

**RAILWAY TRACK MAINTENANCE MACHINERY: CLASSIFICATION,
OPERATING PRINCIPLES, PERFORMANCE PARAMETERS, AND
TECHNOLOGICAL APPLICATIONS IN MODERN TRACK ENGINEERING**

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ABSTRACT: Background: Railway track maintenance machinery constitutes the technical foundation of modern railway infrastructure management, enabling the systematic restoration, monitoring, and optimization of track geometry, ballast condition, and rail surface quality at operational speeds incompatible with manual methods. The global railway network exceeds 1.4 million kilometres of track, requiring continuous mechanical maintenance to ensure train safety, ride comfort, and operational reliability. Modern maintenance machines—tamping machines, ballast regulators, rail grinders, track geometry cars, and dynamic track stabilizers—have transformed track maintenance from labour-intensive manual operations into precision-mechanized industrial processes.

Objective: To provide a systematic, evidence-based review of the principal railway track maintenance machine types, their operating principles, performance parameters, classification by function and working speed, technological applications in preventive and corrective maintenance, and the integration of diagnostic and automation technologies in modern track engineering practice.

Methods: A systematic review of eight primary sources—engineering monographs, railway standards, technical studies, and peer-reviewed journal articles published between 1995 and 2024—was conducted.

Results: Tamping machines achieve track geometry correction tolerances of $\pm 1\text{--}2$ mm for alignment and ± 1 mm for cross-level at production rates of 600–1,200 m/h. Rail grinding machines restore rail profile to $R_a \leq 6.3$ μm surface roughness and extend rail service life by 30–50%. Dynamic track stabilizers reduce post-tamping settlement by 60–80% and increase lateral track resistance by 40%. Track geometry measurement vehicles operating at 80–160 km/h provide real-time versine measurement accuracy of ± 0.3 mm, enabling predictive maintenance scheduling. Continuous welded rail (CWR) flash-butt welding machines produce joints with hardness within 260–320 HB range meeting EN 14730-1 standards.

Conclusion: Modern railway track maintenance machinery enables safe, cost-effective, and precision maintenance of high-speed and heavy-haul railway infrastructure. The integration of GPS positioning, inertial measurement units (IMU), machine learning-based geometry prediction, and autonomous tamping control represents the current frontier of railway maintenance mechanization, significantly reducing track possession time and improving the accuracy and durability of maintenance outputs.

Keywords: railway maintenance machinery, tamping machine, ballast regulator, rail grinding, track geometry car, dynamic track stabilizer, ballast cleaning, flash-butt welding, continuous welded rail, track quality index, predictive maintenance, railway engineering

1. INTRODUCTION

Railway infrastructure maintenance is a technically complex and economically critical function that ensures the operational safety, ride quality, and structural integrity of track systems carrying trains at speeds from 25 km/h on freight branch lines to over 350 km/h on high-speed mainlines [1]. The global railway network—comprising approximately 1.4 million kilometres of standard, broad, and narrow gauge track operated by over 150 national and regional railway administrations—requires continuous mechanical maintenance to counteract the degradation of track geometry caused by repeated dynamic loading from passing trains, temperature-induced rail movement, differential ballast settlement, and seasonal ground movement [2]. The financial scale of this requirement is substantial: track maintenance costs represent 25–40% of total railway infrastructure expenditure in most national railway systems, with mechanized maintenance achieving cost efficiencies 4–8-fold superior to equivalent manual operations while simultaneously delivering superior geometric accuracy and restoration durability [1].

The mechanization of railway track maintenance—beginning with the development of the first self-propelled tamping machines in Austria (Plasser & Theurer, 1950s) and the Soviet Union (VPO series, 1960s)—has evolved from simple mechanical devices into sophisticated electro-hydraulic, computer-controlled, and GPS-integrated systems capable of simultaneously correcting track geometry in three dimensions (longitudinal level, cross-level, and alignment), compacting ballast to engineered density specifications, and recording all operational parameters for quality documentation and maintenance management system integration [3]. For Uzbekistan Railways (O'zbekiston Temir Yo'llari), which operates approximately 6,700 km of mainline track including the high-speed Tashkent-Samarkand corridor (250 km/h design speed) and heavy-haul freight lines carrying 25-tonne axle loads, the systematic deployment of modern maintenance machinery is a strategic infrastructure priority directly linked to network capacity, safety, and international competitiveness [4]. This review synthesizes eight primary sources to provide a structured account of the principal railway track maintenance machine types, their operating principles, performance parameters, and technological applications.

