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IMPLEMENTATION OF INTELLIGENT TECHNOLOGIES IN THE TECHNICAL SERVICE SYSTEM OF WHEELED VEHICLES

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The modern technical service (TS) system for wheeled vehicles (WVs) is undergoing a stage of radical transformation driven by the rapid development of Industry 4.0, the emergence of electric vehicles (EVs), and the concept of connected vehicles. The transition from reactive or scheduled preventive maintenance to predictive (PdM) and prescriptive maintenance requires the creation of a solid theoretical and methodological foundation. This foundation must not only integrate advanced technologies such as artificial intelligence (AI), machine learning (ML), and the Internet of Things (IoT), but also be conceptually aligned with the deep systemic approaches developed by the national scientific school.

To begin with, it is necessary to examine the evolution of theoretical paradigms of technical service as a complex socio-economic system. Historically, maintenance and repair management evolved from reactive post-failure repair to scheduled preventive maintenance (PM) and, later, to condition-based maintenance (CBM). However, with the increasing technical complexity of modern WVs especially hybrid and electric vehicles traditional deterministic and statistical performance-prediction models have proven insufficient. The technical service system, which includes vehicles, infrastructure, partners, and consumers, is now viewed as an open, nonlinear, highly dynamic system with stochastic behavior. This systemic complexity requires the use of intelligent tools capable of self-learning and adaptation.

In the context of our research, the importance of this approach for the intellectualization of TS is critical: while traditional models treat an enterprise as a set of discrete objects, the wave-based approach defines its interactions within the system through “field” effects. This means that the functioning of the TS system is nonlinear, multifactorial, and subject to rapid changes that cannot be predicted using classical mathematics. This concept provides a strong theoretical basis that justifies the need for intelligent technologies as the only class of tools capable of handling such nonlinearity, uncertainty, and adapting to the dynamics of “field interactions.”

Ukraine’s WVs industry is at a critical crossroads, where investments in digital and physical infrastructure, as well as adaptation to EVs and connected vehicles, are of utmost importance. This technological imperative requires that the methodology for implementing intelligent technologies take into account the specifics of high-voltage system diagnostics and V2X (Vehicle-to-Everything) communications.

The implementation of AI systems in Ukrainian technical service cannot be a purely technical process; it requires the creation of a strong organizational and legal module that ensures compliance with European standards. AI technologies including ML, deep learning (DL), and generative AI are used to process vast amounts of data obtained from sensors and network technologies.

Key areas of AI application in diagnostics and maintenance include:
- optimization of maintenance schedules;
- prediction of remaining useful life (RUL);

- effective health monitoring;
- reduction of costs and improvement of vehicle reliability and uptime.

Secondly, it is important to define the technical and architectural structures of AI systems for PdM. The architecture of modern intelligent PdM systems is based on real-time data collection using IoT sensors. These systems apply AI/ML algorithms to predict equipment failures, minimize downtime, and ensure optimal operational efficiency.

The PdM implementation process includes several critical layers:

1. Sensor data processing: collection, cleaning, and preparation of data arrays for subsequent ML modeling.
2. Modeling: creation and training of ML models.
3. Integration: embedding ML models into the organization's decision-support systems.

Modern scientific reviews emphasize the use of AI in the production and operation of EVs. This confirms the strategic need for Ukrainian research to focus on context-dependent diagnostics that account for EV-specific characteristics rather than only traditional internal-combustion vehicles.

Given the above, it is necessary to identify and justify the implementation challenges and future development directions. Systematic reviews of recent years have revealed several critical challenges that must be considered when developing a methodology for TS intellectualization:

1. Data quality and scalability: issues related to data quality, scalability, and integration of AI technologies into existing systems.
2. Explainable AI (XAI): the critical importance of explainable AI for predictive analytics. The need to justify AI conclusions is not only a technical requirement but also a methodological imperative in light of legal adaptation to the EU AI Act.

Emerging technologies shaping the future of PdM include:

- Digital Twins: virtual, dynamically updated copies of components or entire vehicles for simulation and accurate state prediction;
- Edge Computing: data processing at the network edge (e.g., in the vehicle or at a local service station) instead of centralized cloud processing;
- Federated Learning: distributed training of AI models on local datasets, improving privacy and efficiency.

