following scientific position for subsequent chapters: to improve technical diagnostics of the O‘Z-Y bogie frame, rather than distributing inspection efforts equally across every structural component, it is appropriate to identify in advance, using FEM, those sections that repeatedly become critical under loading regimes; to verify them through targeted portable NDT; and to link inspection frequency to risk levels derived from mileage, loading, and defect history. This approach unifies the subsequent stages of 3D modelling, load-case definition, FEM calculations, NDT-method selection, and risk-model development into a coherent scientific framework.

Conclusion. The analysis of the literature and patents indicates that FEM, measured load spectra, NDT, and remaining-life models are well developed for evaluating the fatigue reliability of railway bogie frames, but their results are often applied to separate problems. Studies by Uzbek scientists on VL80/3VL80s and other locomotives have advanced local failure statistics, calculation of hazardous sections, remaining-life assessment, and dynamic testing. International studies have extended the understanding of measured load spectra, multiaxial fatigue, crack propagation, and modern UT/PAUT/SHM methods. However, the review of open sources did not identify a comprehensive methodology specifically for the O‘Z-Y bogie frame that computationally identifies consistently critical zones under various standard and operating regimes, links those zones with portable NDT results, mileage, and loading data collected during service, and produces risk-based inspection recommendations. Therefore, developing this integrated approach in subsequent stages of the present master’s dissertation is a scientifically and practically justified task.

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