2. MATERIALS AND METHODS

A systematic literature search was conducted in Scopus, Web of Science, Google Scholar, and the TRIS (Transportation Research Information Services) database using the terms: "railway track maintenance machinery," "tamping machine track geometry," "ballast cleaning machine performance," "rail grinding surface quality," "track geometry measurement car," "dynamic track stabilizer ballast," "flash butt welding railway rail," "predictive maintenance railway," and "track quality index TQI." Eight primary sources—engineering textbooks, peer-reviewed railway engineering journals (Proceedings of the Institution of Mechanical Engineers Part F, Journal of Rail and Rapid Transit, Transportation Geotechnics), EN/UIC technical standards, and national railway technical regulations—published between 1995 and 2024 were selected. Machine performance data were taken directly from primary sources or manufacturers' certified technical specifications. Key source characteristics are presented in Table 1; principal machine types with technical parameters are compiled in Table 2.

Table 1. Primary sources included in this review

Re f.	First Author Source	Pub. / Type	Scope	Primary Focus	Key Contribution
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f.	Re Author	First Source	Pub. Type	Scope	Primary Focus	Key Contribution
[1]	Esveld, C.		Textbook (MRT Press)	Track engineering	Modern Railway Track	Comprehensive track engineering reference
[2]	Lichtberger, B.		Textbook (Eurailpress)	Track maintenance	Track Compendium	Maintenance machinery & methods
[3]	Sysyn et al.		J. Rail Rapid Transit	Tamping performance	Geometry correction	Tamping quality modelling study
[4]	O'zbekiston TY		Technical Regulations	UTY network	Track maintenance norms	National maintenance standards
[5]	Kabo et al.		Wear Journal	Rail grinding	Surface fatigue & RCF	Grinding interval optimization
[6]	Fortunato et al.		Transport Geotech	Ballast mechanics	Fouling & cleaning	Ballast particle degradation model
[7]	Specht et al.		Proc IMechE Part F	Track geometry cars	Measurement accuracy	IMU-based geometry measurement
[8]	Zarembski & Patel		J Transp Eng	CWR welding	Flash-butt weld quality	Weld hardness & fatigue life

3. RESULTS

3.1 Track Geometry Degradation and Maintenance Strategy

Railway track geometry degrades continuously under repeated dynamic loading from passing trains, governed by the accumulation of permanent deformation (plastic settlement) in the ballast and subgrade layers [1]. The principal geometry parameters monitored and corrected by maintenance machinery are: longitudinal level (rail top surface vertical deviation from design level, measured as versine over 10 m chord, tolerance $\pm 3-6$ mm on mainlines); cross-level

(height difference between left and right rail at a given cross-section, tolerance ± 3 mm); alignment (lateral rail deviation from design axis, measured as versine, tolerance ± 4 mm); gauge (transverse distance between inner rail faces at 14 mm below rail top, nominal 1,520 mm for Uzbekistan broad-gauge standard, tolerance $+4/-2$ mm); and twist (rate of change of cross-level over 3 m base, tolerance 2–3 mm/m) [1]. Track quality is quantitatively assessed by the Track Quality Index (TQI)—a composite standard deviation of geometry parameter deviations computed over 100 m or 200 m analysis windows—which triggers preventive or corrective maintenance when it exceeds class-specific thresholds defined in national technical regulations and UIC Code 712 [4].

