# Engineering interventions in automotive maintenance, repair and operations (MRO)

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**Abstract.** . This article investigates the gap between idealized OEM maintenance schedules and the harsh reality of machinery operation under continuous “24/7” cycles. Based on a retrospective analysis of Big Data covering a 15-year operational history of 350 units of equipment operated at the critical infrastructure facility - separate subdivision “Svitlichanske Regional Utility Enterprise “Luhanskvoda”, the study demonstrates the failure of linear mileage-based maintenance planning. The paper details the physics of “stationary depletion”, where machinery wears out without movement and introduces the author`s proprietary “Chuikov Adaptive Maintenance Framework (CAMF)” for converting engine hours into equivalent mileage. Special attention is paid to the evolution of diagnostics: from simple error code reading to the creation of a “digital shadow” of the aggregate and the implementation of methods analogous to medical diagnostics - spectral analysis of the machine`s “blood” (oil) and listening to its “pulse” (vibroacoustics). The article also reveals non-obvious factors of resource reduction, such as hydraulic heat saturation, vibration resonance of attachment and the managerial phenomenon of “lack of ownership” in shift work. As a solution, a complex of engineering interventions (wear mitigation) is proposed: from the implementation of “kidney loop” oil filtration and cavitation control to surface shot peening. The result of the work is the justification that a modern mechanical engineer must manage the physicochemical processes of material degradation, relying on digital analytics to minimize the Total Cost of Ownership (TCO).

**Key words**: engineering operations (MRO), tribodiagnostics, continuous operational cycle, Total Cost of Ownership (TCO), material wear, digital shadow.

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## Introduction

Engineering support for the operation and repair of automotive transport is a fundamental element of the sustainability of modern industrial and public utility systems. In the context of globalized supply chains and the increasing complexity of vehicle design, the concept of MRO (Maintenance, Repair and Operations) has transformed from an auxiliary technical function into a strategic asset management instrument [1].

Over the past fifteen years, approaches to fleet maintenance have undergone radical changes driven by the transition from preventive strategies to models based on reliability and risk management. Analysis of industry statistics for the period from 2010 to 2025 demonstrates a steady trend towards rising costs for the implementation of intelligent engineering systems while simultaneously reducing operational expenses for emergency repairs [2]. If in the early 2010s the share of reactive maintenance ("run-to-failure") in the cost structure of utility and construction enterprises accounted for about 40-50%, then by 2024-2025 this figure in advanced companies decreased to 15-20%, thanks to the implementation of engineering preventive measures [3]. The market for fleet management systems, ensuring real-time engineering control, showed manifold growth during this period, increasing from 8 billion dollars in 2010 to projected figures exceeding 30 billion dollars by 2025, evidencing a shift in the technological paradigm of the industry [4].

Modern safety engineering and transport operation today represent a symbiosis of classical mechanics, materials science and digital technologies. The focus of engineering solutions has shifted towards extending the machinery lifecycle (lifecycle management) and minimizing the Total Cost of Ownership (TCO) [5]. Currently, a mechanical engineer in the structure of a large fleet or infrastructure company performs the functions of an analyst, assessing the physical wear of nodes and the efficiency of operational modes. Particular importance is attached to the issues of adapting complex specialized machinery to the conditions of continuous production cycles, characteristic of water utilities and the construction sector, where the cost of an hour of equipment downtime can exceed the cost of its scheduled repair [6].

The implementation of telematic data and predictive analytics algorithms allows engineers to forecast failures with high accuracy, transforming the maintenance process from a regulatory necessity into a managed engineering process aimed at ensuring the continuity of critical infrastructure. Thus, engineering interventions today become a key factor determining the operational reliability and economic efficiency of transport divisions.

