Eksploatacja i Niezawodnosc – Maintenance and Reliability

Volume 28 (2026), Issue 4

journal homepage: http://www.ein.org.pl

Article citation info:

Nowakowski T, Jüngst M, Komorski P, Condition-based maintenance of traction motor cooling fans in EMUs: case study and implementation challenges, Eksploatacja i Niezawodnosc – Maintenance and Reliability 2026: 28(4) http://doi.org/10.17531/ein/219910

Condition-based maintenance of traction motor cooling fans in EMUs: case study and implementation challenges

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Highlights

- This is highlights. Vibration-based CBM for EMU cooling fans using adaptive statistical limits.
- Detection of faults ignored by ISO 10816-3 standards using Cempel's method.
- 92.9% agreement between adaptive statistical and normative classifications.
- Validated 19-minute diagnostic procedure for routine light maintenance.
- A roadmap for ECM and CSM RA compliance in predictive rail maintenance.

Abstract

The transition from Time-Based Maintenance (TBM) to Condition-Based Maintenance (CBM) remains a challenge for the railway sector due to stringent safety regulations. This paper addresses this gap by presenting a framework for diagnostic monitoring of traction motor cooling fans in Electric Multiple Units. Using vibration analysis and adaptive statistical thresholds, the study demonstrates increased sensitivity compared to ISO 10816-3 limits. Research on 42 fans revealed that the proposed method achieved a 92.9% agreement with normative classifications while identifying early-stage degradations. A crucial part of the study is the formal analysis of change significance in accordance with the 402/2013 (CSM RA) regulation, providing a systematic approach to managing safety risks during technology implementation. The article provides a practical roadmap for integrating this 19-minute procedure into routine light maintenance, offering a scalable solution to overcome formal and technical barriers in adopting predictive maintenance for safety-critical systems.

Keywords

condition-based maintenance, vibration diagnostics, electric multiple units, railway maintenance management, fault detection, risk assessment

1. Introduction

Industry 4.0, characterized by the integration of advanced technologies such as the Internet of Things (IoT), artificial intelligence (AI), cloud computing, and big data analytics, has revolutionized maintenance practices in numerous industrial sectors, leading to the concept of e-maintenance [1,2]. This digitally enabled maintenance strategy has been widely implemented in aviation, manufacturing, logistics, and other industries, delivering significant improvements in asset reliability, operational efficiency, and cost reduction. However, despite these advantages and global trends toward digital transformation, the railway sector, particularly in Poland and other similarly developed markets, remains hesitant to adopt these innovations. Existing railway maintenance practices remain largely reliant on traditional scheduled inspections and manual interventions, lacking widespread adoption of predictive analytics, sensor-based diagnostics, and integrated maintenance management systems characteristic of the Industry 4.0 paradigm.

Condition-Based Maintenance (CBM), a key component of modern e-maintenance strategies, has proven successful in various global industries. For example, in aviation, advanced IoT sensor networks combined with machine learning have

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optimized aircraft maintenance, improving safety while significantly reducing downtime [3,4]. Likewise, oil and gas companies have adopted CBM to proactively manage critical equipment, leveraging smart sensors and AI-driven analytics to prevent costly failures and minimize operational disruptions [5]. Similarly, manufacturing sectors have integrated sensor-rich smart factories with predictive maintenance solutions, resulting in lower maintenance costs and improved productivity [6].

In Europe, the maintenance process of railway vehicles is governed primarily by unified standards defined at the EU level, focusing on interoperability, safety, and clear delineation of responsibilities. Directive (EU) 2016/797, concerning the interoperability of the EU railway system, mandates that technical standards and maintenance protocols must ensure seamless cross-border operation of trains, including unified approaches to vehicle upkeep to minimize disruptions and maximize efficiency [7]. Complementarily, Commission Implementing Regulation (EU) 2019/779 explicitly outlines the roles and obligations of Entities in Charge of Maintenance (ECM), assigning these bodies comprehensive responsibility for establishing maintenance systems, documenting procedures, and ensuring safety and compliance through standardized maintenance processes [8]. Moreover, Directive (EU) 2016/798 emphasizes safety management, requiring rail operators to systematically manage risks and continuously improve safety performance across all operational activities, including maintenance [9].