Maintenance strategy in modern railway engineering follows the predictive (condition-based) maintenance paradigm, in which track geometry measurement vehicle data are processed by software platforms (LIMS, IRISSYS, TGMS) to forecast geometry degradation trajectories and optimize the timing and type of maintenance intervention [2]. This approach—contrasted with the traditional time-based (periodic) maintenance scheduling—reduces unnecessary maintenance interventions by 20–35%, extends track maintenance intervals by 15–25%, and prevents geometry from degrading to corrective maintenance thresholds that require slower production speeds and greater restoration depth, thereby reducing both maintenance cost and track possession time [2]. The degradation rate of track geometry is quantified by the geometry degradation coefficient (γ , mm/MGT—millimetres of TQI increase per million gross tonnes of traffic), which varies from $\gamma = 0.15$ – 0.5 mm/MGT on well-maintained hard-subgrade mainlines to $\gamma = 0.8$ – 2.5 mm/MGT on soft-subgrade, frost-susceptible, or heavily trafficked lines—providing the input data for maintenance planning algorithms [3].

3.2 Tamping Machines: Principles and Performance

The tamping machine is the primary geometry correction tool of the railway maintenance fleet, simultaneously performing three coordinated operations: lifting and aligning the track (shifting it to the correct three-dimensional geometric position by hydraulic lifting and lining cylinders acting on the rails), and tamping (compacting ballast beneath each sleeper by pairs of vibrating tamping tines inserted into the ballast on both sides of each sleeper, squeezed together under hydraulic pressure of 100–180 kN, and vibrated at 35–45 Hz) [2]. The tamping unit—the machine's core operating element—typically consists of 4 to 16 pairs of tamping tines (on multi-sleeper tamping machines capable of tamping 2–4 sleepers per tamping cycle) driven by eccentric vibrators and hydraulic squeeze cylinders. The geometric control system uses reference lines established by tensioned piano wire or laser/optical chord reference systems (measuring versine at mid-chord of a 10 m alignment chord and longitudinal level at mid-chord of a 10 m level chord) to compute the required lifting and lining corrections at each sleeper [3].

Modern tamping machines (Plasser & Theurer 09-3X, Matisa B 66 UE, Robel, VPO-3-3000) achieve geometry correction to ± 1 mm cross-level and ± 2 mm alignment tolerance at production rates of 600–1,200 m/h on plain track, measured immediately post-tamping by the machine's on-board recording system [3]. A critical limitation of tamping alone is the instability of freshly tamped track: ballast particles disturbed by tamping tine insertion require 200,000–500,000 gross tonnes (MGT) of traffic consolidation to achieve stable density, during which the track is vulnerable to rapid geometry deterioration and must be operated at reduced speed (typically 80–160 km/h speed restriction, T1/T2 speed category, for 24–48 hours post-tamping) [3]. Dynamic track stabilizers (DTS), operated immediately after tamping, address this limitation by applying controlled vertical vibration (30–45 Hz) and simultaneous lateral horizontal force (120–180 kN) to the rails via flanged roller clamps, consolidating the disturbed ballast to 95–100% of pre-

tamping density while preserving the geometric corrections—reducing post-tamping settlement by 60–80% and allowing speed restriction removal within 2–4 hours rather than 24–48 hours [2].

3.3 Ballast Management: Cleaning and Regulation

Ballast—the crushed stone aggregate (granite, basalt, or limestone, particle size 25–60 mm) that supports sleepers, distributes train loads to the subgrade, and enables track drainage—degrades progressively through particle breakage under repeated loading, contamination by fine particles (clay, silt) from subgrade pumping and sleeper abrasion, and frost heave cycling [6]. The fouling index (FI = mass fraction of particles passing a 4.75 mm sieve in a ballast sample) quantifies contamination: FI < 1% represents clean ballast; FI > 40% represents highly fouled ballast with substantially impaired drainage (hydraulic conductivity reduced from 10^{-2} m/s to $< 10^{-5}$ m/s) and load-bearing capacity [6]. When FI exceeds 25–30% on mainlines, ballast cleaning by high-output screening machines (RM 900, RM 80, SRP-19) becomes necessary: these machines excavate the full ballast bed depth (300–400 mm) by a rotating chain-driven excavating unit, transport the excavated material to onboard vibrating screens that separate clean ballast (returned to the track) from fouled fines (conveyed to side spoil wagons), and re-level the cleaned ballast to design profile [6]. Ballast cleaning production rates of 100–300 m/h are achievable on broad-gauge track, with post-cleaning ballast quality meeting the < 8% FI specification required before track re-lifting and tamping [6].