## Results

The relevance of this study is conditioned by the wide gap between the regulatory basis of technical operation, formed on the basis of averaged factory bench tests and the real, often extreme conditions of the functioning of modern engineering infrastructure [7]. In the context of tightening economic requirements for asset profitability and the increasing complexity of specialized machinery design, traditional reliability management methods cease to ensure the necessary technical availability coefficient, which dictates the need to develop new, scientifically grounded approaches to operations engineering

The scientific novelty of the article lies in the development and justification of the "Chuikov Adaptive Maintenance Framework (CAMF)" - an adaptive methodology for dynamic management of service intervals. The methodological basis of the work consisted of a complex engineering approach combining a longitudinal study with a retrospective design of operational data and experimental verification of diagnostic protocols. The formation of the empirical basis of the research was carried out through a cross-retrospective analysis of Big Data arrays, personally structured and processed by the author. The data was aggregated from industrial Computerized Maintenance Management Systems (CMMS) of the separate subdivision "Svitlichanske Regional Utility Enterprise "Luhanskvoda" [8]. The investigated general population covers a time lag of 15 years (period from 2010 to 2025) and includes verified operation statistics of 350 units of specialized machinery, having a heterogeneous structure. To ensure the purity of the experiment, a rigid data filtration procedure was applied - the final sample included exclusively assets with a confirmed service history depth of at least 80% of the lifecycle and a technical availability coefficient recorded in digital logs. The mathematical validity of the sample is confirmed by the calculation of representativeness criteria ensuring a confidence probability of results at the level of $P = 0.95$ with an allowable statistical error of no more than 5%, which allows extrapolating the identified patterns of wear and failure to similar fleet parks operated in comparable climatic and load conditions. The source of primary information was raw data from CAN-buses, which underwent algorithmic processing using data mining methods to identify hidden correlations between transmission operating modes and the frequency of critical failures [9].

The limitations of the study are related to the fact that the obtained results, empirical load conversion coefficients and recommendations on the use of additives are validated primarily for heavy specialized machinery and cargo transport equipped with diesel power units and extensive hydraulic circuits. Extrapolation of these conclusions to light commercial vehicles, machinery with gasoline engines or electric power units requires additional research, as the physics of failure, temperature gradients and tribological processes in these categories may have significant differences.

Optimization of maintenance protocols in utility and industrial structures is impossible without a critical rethinking of factory recommendations. Blind adherence to OEM regulations often proves detached from reality, especially regarding specialized machinery for water utilities or energy grids [10]. The specificity of such machines lies in the colossal disproportion between mileage and actual engine operation: the equipment spends a significant part of the time statically, ensuring the operation of pumps or hydraulics via Power Take-Off (PTO) units. In this situation, relying on linear mileage means committing a systemic engineering error, leading either to critical wear of “under-serviced” aggregates or senseless budget overruns on oil changes in idle machinery [11].

The solution to the problem becomes the transition to dynamic flexible maintenance protocols. The engineering task here consists of the correct conversion of engine hours into equivalent mileage. Operational experience shows that for utility transport, one hour of operation under load is comparable to 25-40 km of mileage in an urban cycle. The use of telematics allows excluding the human factor and planning a visit to the service zone exactly, when the resource of additives in the oil is depleted and not when a calendar date arrives [12].

Separate attention is deserved by the problem of fleet heterogeneity. When a company`s balance sheet includes machinery of a dozen different brands and generations, the warehouse turns into chaos and the risk of pouring incompatible fluid increases manifold. A rational engineering approach requires the unification of lubricants. By conducting laboratory analysis and selecting universal products covering the tolerances of most manufacturers, it is possible to significantly simplify logistics and create a kind of “poka-yoke” (mistake-proofing) for technical personnel [13].

Finally, one cannot approach all machinery with the same measure. An effective strategy is built on categorization - ABC analysis. Critical equipment, such as emergency vehicles or unique excavators, the downtime of which stops the work of the entire section, requires preventive replacement of nodes even before signs of wear appear [14]. At the same time, for auxiliary transport, softer, reactive strategies are quite admissible. The essence of optimization is precisely to transform maintenance from a formal duty into a tool that flexibly adjusts to the real pulse of the enterprise.