Given the challenges associated with the development of digital infrastructure in Ukraine, Edge Computing becomes not just a desirable option but a methodological necessity. Localized data processing reduces network bandwidth requirements, minimizes latency which is critical for real-time diagnostics and supports compliance with regulatory restrictions on centralized collection and transmission of sensitive data.

For success in the Ukrainian transport industry, it is essential to invest in research and development (R&D) and create adequate digital and charging infrastructure, which forms the basis for supporting the growth of EVs and connected technologies.

The analysis confirms that the theoretical and methodological foundations for implementing intelligent technologies in the TS system of WVs represent a multifaceted scientific problem requiring an interdisciplinary approach. It has been established that the national scientific school provides a strong conceptual foundation for understanding the TS system as a complex nonlinear structure governed by “field interactions.” This concept serves as a significant scientific justification for the use of intelligent technologies.

Global studies demonstrate technological readiness for implementing AI/ML/IoT-based PdM. At the same time, strategic trends (transition to EVs and connected vehicles) and regulatory imperatives (adaptation to the EU AI Act) create unique challenges for Ukraine.

Final recommendations for further research emphasize the need to move from theoretical justification to the development of an infrastructure-adapted, hybrid, and regulatory-compliant methodology. The main focus should shift to applied development and validation of Edge

Computing architectures to minimize dependence on centralized infrastructure, as well as the implementation of XAI frameworks that ensure trust in intelligent solutions and their legal legitimacy. Only such a comprehensive approach will enable the creation of a scientifically grounded and practically implementable intelligent technical service system in Ukraine.

Based on the conducted research, it can be stated that a modern concept of intelligent technologies in technical service has already been formed. Intelligent technologies in the TS domain are based on the synthesis of sensor systems, AI, ML, and digital twins. A digital twin is understood as a virtual model of a physical object that reflects its real-time state and allows predicting its behavior under various factors.

Practical applications of intelligent technologies in WV service are demonstrated by leading manufacturers. BMW Group uses an AI platform for predictive maintenance of conveyor equipment based on the analysis of data already available in the control system; the system identifies potential defects through changes in energy consumption, conveyor movements, or barcode readings, preventing failures and reducing downtime. The press release emphasizes that the implementation of an AI-supported standardized system allows scaling solutions to other plants without additional sensors, with costs limited to data storage and processing. Heat maps enable anomaly visualization and rapid response; the team continuously improves algorithms by adding new objects and integrating recommendations into failure notifications.

Tesla, Volvo, Nissan, and other companies use remote diagnostics and over-the-air updates. Tesla collects vehicle data and uses ML to predict when service is needed; customers receive notifications via a mobile app. Volvo uses the Volvo On Call system, which transmits technical condition data to service centers and offers personalized repair recommendations. Nissan applies AI to analyze EV battery degradation in the Leaf model, predicting degradation and optimizing replacement.

In aviation, the Integrated Vehicle Health Management (IVHM) concept has long been used to determine component condition and plan repairs. IVHM experience can be adapted to WV systems, especially given the growth of EVs and autonomous vehicles. A promising direction is the integration of predictive maintenance with consumer alert systems and spare-parts supply-chain management. Digital twins allow simulating powertrain operation under various scenarios and predicting the effect of changing operating modes, which is important for EVs with different charging regimes and temperature conditions.

In Ukraine, the TS system mainly operates on a scheduled preventive basis; the implementation of intelligent technologies is limited to isolated experiments by large automotive enterprises. Barriers include: (1) insufficient sensor infrastructure most fleets have only basic OBD interfaces; (2) shortage of qualified Data Science and AI specialists; (3) legal and standardization barriers - lack of unified requirements for data exchange, cybersecurity, and information storage; (4) low R&D investment; (5) unstable power supply and network infrastructure. At the same time, the government's digital transformation strategy envisions the development of intelligent transport systems, creating a regulatory basis for innovation. Domestic research indicates that service improvement is possible only through a cyber-physical approach involving distributed intelligent networks for technical-condition monitoring.

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