Ballast regulators (wing spreaders) distribute ballast delivered by hopper wagons to the correct cross-sectional profile, shape shoulder and drainage berm geometry, and remove excess ballast from between and outside rails by adjustable wing blades and undercutting ploughs operating at 1,000–4,000 m/h [2]. The ballast cross-section profile is defined by national track standards (for Uzbekistan Railways: shoulder width 450–500 mm, shoulder height 150 mm above sleeper base, ballast depth 300–350 mm under concrete sleepers) and must be restored after any tamping cycle that redistributes ballast laterally [4]. Modern ballast regulators incorporate laser profile scanners that measure the actual ballast cross-section continuously and compare it to the design profile, automatically adjusting wing blade positions to achieve ± 20 mm shoulder profile accuracy without operator intervention—a significant advance over earlier purely manual blade positioning [2].

3.4 Rail Grinding and Welding Technology

Rail surface integrity is essential for rolling contact fatigue (RCF) prevention, wheel-rail noise reduction, and structural rail service life [5]. Rail grinding machines—equipped with multiple abrasive grinding stones or grinding wheels (typically 48–96 stones per rail on high-production machines such as the Speno RR-48) rotating at 1,500–3,000 rpm against the rail surface—remove material at controlled depth (0.05–0.3 mm per pass) to: eliminate surface-initiated RCF defects (head checks, squats, shelling) before they propagate to critical depth; restore the correct transverse rail profile to the designed template (deviations from design profile corrected to ± 0.1 mm); and reduce surface roughness to $R_a \leq 6.3 \mu\text{m}$, minimising corrugation growth and airborne noise emission [5]. Grinding extends rail service life by 30–50% on heavy-haul and high-speed lines by preventing crack propagation from fatigue initiation sites: a study of heavy-haul mining railway rails demonstrated that preventive grinding at 50 MGT intervals more than doubled rail service life from 800 MGT to 1,800+ MGT compared to no-grinding control sections [5]. Modern grinding machines integrate profiler measurement systems (optical or tactile transverse profile scanners) and GPS-referenced longitudinal defect mapping that creates a pre-grinding and post-grinding data record used to verify grinding quality and plan the next grinding cycle [5].

Continuous welded rail (CWR) formation—eliminating the conventional bolted joint every 12–18 m that causes impact loading and geometric irregularity—is achieved by flash-butt welding, the primary rail joining method in modern high-quality track [8]. Flash-butt welding machines (K-1000, AWeld, K-920) apply 200–400 kN clamping force to two rail ends, pass high current (20,000–30,000 A) through the joint to create a flashing arc that pre-heats the rail ends, then rapidly upset (forge) the ends together under 500–800 kN hydraulic force at precisely the moment of optimal plastic temperature (1,200–1,300°C), producing a solid-state weld with metallurgical properties approaching those of the parent rail [8]. Post-weld quality is verified by hardness testing (260–320 HB in the heat-affected zone for standard R260 grade rail), ultrasonic inspection (longitudinal and transverse defect detection), and geometry measurement confirming rail top surface straightness within ± 0.3 mm over 1 m [8]. Thermite (aluminothermic) welding—using chemical reaction of aluminium powder with iron oxide to produce liquid steel that fills the joint mould—is used for closure welds in locations inaccessible to flash-butt welding machines [8].

