

**SERVICE AND MAINTENANCE OF ELECTRIC AND HYBRID VEHICLES**

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**Abstract:** This study explores the evolving practices of service and maintenance in electric and hybrid vehicles. As electrification transforms the automotive industry, traditional maintenance paradigms are replaced by advanced diagnostics, high-voltage safety protocols, battery management, and software-driven interventions. The research highlights the importance of predictive maintenance, digital twin technology, and condition-based servicing for extending vehicle lifespan and ensuring safety. Emerging challenges in charging infrastructure, hybrid powertrain integration, and workforce training are also examined. The study emphasizes that the successful adoption of these technologies is essential for improving vehicle reliability, reducing operational costs, and supporting sustainable transportation.

**Keywords:** Electric Vehicles, Hybrid Vehicles, Battery Maintenance, High-Voltage Safety, Predictive Maintenance, Digital Twin, Charging Infrastructure, Powertrain Diagnostics, Vehicle Software, Sustainable Transportation

The rapid development of electric and hybrid vehicle technologies represents one of the most significant transformations in the global automotive industry in the twenty-first century. Driven by increasing environmental concerns, stricter emission regulations, rising fuel prices, and advancements in energy storage systems, electric vehicles (EVs) and hybrid electric vehicles (HEVs) have become a strategic focus for governments, manufacturers, and consumers worldwide. According to the International Energy Agency, the global electric vehicle fleet surpassed 40 million units by 2023, demonstrating an exponential growth trend compared to internal combustion engine vehicles. This technological transition has fundamentally altered traditional concepts of vehicle service and maintenance, requiring new competencies, tools, safety protocols, and diagnostic methodologies.

Electric and hybrid vehicles differ substantially from conventional vehicles in terms of powertrain architecture, energy sources, and control systems. Electric vehicles rely primarily on high-voltage lithium-ion battery packs, electric traction motors, inverters, and power electronics, while hybrid vehicles combine these components with internal combustion engines. As a result, the service and maintenance processes for these vehicles are characterized by reduced mechanical complexity but increased electrical and electronic system sophistication. Traditional maintenance tasks such as oil changes, exhaust system repairs, and fuel system servicing are either eliminated or significantly reduced, while new procedures related to battery health monitoring, high-voltage system diagnostics, and software updates become critical. One of the most important aspects of electric and hybrid vehicle maintenance is high-voltage safety. EV and HEV systems typically operate at voltages ranging from 200 to over 800 volts, which poses serious risks if improper service procedures are followed. International standards such as ISO 6469 and SAE J1766 define safety requirements for electric vehicle systems, including insulation resistance, isolation monitoring, and emergency disconnect mechanisms. Service personnel must undergo specialized training to handle high-voltage components, use insulated tools, and follow lockout-tagout procedures

to prevent electric shock. Failure to comply with these safety protocols can result in severe injury or fatal accidents.

Battery systems represent the most critical and expensive component in electric and hybrid vehicles, accounting for approximately 30–40 percent of total vehicle cost. Lithium-ion batteries require precise thermal management, voltage balancing, and charge control to ensure optimal performance and longevity. Maintenance of battery systems does not typically involve frequent physical intervention; instead, it relies heavily on diagnostic software that monitors parameters such as state of charge (SOC), state of health (SOH), internal resistance, and temperature distribution. Studies indicate that modern lithium-ion batteries can retain up to 80 percent of their original capacity after 8–10 years or 160,000 kilometers, provided that proper charging and thermal management conditions are maintained.

Thermal management systems play a crucial role in battery maintenance. Electric and hybrid vehicles employ liquid or air-based cooling systems to regulate battery and power electronics temperatures. Unlike traditional engine cooling systems, these systems must operate within narrow temperature ranges to prevent thermal degradation and capacity loss. Service procedures include inspection of coolant quality, leak detection, pump operation verification, and software-controlled thermal regulation checks. Improper thermal management can accelerate battery aging, reduce driving range, and increase the risk of thermal runaway events. Electric motors used in EVs and HEVs, such as permanent magnet synchronous motors and induction motors, require significantly less maintenance compared to internal combustion engines. These motors have fewer moving parts, no combustion process, and minimal mechanical wear. However, maintenance tasks still include inspection of bearings, cooling systems, insulation integrity, and power connections. Power electronics, including inverters and converters, are sensitive to heat, vibration, and moisture, making regular diagnostic testing essential. Advanced diagnostic tools enable technicians to identify inverter faults, sensor malfunctions, and control algorithm errors through onboard diagnostic systems.