Despite this robust regulatory framework that advocates for efficient, safety-oriented, and harmonized maintenance practices across Europe, implementation continues to rely heavily on traditional preventive maintenance (PM) approaches. European rail maintenance predominantly utilizes periodic schedules or predefined mileage intervals, characterized by systematic checks and standardized procedures rather than real-time condition assessments or predictive analytics. While these traditional methods offer simplicity, they often lead to unnecessary downtime, inflated operational costs, and inefficient resource utilization. Components may either be serviced too frequently, increasing costs without proportional benefits, or too infrequently, risking undetected faults that could result in expensive repairs and service disruptions. Consequently, there remains a considerable gap between regulatory aspirations and actual maintenance practice, where modern Industry 4.0 elements such as predictive diagnostics, real-time monitoring, IoT-driven condition assessments, and AI-supported decision making are scarcely applied. This gap highlights a significant deficiency: despite regulatory encouragement towards innovative practices, European rail maintenance strategies continue to lag behind other sectors, missing opportunities offered by e-maintenance and Industry 4.0 technologies. Operators frequently hesitate due to concerns about the complexity, perceived high costs of implementing sophisticated diagnostic systems, and uncertainties surrounding compliance with existing Safety Management Systems (SMS) and Maintenance Management Systems (MMS).

The main aim of the article is to present a comprehensive and practically applicable concept of CBM for traction motor cooling fans in electric multiple units (EMUs), demonstrating how such an approach can replace conventional distance- or time-based maintenance activities. Traction motor cooling fans were selected as the focus of this study because they represent a highly failure-prone auxiliary subsystem whose condition directly affects traction motor reliability, yet for which no dedicated diagnostic framework is currently employed in railway practice.

This article does not aim to introduce new vibration-analysis algorithms or advanced signal-processing techniques. Instead, it focuses on demonstrating that a simplified, fast and operationally feasible diagnostic procedure can be successfully integrated into existing maintenance workflows and formally implemented within the regulatory framework defined by the ECM requirements, MMS, and the Common Safety Method for Risk Assessment (CSM RA) [10]. Therefore, the study provides not only a technical proof of concept, but also a complete implementation pathway that enables railway operators to adopt CBM for auxiliary subsystems in a compliant and practically achievable manner.

2. Literature review: CBM implementations in railways

This section provides a structured overview of scientific research and practical industrial deployments related to CBM in the railway sector. The review covers three areas: (i) research on algorithms, monitoring methods, and data-driven approaches; (ii) real-world applications and commercial systems; and (iii) challenges that impede the operational adoption of CBM.

2.1. Scientific research on CBM in railways

CBM is a proactive maintenance strategy that uses real-time condition data from equipment to inform maintenance decisions, performing interventions only when needed based on actual asset health rather than fixed intervals [11,12]. Over recent decades, advances in sensing and information technology have fueled rapid growth in CBM research and applications [2,3,5,12]. Studies confirm that when properly implemented, CBM can improve the reliability of assets while reducing maintenance costs by preventing unnecessary work and avoiding unexpected failures [11,13,14]. This approach has gained significant traction in the railway sector and beyond, where complex systems benefit from timely predictive interventions. Rail operators have the potential to effectively implement CBM for critical rolling-stock components, such as wheels, bearings, and traction motors, as well as infrastructure, significantly enhancing safety and operational availability. For example, modern rail companies would deploy extensive sensor networks and data analysis to continuously monitor the condition of wheels, brakes, axle bearings, and even track conditions, shifting maintenance from a reactive to a predictive paradigm [11,15]. The effectiveness of CBM relies not solely on technology but equally on integrating monitoring insights directly into maintenance workflows – a recurring emphasis in recent literature.

The railway industry has been actively exploring CBM, with numerous pilot studies and conceptual frameworks proposed for both onboard and wayside monitoring systems to track asset health in real-time. A representative example is provided by authors in [11], who presented a conceptual CBM system for train axle bearings based on continuous streaming data from multiple onboard sensors. In this study, vibration and temperature sensor data were processed using advanced algorithms to estimate the Remaining Useful Life (RUL) of bearings. Specifically, the authors developed an online Support Vector Regression model tailored to forecast bearing degradation, introducing heuristics designed to balance prediction accuracy and computational efficiency suitable for real-time scenarios. Their tests on real-world data demonstrated that big-data-driven analytics have significant potential to anticipate bearing failures and optimize maintenance schedules.

In [2], authors provided an extensive literature review addressing the concept of e-maintenance systems specifically applied to railway infrastructure. In their study, the authors analyzed a wide range of published research, conceptual approaches, and pilot implementations related to digital and remote maintenance practices in railway systems. The authors identified common patterns and gaps in current literature, highlighting the benefits of integrating advanced technologies, such as IoT, AI, and big-data analytics, into railway infrastructure maintenance practices. While their analysis confirmed significant potential for improving asset reliability, maintenance efficiency, and operational safety, it also underscored the predominantly conceptual or experimental nature of existing e-maintenance approaches. Despite acknowledging clear technical feasibility and documented advantages in pilot and laboratory conditions, authors emphasized that industry-wide adoption of comprehensive e-maintenance frameworks in rail infrastructure remains limited, with most reviewed examples representing theoretical models or isolated case studies rather than fully operational, broadly deployed systems.