3.5 Track Geometry Measurement and Diagnostic Systems

Track geometry measurement vehicles (GMVs)—self-propelled railway vehicles equipped with non-contact measurement systems—provide continuous, high-resolution documentation of all track geometry parameters at operating speeds of 80–160 km/h (or up to 300 km/h on high-speed lines) without requiring track possession or train service interruption [7]. Modern GMVs employ inertial measurement units (IMU)—gyroscopes and accelerometers in three axes—combined with laser triangulation sensors for absolute rail position measurement, chord reference systems for relative versine measurement, and GPS/GNSS positioning for kilometre-accurate data georeferencing [7]. The inertial measurement approach, replacing the earlier mechanical chord reference systems, enables accurate measurement of long-wavelength geometry variations (wavelengths of 3–300 m) that are critical for high-speed passenger train ride quality but invisible to short-chord mechanical systems [7]. Specht et al. demonstrated that IMU-based geometry measurement systems achieve versine measurement accuracy of ± 0.3 mm (standard deviation across 100 measurement runs on a calibration track), cross-level accuracy of ± 0.2 mm, and gauge accuracy of ± 0.1 mm—sufficient to detect geometry defects before they reach intervention thresholds, enabling predictive maintenance scheduling that reduces reactive maintenance by 25–30% [7]. GMV data are processed by maintenance management information systems (MMIS) that automatically classify geometry deviations by severity (immediate safety intervention, scheduled maintenance, monitoring), generate maintenance work orders, and track geometry quality trends over time to validate maintenance effectiveness [2].

Table 2. Principal railway track maintenance machines: function, performance and parameters

Machine Type	Primary Function	Accuracy / Tolerance	Production Rate	Key Outcome
Tamping Machine (Dynamic Track Stabilizer)	Sleeper compaction; ballast consolidation	± 1 mm cross-level; ± 2 mm alignment	600–1,200 m/h	Plasser & Theurer 09-3X; Matisa B 66 UE
Ballast Regulator (Wing)	Ballast distribution &	± 50 mm shoulder	1,000–	Plasser USP 5000;

Machine Type	Primary Function	Accuracy / Tolerance	Production Rate	Key Outcome
Spreader)	shoulder shaping	profile tolerance	4,000 m/h	BNS 63-4
Ballast Cleaning Machine (Shoulder Cleaner)	Fouled ballast excavation & screening (16–50 mm)	< 8% fouling index post-cleaning	100–300 m/h	RM 900 (Plasser); SRP-19 (Soviet)
Rail Grinding Machine (Cylindrical & Profiled)	Surface defect removal; rail profile restoration	$Ra \leq 6.3 \mu\text{m}$; profile deviation $\leq 0.1 \text{ mm}$	500–2,000 m/h	Speno RR-48; Speno RGH-20C
Track Geometry Car (Measurement Vehicle)	Geometry parameter measurement & recording	Versine $\pm 0.3 \text{ mm}$; cant $\pm 0.2 \text{ mm}$ accuracy	80–160 km/h	ROGER 1000; EMSAT (JSC RZhd)
Rail Welding Machine (Flash Butt / Thermite)	Continuous welded rail joint formation	Weld zone hardness 260–320 HB	8–12 welds/shift	K-1000 (AWeld); GSP-01 (Thermite)
Switch Tamping Machine (Universal)	Turnout area compaction; crossing geometry	$\pm 1.5 \text{ mm}$ in switch zones	150–400 m/h	Plasser 09-3X Unimat; VPO-3-3000
Dynamic Track Stabilizer (DTS)	Post-tamping ballast densification under load	Settlement reduction 60–80%; FPL $\uparrow 40\%$	1,000–2,000 m/h	Plasser DGS 62 N; Matisa STM 62

4. DISCUSSION

The integration of precision electro-hydraulic control, digital measurement, and GPS/GNSS positioning into modern railway maintenance machinery has transformed track maintenance from a craft-dependent manual activity into a reproducible, quality-assured engineering process [2, 3]. The tamping machine's evolution from purely mechanical geometry correction to computer-controlled, multi-parameter simultaneous correction—using on-board inertial reference systems that continuously update the machine's position in three-dimensional space relative to the design alignment stored in its maintenance computer—is the single most impactful technological advance in track maintenance mechanization of the past three decades, enabling

consistent achievement of ± 1 mm geometry tolerances that would be unattainable by manual methods [3]. The combination of GPS-referenced measurement data from track geometry cars, predictive maintenance scheduling algorithms, and automated tamping correction calculation has created a closed-loop quality management system in which each maintenance cycle's inputs (measured geometry deficiency) and outputs (achieved geometry improvement) are quantitatively documented, enabling continuous improvement of maintenance planning and machine calibration [7].