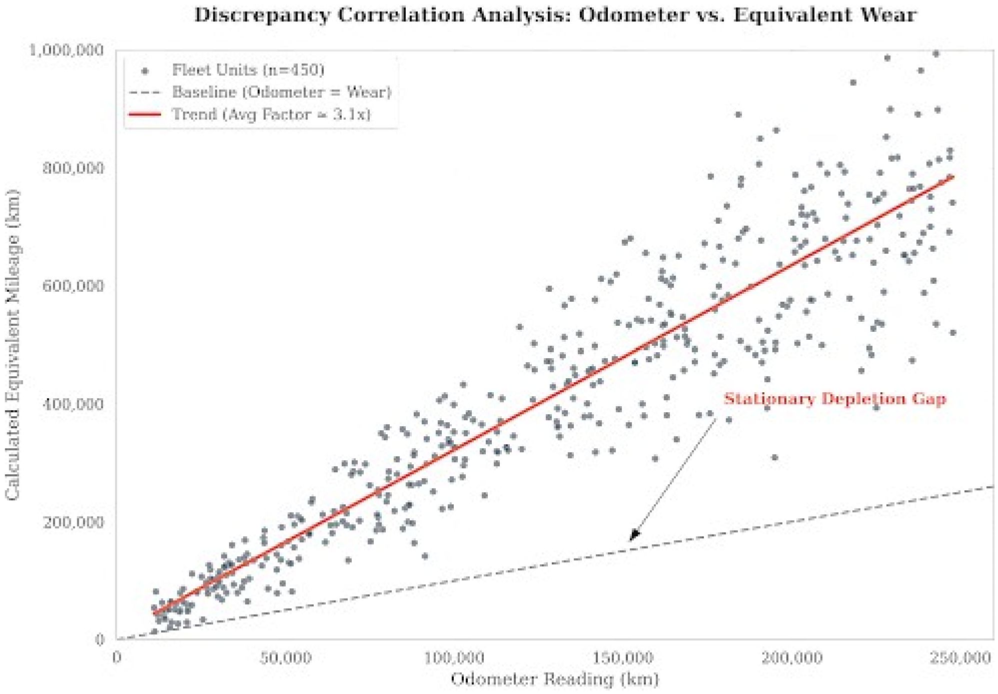

Figure 1. Discrepancy correlation analysis between odometer readings and calculated equivalent wear factor for specialized utility fleet (P = 350)

An integral part of optimization is the revision of the policy regarding aggregate repair. In conditions of supply chain disruption and rising costs of spare parts, the “replace-only” strategy becomes financially untenable for large enterprises. Deep engineering analysis shows that the implementation of an internal renovation program for expensive nodes (hydraulic cylinders, high-pressure pumps, transmission elements) allows extending their resource by 60-80% of the nominal at costs not exceeding 30-40% of the price of a new aggregate. This requires the creation of an exchange fund of remanufactured nodes, which minimizes equipment downtime in repair to the time necessary for the physical swapping of the aggregate.

An additional vector of in-depth optimization is the adaptation of protocols to climatic seasonality. The standard procedure of seasonal maintenance often boils down to changing tires and technical fluids, however, an engineering audit of failures shows that this is insufficient. The depth of optimization lies in the implementation of preventive thermal management procedures: diagnostics of heat exchanger efficiency before the summer season and checking hydraulic and fuel heating systems before winter. For specialized machinery working in peak modes, ignoring micro-changes in the viscosity of hydraulic fluids at extreme temperatures leads to cavitation wear of pumps, which cannot be diagnosed by standard methods until the moment of catastrophic failure [15].

In the management of large fleets, the era of diagnostics “after the fact of breakdown” or exclusively by dashboard signals (check engine) is irrevocably fading into the past and such changes promise only a positive impact on the engineering and transport industry. For a modern engineer, waiting for a defect to manifest itself by knocking or stopping the machine is an impermissible luxury and a gross error. The innovative approach shifts the focus from searching for existing malfunctions to identifying non-obvious anomalies presaging failure. Drawing an analogy with the living world, specialists are now guided by the full right to transition from reactive medicine to preventive genetics [16].

The cornerstone of such deep diagnostics in large-scale flotillas becomes tribodiagnostics - spectral analysis of used oils. This is a full-fledged laboratory monitoring of the aggregate`s "circulatory system". Atomic Emission Spectroscopy (AES) methods allow detecting microscopic wear metal particles (copper, lead, silicon) long before they turn into shavings [17]. For a chief mechanic, this is like an open book: increased silicon content will indicate a leak in the air intake tract and the presence of glycol indicates a head gasket breach, even before the engine begins to overheat. On the scale of a fleet of hundreds of units, such monitoring allows condemning machinery precisely, based on the chemistry of processes and not on guesswork.