Hybrid vehicles introduce additional complexity due to the coexistence of electric and conventional powertrains. Maintenance procedures must address both systems while ensuring proper integration and communication between them. Hybrid transmissions, regenerative braking systems, and energy management controllers require specialized diagnostic approaches. Regenerative braking, for example, significantly reduces wear on traditional friction brakes, extending brake pad and disc lifespan by up to 50 percent compared to conventional vehicles. However, maintenance must ensure that braking systems remain responsive and corrosion-free, particularly in regions with humid or cold climates. Software has become a central element of electric and hybrid vehicle maintenance.

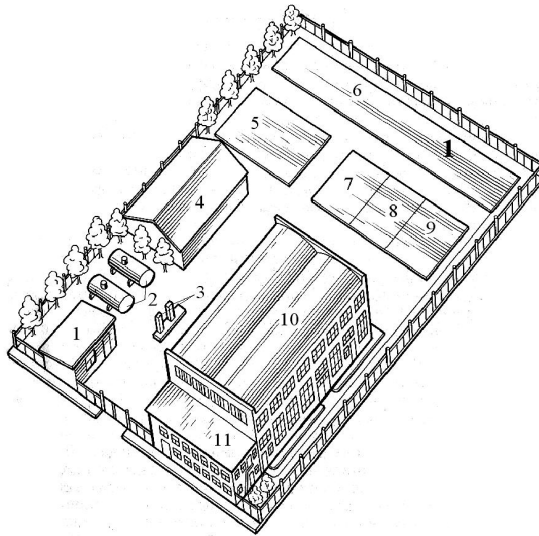
Modern vehicles rely on complex control algorithms for energy management, battery protection, driver assistance systems, and connectivity features. Over-the-air software updates allow manufacturers to improve vehicle performance, address faults, and enhance safety without physical service intervention. This paradigm shift requires service centers to focus on cybersecurity, software diagnostics, and data analysis. Research indicates that software-related issues account for a growing proportion of service interventions in electric vehicles, highlighting the need for interdisciplinary expertise combining mechanical, electrical, and information technologies.

Charging systems and infrastructure also form an integral part of electric vehicle servicing. Maintenance of onboard chargers, charging ports, and communication interfaces is essential to ensure compatibility with various charging standards such as CCS, CHAdeMO, and Type 2 connectors. Faults in charging systems can result from cable wear, connector contamination, or software communication errors. Regular inspection and diagnostic testing help prevent charging failures and ensure user safety. Studies show that proper maintenance of charging components can reduce downtime and improve overall vehicle reliability.

From an environmental perspective, electric and hybrid vehicle maintenance contributes to sustainability by reducing waste and emissions. The absence of oil changes, reduced brake wear, and extended component lifespans result in lower material consumption and environmental impact. Battery recycling and second-life applications are emerging as important aspects of long-term maintenance strategies. Research conducted by the European Commission indicates that up to 70 percent of battery materials can be recovered and reused, reducing dependency on critical raw materials such as lithium, cobalt, and nickel.

Organizations that own fleets of construction and land-reclamation machinery have their own bases equipped with workshops for technical maintenance and repair of the machines (Fig. 1). The base area is enclosed by a fence and includes an administrative and service building, a workshop, a warehouse for petroleum products constructed in compliance with fire safety requirements along with storage tanks, fire-fighting materials and equipment, a fueling station for supplying fuel and lubricants, facilities and areas for storing machinery, a site for placing machines under repair, an area for storing raw metal materials, as well as zones for external inspection and washing of machines.