Ballast degradation and the associated maintenance challenge of increasing fouling and loss of drainage represent the principal long-term infrastructure threat to conventional ballasted track, particularly on high-traffic-density lines where annual MGT loading accelerates particle breakage [6]. The economic decision between ballast cleaning (restoring existing ballast) and ballast renewal (complete replacement) depends on the relationship between FI, ballast particle size distribution, and the projected traffic tonnage until next required intervention: life-cycle cost modelling consistently shows that cleaning is economically superior to renewal when FI is between 25–40%, while renewal becomes more cost-effective when FI exceeds 40% or when ballast particle breakage has reduced the proportion of oversized particles below specification [6]. For Uzbekistan Railways, where significant portions of the network traverse soft loess subgrade susceptible to seasonal moisture variation and subgrade pumping that accelerates ballast fouling, the strategic planning of ballast cleaning cycles based on systematic FI monitoring represents a high-priority maintenance engineering challenge requiring adapted maintenance machine selection and ground stabilization measures [4].

The emerging application of machine learning and artificial intelligence to railway track maintenance represents the next technological frontier [2]. Neural network models trained on historical geometry measurement data and traffic records can predict geometry degradation trajectories at individual track section level with mean absolute error of 0.3–0.8 mm TQI per MGT—sufficient accuracy for 3–6 month maintenance scheduling optimization. Autonomous tamping control systems—in which the tamping machine's lifting and lining corrections are computed in real time from on-board measurement data rather than pre-loaded survey data—are in advanced field trial stages on several European railway networks, promising 15–25% improvement in post-tamping geometry quality and 20–30% reduction in track possession time by eliminating the pre-tamping survey operation [3]. For JSC O'zbekiston Temir Yo'llari, the adoption of these technologies alongside investment in modern high-output maintenance machines (replacing ageing Soviet-era VPO-3-3000 tampers and SRP-19 cleaners with current-generation Plasser or Matisa equivalents) represents the maintenance infrastructure modernization pathway to support the planned expansion of the Uzbek railway network, including the Tashkent-Ferghana high-speed corridor and the Trans-Caspian international transport route [4].

5. CONCLUSION

Railway track maintenance machinery—encompassing tamping machines, ballast cleaners and regulators, rail grinding machines, dynamic track stabilizers, track geometry measurement vehicles, and rail welding systems—constitutes the technical core of modern railway infrastructure management, enabling the precision, speed, and quality of maintenance operations that safe railway operation demands. Tamping machines achieve ± 1 –2 mm geometry correction tolerances at 600–1,200 m/h production rates; dynamic track stabilizers reduce post-tamping settlement by 60–80% and restore traffic speed within hours; rail grinding extends rail service life by 30–50% through early removal of rolling contact fatigue defects; and track geometry

measurement vehicles provide continuous, 160 km/h-speed geometry documentation with ± 0.3 mm versine accuracy that drives predictive maintenance scheduling. The integration of GPS, IMU, and machine learning technologies is transforming track maintenance from periodic intervention to condition-based precision management, reducing maintenance costs and track possession requirements while improving geometry quality and durability.

For Uzbekistan Railways and the broader Central Asian railway network, systematic modernization of the maintenance machine fleet—replacing ageing equipment with current-generation computer-controlled tamping, cleaning, and measurement machines—combined with the establishment of condition-based maintenance management information systems and the training of railway engineering personnel in modern maintenance methodology, represents the highest-priority technical investment for ensuring the safety, capacity, and international competitiveness of the region's rail transport infrastructure. The development of national track maintenance standards aligned with UIC Code 712 and EN 13848 quality requirements, adapted to the specific conditions of Uzbekistan's broad-gauge network, loess subgrade geology, and climatic extremes, will provide the technical regulatory foundation for implementing evidence-based maintenance practices across the entire network.

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