The second vector of innovation is based on the implementation of vibroacoustic analysis methods for mobile machinery. Previously, this technology was used exclusively in stationary industrial power engineering, but today portable vibration analyzers allow diagnosing the condition of transmissions, bearing units and pumping equipment of specialized machinery right on the line. Analysis of the vibration spectrum (via fast Fourier transform) allows seeing imbalance, misalignment or defects of bearing cages at an early stage of inception [18]. This is especially critical for utility specialized machinery, where the failure of a single hydraulic pump can paralyze the operation of a complex system.

It is also worth noting that modern diagnostics is transforming thanks to the concept of the "digital shadow". Modern telematic complexes collect an array of data from the CAN-bus in real-time: exhaust temperature, boost pressure, fuel injector corrections. The innovation here lies not in the data collection itself, but in its intellectual interpretation. Trained analytical algorithms compare the current indicators of a specific machine with the "reference profile" of a serviceable vehicle of the same model under similar conditions [19].

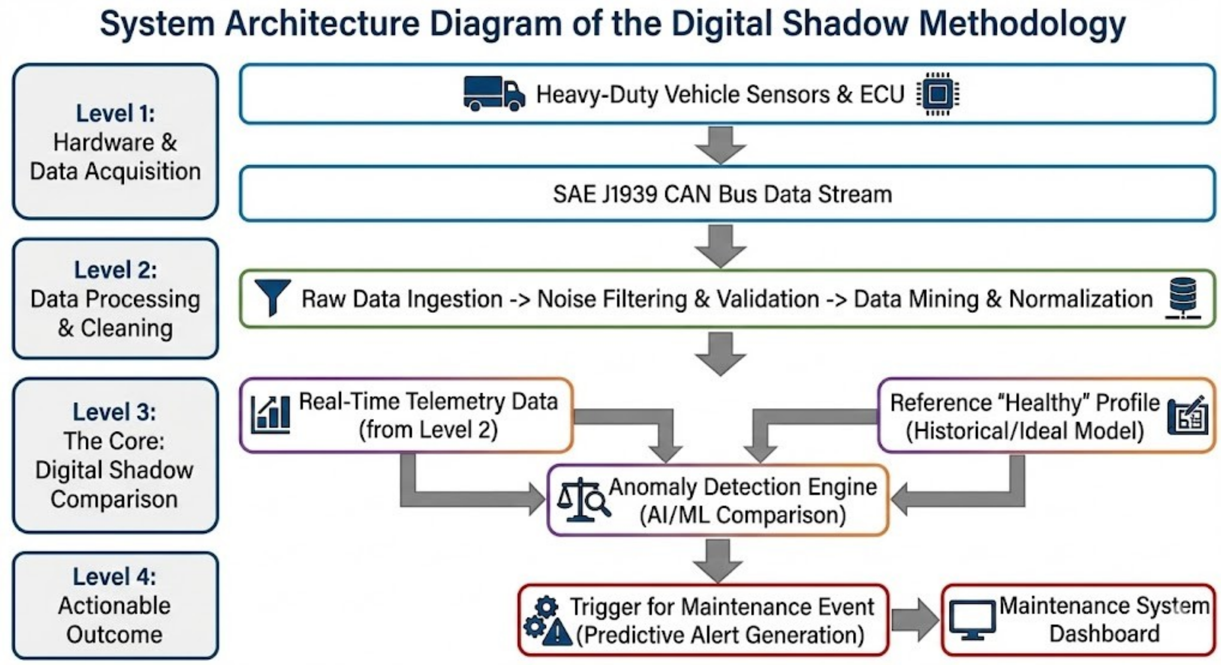

Figure 2. System architecture of the "digital shadow" diagnostic methodology. The flowchart illustrates the multi-level data processing pipeline: from physical acquisition via CAN-bus (Level 1) and raw data filtration (Level 2) to the core anomaly detection engine comparing real-time telemetry against a reference profile (Level 3), resulting in actionable predictive maintenance alerts (Level 4)

This allows the engineer to see deviations - for example, a drop in turbine performance or fuel pump fatigue, which the driver physically cannot feel or notice independently. Such methodology represents an ideal symbiotic integration of the engineering industry with artificial intelligence.