The base is also equipped with mobile technical facilities designed to provide maintenance and repair services for machines operating in the field. These mobile units are furnished with special measuring instruments, various tools, and sets of wrenches of different sizes. Mobile technical facilities include mobile fueling machines that supply machinery with fuel and lubricants, as well as mobile workshop vehicles used for technical servicing and repair of machines. The main performance indicator of a base is its capacity. The capacity of a base is defined as the number of machines that can be serviced when its area and equipment are used to their maximum potential. The capacity of different types of bases is evaluated based on the amount of financial resources spent on the work performed over the course of one year.



**Figure 1. Repair base:** 1 — petroleum products warehouse; 2 — containers for storing petroleum products; 3 — fuel and lubricants filling station; 4 — machine storage building; 5, 6 — machine storage areas; 7 — area for placing machines under repair; 8 — raw metal storage area; 9 — area for external inspection and washing of machines; 10 — workshop; 11 — service and administrative building.

The transition to electric and hybrid vehicle servicing also has significant implications for workforce development and vocational education. Technicians must acquire new competencies in high-voltage systems, digital diagnostics, and safety management. Educational institutions and training centers are increasingly integrating electric vehicle maintenance modules into automotive engineering curricula. According to industry reports, the demand for certified EV technicians is expected to grow by more than 30 percent by 2030, reflecting the expanding adoption of electrified transportation. The service and maintenance of electric and hybrid vehicles represent a fundamental shift from traditional automotive practices toward a technology-driven, safety-oriented, and environmentally sustainable model. While these vehicles require less frequent mechanical maintenance, they demand higher levels of technical expertise, advanced diagnostic tools, and strict adherence to safety standards. The successful development of electric and hybrid vehicle service infrastructure is essential for ensuring reliability, consumer confidence, and long-term sustainability of modern transportation systems. As electrification continues to reshape the automotive sector, continuous research, professional training, and technological innovation will remain critical factors in the effective maintenance and servicing of electric and hybrid vehicles.

Recent advances in predictive maintenance and condition-based servicing are redefining how electric and hybrid vehicle fleets are maintained. Rather than adhering to fixed mileage-based schedules, many service organizations now implement continuous health monitoring using telematics and cloud analytics. Onboard sensors capture high-resolution time-series data from battery management systems (BMS), traction inverters, motors, and thermal circuits; machine-learning models trained on large fleet datasets detect subtle deviations in impedance, temperature gradients, and charge acceptance that precede functional decline. These probabilistic forecasts enable targeted interventions — such as passive cell rebalancing, localized thermal management servicing, or inverter capacitor replacement — reducing unnecessary part changes and lowering total cost of ownership. Implementing these systems requires new workflows in service centers: data ingestion pipelines, model validation routines, and secure remote-update procedures. Digital twin technology is emerging as a practical tool

for complex repairs and warranty analysis. A digital twin replicates a vehicle's electrical, thermal, and mechanical state in software, allowing technicians to simulate repair effects, validate firmware patches, and assess long-term battery degradation scenarios without risk to the physical vehicle. Digital twins can accelerate root-cause analysis for intermittent faults by replaying logged events (e.g., voltage transients or CAN-bus anomalies) and can be integrated into warranty dispute resolution to demonstrate whether field conditions contributed to component failure.

Battery care has grown more granular with advanced diagnostics such as electrochemical impedance spectroscopy (EIS) and incremental capacity analysis (ICA). Where earlier maintenance relied on SOC/SOH estimates from the BMS, these deeper analyses reveal electrode-level aging mechanisms: loss of lithium inventory, SEI thickening, and cathode structural changes. Service protocols that incorporate periodic EIS scans can identify early signs of cell mismatch or localized aging, allowing for cell-level conditioning or selective module replacement rather than full-pack substitution. Complementary techniques include non-invasive thermal imaging to map internal cell hot-spots and ultrasound inspections to detect internal separator delamination in pouch cells.