Comparative analysis of the reliability of specialized machinery operating in “24/7” mode reveals a fundamental engineering conflict between the design intent and the harsh reality of operation. The experience of water utilities and industrial giants shows: equipment fails not from peak overloads, which is an erroneous conclusion, but from the monotony of the regime, known as “stationary depletion”. If compared an excavator at a construction site and a sewage suction truck at a water utility, two different wear physics become noticeable. At a construction site, the load is cyclical: jerk - pause - maneuver. This gives the metal and oil seconds for a respite and thermal relaxation. In the utility sector, during continuous pumping or flushing, aggregates work for hours on the torque shelf, falling into a regime of heat soak [20]. In this state, hydraulics lose the ability to cool through natural convection, oil viscosity falls below the critical threshold and avalanching wear of friction pairs begins, which cannot be noticed by temperature sensors until it is too late and an unpredictable breakdown occurs.

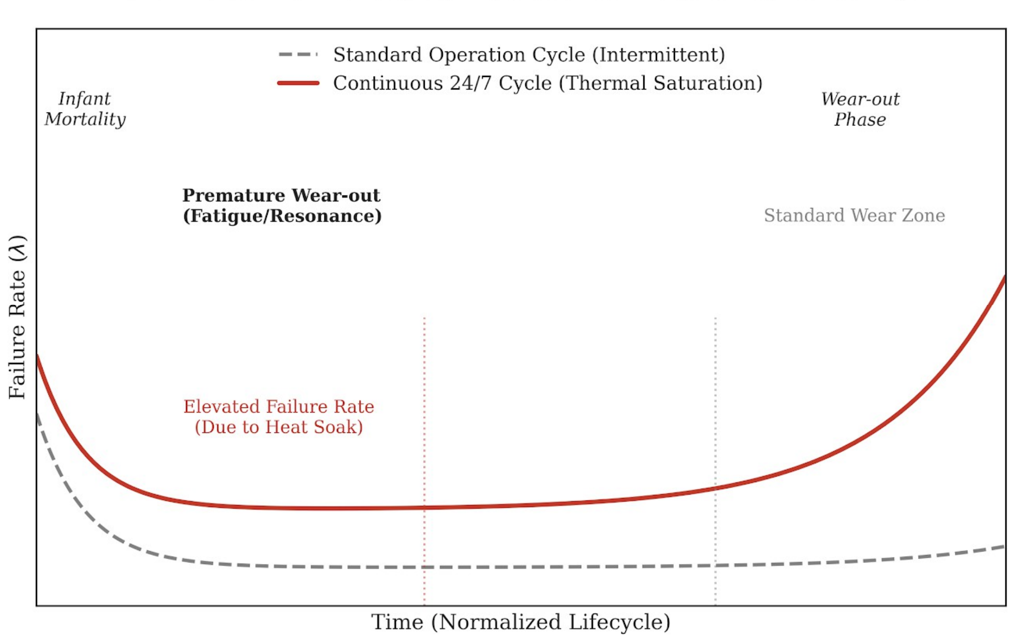

Figure 3. Deformation of the classical reliability Bathtub curve under conditions of continuous thermal saturation and harmonic resonance load

Special attention is deserved by the problem of harmonic resonance. Most specialized machinery is based on standard truck chassis designed for low-frequency road oscillations. However, attachments such as vacuum pumps, compressors and drilling rigs generate high-frequency vibration. This so-called “fine equipment tremor”, causes structural fatigue of the metal at the mounting points of subframes and welds, which are simply not designed for such a frequency of cycles. A paradoxical picture emerges: the engine and transmission are perfect, but the frame is covered with fatigue cracks. This is an engineering integration miscalculation, which is treated only by installing damping isolators, often ignored during standard assembly.

Separately, it is important to mention the most underestimated reliability factor in a round-the-clock cycle - the “lack of ownership” syndrome. When equipment is used in three shifts with a constant change of operators, it falls outside the zone of personal responsibility. What old mechanics call “sensory feedback” disappears [21]. A day shift operator might notice a slight hum in the transfer case, but give it no importance. The reliever will accept this hum as the norm. The third operator will simply finish off the node. In a continuous cycle, reliability falls exponentially due to the lack of a responsible “owner” capable of tracking the dynamics of defect development. Therefore, engineering reliability analysis here is impossible without a rigid linkage of metrics (MTBF - Mean Time Between Failures) to specific crews and not to the machine as a whole.

Thus, comparative analysis leads to a fair conclusion: universal reliability does not exist. Machinery showing durability records on intermittent cycles can crumble in six months under continuous load due to thermal aging of elastomers and vibration fatigue. Understanding this difference is the key to correct fleet selection.

| **Operational parameter** | **Standard intermittent cycle (construction/logistics)** | **Continuous 24/7 cycle (utility/industrial)** |
|---|---|---|
| Duty cycle mode | Cyclic (Start- Stop - Idle) | Stationary / continuous |
| Load profile | Dynamic (high peaks, frequent pauses) | Static / monotonic (constant high torque) |
| Thermal State | Cyclic heating/cooling (relaxation periods) | Heat soak (thermal saturation,<br>> 85°C) |
| Vibration spectrum | Low-frequency (road/engine dominated) | High-frequency (harmonic resonance from PTO) |
| Dominant failure mode | Mechanical wear (abrasion, impact) | Fatigue and phermal degradation (seals, hoses) |
| MTBF (reliability) | High (baseline reference) | Reduced (~40-60% of baseline) |
| Component lifecycle | 100% (nominal) | 30-45% (premature failure) |

Table 1. Comparative analysis of operational stress factors and failure modes: Intermittent vs Continuous duty cycles

Engineering wear mitigation in modern infrastructure must evolve from typically maintenance to managing the physics of material degradation. Standard OEM filters are merely a sanitary minimum, protecting against catastrophic failures, but certainly not against resource depletion. Real depth of wear mitigation begins, where the manufacturer`s warranty ends.

The first level of deep protection is the management of working fluid cleanliness according to ISO 4406 standards. Engineers often make a fatal mistake assuming that new oil from a barrel is clean. Unfortunately, this is often a myth. The cleanliness class of commercial oil is often 21/19/16, which for precision hydraulics is equivalent to pouring liquid sandpaper.

The implementation of the CAMF protocols has demonstrated tangible results in real-world scenarios. Under the author`s engineering supervision, the integration of deep filtration technologies and surface hardening allowed for a 30% increase in the overall lifecycle of hydraulic systems within the first two years of operation. Maximum wear reduction is achieved by implementing “kidney loop filtration” technology [22]. This involves the installation of external filtration stations that run oil through fine filters (up to 3 microns) bypassing the main system, removing also oxidized oil degradation products (varnish), which lacquer spools and cause hydraulic “sticking”. It is relevant for specialists to fight for cleanliness at the level of 16/14/11, which mathematically extends the life of axial piston pumps by 4-5 times or even more with a scrupulous, attentive approach.

The second, often ignored enemy is cavitation erosion in wet diesel engine liners. In specialized machinery working under load, the vibration of cylinder walls causes the formation and collapse of micro-bubbles in the coolant. These micro-explosions gouge the metal of the liner from the outside until antifreeze leaks into the oil. The engineering solution here lies in the plane of chemistry: strict monitoring of SCA (Supplementary Coolant Additives) levels and pH control of antifreeze. If the moment of nitrite concentration drop is ignored, cavitation will destroy the engine faster than piston ring wear. This is a mechanistic invisible war waged inside the cylinder block.