Fast-charging behavior and high-power DC charging infrastructure have introduced new maintenance considerations. Repeated high-power charging increases transient lithium plating risk and accelerates certain aging modes; service centers must therefore track customers' charging profiles and advise charging strategies, including dynamic charge-power limits implemented via software. Charging hardware at service facilities also requires unique upkeep: medium-voltage insulation tests, liquid-cooling loop maintenance for liquid-cooled cables, and firmware validation for smart charging station communication (OCPP/ISO 15118 stacks). Preventive maintenance of charging stations must be coordinated with grid interconnection agreements and utility-managed firmware controls to prevent cascade failures.

Modular battery design and standardized module interfaces are changing spare-parts logistics. Where pack-level replacements were once expensive and slow, manufacturers increasingly design packs with swappable modules and standardized mechanical/electrical connectors. This trend enables faster in-shop repairs, facilitates second-life reuse workflows (where modules with remaining capacity are repurposed for stationary storage), and supports emerging "battery-as-a-service" (BaaS) commercial models. BaaS demands rigorous traceability: battery passports or ledger records that document manufacture date, cycling history, and repair events help service centers make safe lifetime decisions and enable compliant recycling.

Thermal runaway mitigation has evolved beyond passive containment. New service protocols include verifying active cell-level monitoring, testing of venting pathways, and inspection of flame-arresting and coolant isolation systems. For high-energy packs, clinics employ sacrificial thermal fuses and automated isolation relays that can be validated through controlled diagnostic tests. Service technicians must be trained to interpret BMS fault codes that indicate pre-thermal conditions (e.g., cell over-voltage coincident with internal-resistance rise) and to perform safe transport procedures for at-risk packs. Hybrid vehicles present specific maintenance niches as powertrain control strategies become more complex. Service routines increasingly examine the coordination software between internal combustion and electric subsystems: start-stop smoothing algorithms, catalyst light-off timing (affected by

reduced engine-run time), and thermal strategies for dual cooling circuits. Exhaust aftertreatment maintenance cycles may change because hybrid engines run fewer hours but with more transient load profiles—this alters soot accumulation patterns and catalyst aging curves, requiring updates to emission-test intervals and service actions.

Augmented reality (AR) and guided service augmented with remote expert assistance are being adopted to speed repairs and reduce error rates. AR overlays can show torque specifications, HV interlock statuses, and wiring harness routing directly on a technician's headset while connected remote engineers provide stepwise guidance. This is particularly advantageous for geographically distributed service networks handling complex inverter calibrations or software-enabled repairs. Regulatory and insurance frameworks are also shifting. Regulators are moving toward requirements for battery provenance and recycling obligations; service centers will need compliance processes for documenting end-of-life handling and providing customers with transparent battery health reports. Insurers are developing EV-specific underwriting protocols that account for software updates, remote-diagnostics history, and manufacturer telematics — influencing repair authorization criteria and liability allocation when firmware changes affect vehicle behavior.

Supply chain resilience for EV service parts is an operational concern. Critical parts such as power semiconductors, inverter capacitors, and proprietary HV connectors have experienced constrained availability at times; service operations mitigate this with cross-manufacturer interchangeable component strategies, local stocking of high-failure-rate items, and calibrated refurbishment programs (e.g., inverter module reconditioning). Calibration laboratories for power-electronics test benches — capable of validating switching waveforms, harmonic emissions, and thermal performance — are becoming standard assets for larger service groups. Human capital development has matured into multi-tiered certification ecosystems. Effective programs combine hands-on HV safety drills, software debugging apprenticeships, and data-analytics literacy so that technicians can interpret fleet-level degradation trends. Employers increasingly partner with community colleges, OEM training academies, and independent certifiers to provide stackable credentials that reflect both electrical safety competence and software/diagnostics proficiency.

Finally, research gaps persist that warrant further study: quantifying the long-term effects of mixed charging regimes on specific cell chemistries under real-world duty cycles, defining standardized second-life qualification metrics for reused modules, and developing universal diagnostic communication protocols that protect cybersecurity while enabling transparent servicing. Addressing these gaps will require interdisciplinary collaboration across materials science, power electronics, data science, and regulatory policy to ensure that service paradigms keep pace with vehicle electrification.

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