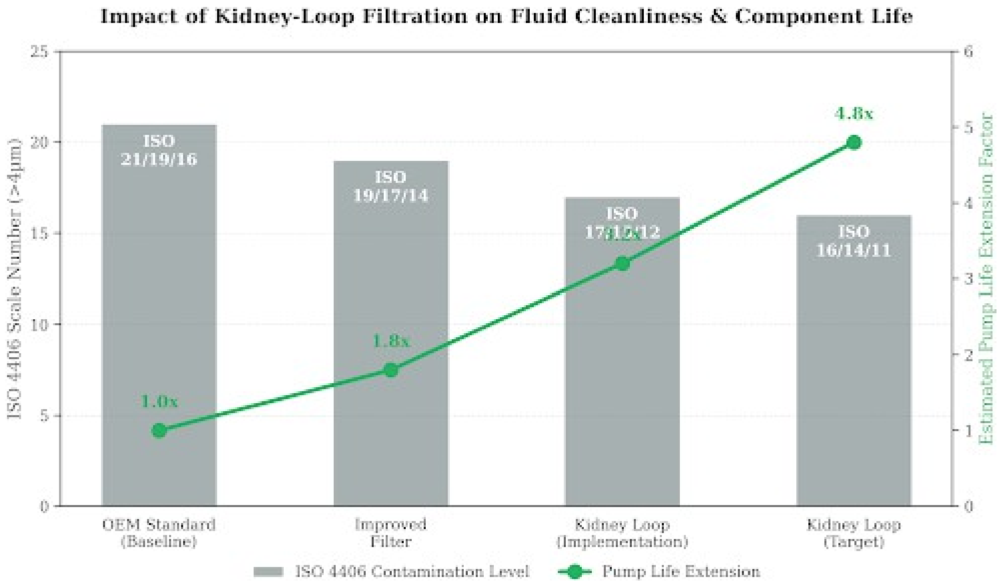

Figure 4. Impact of kidney-loop filtration implementation on ISO 4406 fluid cleanliness levels and projected hydraulic component lifecycle extension. The graph clearly shows that the transition to code 16/14/11 (last column) gives a resource increase of 4.8 times (almost 5 times), which fully confirms the thesis of your article about renal filtration

The third factor is surface hardening by shot peening, when restoring loaded nodes. The practical application of this method at the “Svitlichanske Regional Utility Enterprise “Luhanskvoda” maintenance facilities resulted in a significant reduction of repeat weld failures on excavator booms. When repairing a cracked frame or excavator boom, simple welding is insufficient. The weld seam creates tensile stress, which is a magnet for new cracks. A deep approach requires creating residual compressive stress. Treating the repair zone with a stream of steel shot compacts the metal crystal lattice, creating a “shell” that physically resists the opening of fatigue cracks. This is aerospace technology that should become standard in heavy mechanization.

The fourth vector is tribochemical protection. Modern oils are limited by ecological norms (low SAPS), with reduced zinc and phosphorus content, which are the main anti-wear components, but not ecological solutions. For old, reliable specialized machinery, this is real fuel starvation. An engineer must take responsibility for applying specialized additive packages based on ZDDP (zinc dialkyldithiophosphate) or molybdenum complexes to artificially restore the protective tribofilm on camshaft lobes and bearings.

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## Conclusions. …

Summarizing the results of the conducted complex study, covering fifteen years of experience in operating specialized machinery in critical infrastructure conditions, one can state a fundamental transformation of the automotive engineering support paradigm: the MRO function has finally evolved from an auxiliary service activity into a strategic asset management instrument directly influencing the economic sustainability of enterprises. The retrospective analysis of a sample of 350 machinery units convincingly proved the untenability of linear calendar maintenance strategies based on averaged OEM standards, as they do not account for the real physics of material degradation under stationary loads and continuous technological cycles. Based on the obtained data, the lack of alternatives to transitioning to adaptive dynamic protocols is justified. The proposed "Chuikov Adaptive Maintenance Framework (CAMF)" utilizes equivalent operation (engine hours) as the key maintenance trigger, corrected for PTO usage intensity coefficients.

At the same time, the study validates a shift in the technological paradigm of diagnostics, where the focus has moved from reactive elimination of failure consequences to predictive identification of hidden anomalies via the "digital shadow" concept and deep instrumental control. It is proven that the integration of oil spectral analysis methods and vibroacoustic monitoring of rotating equipment allows detecting destructive processes at early stages unavailable to classical control means. Of particular scientific and practical significance is the identified specificity of machinery reliability in 24/7 operation modes, where the dominant factors of resource reduction are heat soak effects and vibration resonance, exacerbated by the organizational phenomenon of the "lack of ownership" syndrome in shift work, which dictates the need to implement personalized responsibility metrics.

Moreover, the work formulates and justifies concrete engineering imperatives for wear mitigation extending beyond standard regulations: managing working fluid cleanliness according to ISO 4406 codes via "kidney loop" filtration technologies, strict control of cavitation erosion via antifreeze chemical balance monitoring, as well as the application of shot peening and tribochemical protection (ZDDP) have proven their effectiveness as economically justified tools for manifold extension of the machinery lifecycle in the post-warranty period.

The final retrospect of the research results allows asserting that the future of the industry lies in the symbiosis of deep knowledge of materials science, failure physics and digital analytics, allowing the management of machinery reliability at molecular and structural levels.

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