To sum up, contemporary research on rolling stock maintenance systems indicates a measurable economic advantage of CBM strategies over traditional time-based maintenance approaches. Recent comparative analyses demonstrate that an optimal CBM strategy applied to mechanical systems can reduce the maintenance cost rate by up to 45% [16]. In railway-specific applications, such as braking systems, it has been shown that integrating diagnostic data with global maintenance planning can reduce average annual maintenance costs by 12.1% [17]. Analytical models developed for wagon bogie components further confirm that the selection of an appropriate condition monitoring algorithm may reduce life-cycle cost (LCC) values from 509 to 355 cost units [18].

2.2. Industrial implementations and practical challenges

Worldwide, rail operators and infrastructure managers are increasingly investing in e-maintenance and CBM. In Europe specifically, programs led by the Europe's Rail Joint Undertaking, continuing from earlier initiatives like Shift2Rail, have prioritized intelligent maintenance systems, that combine wayside detectors, onboard sensors, and analytics to enable condition-based interventions on rolling stock and infrastructure. Paper [19] presents a field-based e-maintenance concept for railway wheel condition monitoring that combines two wayside systems: Wheel Impact Load Detectors (WILD) and a laser wheel-profile measurement station. Using data from 1,500 wheel-defect alarms gathered over one winter season in northern Sweden, the authors link high impact forces to low ambient temperatures and specific axle positions. They then outline a three-layer framework (data acquisition, diagnostics/prognostics, and maintenance decision support) that feeds condition information into a computerized MMS. Although the study demonstrates clear diagnostic value and proposes an integrated Prognostics and Health Management (PHM) workflow, it remains a pilot-scale implementation rather than a fleet-wide standard, highlighting the gap between promising e-maintenance concepts and large-scale railway adoption. It should be noted, that wayside and onboard diagnostic systems of this type are widely deployed across railway networks. These monitoring systems enable rapid detection of mechanical defects such as wheel flats and wheelset wear [20,21], drivetrain or gearbox anomalies [22–24], pantograph malfunctions [25], axle-bearing issues [26–28], and overheating components or brake failures [29–31]. Real-time sensor data from these systems are processed using advanced algorithms, often leveraging artificial intelligence for automated defect classification. Despite numerous well-documented commercial and research solutions in this field [32], such systems do not influence decisions regarding a shift in railway maintenance philosophy towards a comprehensive CBM approach; they solely facilitate real-time fault detection. Furthermore, despite extensive research covering wheels, bearings, bogies, pantographs and traction components, no scientific or industrial work addresses a practical CBM framework for traction motor cooling fans or similar auxiliary systems. This subsystem therefore represents an important yet unexplored area for predictive maintenance.

Poland's rail industry is likewise moving toward modern maintenance methodologies, although it faces unique challenges. The Polish railway network, exceeding 19,000 km of track, is one of the largest in Europe yet has historically lagged in safety performance [33]. In recent years, efforts have been made to reform maintenance practices and incorporate condition-based strategies. In [33], authors note that the national infrastructure manager introduced a new maintenance process in 2015, aiming to replace rigid, long-established rules with

a more dynamic, condition-focused approach. However, audits revealed that this new process was not being applied effectively in practice. To bridge this gap, the authors proposed a novel layered maintenance decision model and Maintenance Board system, which would integrate risk assessment and condition data into maintenance planning in a structured way [33]. This framework is intended to prioritize maintenance activities objectively based on actual condition and risk (rather than on subjective or schedule-driven criteria), all without requiring major capital investments. Such initiatives indicate that Polish rail experts recognize the need to better connect CBM technologies with managerial processes (what is very difficult in practical way) – aligning with global trends while tailoring solutions to local organizational contexts. These findings highlight that the organisational and procedural challenges described in the Polish context directly influence the feasibility of CBM implementation – issues that are further analysed in the case study presented in this article. Wardahni and Latief also highlight that technology alone is not a panacea – organizational and process integration remains a critical frontier [2]. They observed that many e-maintenance efforts emphasize the technical side (data acquisition and ICT infrastructure) but often lack proper integration with managerial aspects such as regulatory compliance, workflow design, risk management, and safety culture.

There are several critical elements and implementation challenges that determine whether CBM moves from concept to practice. Robust data-and-sensing infrastructure must come first, because dense, reliable sensor networks with edge telemetry are indispensable for acquiring and pre-processing the high-volume streams generated by fans, auxiliary motors and wheelsets. Next, analytical models and AI algorithms translate these raw signals into fault classifications and Remaining Useful Life estimates, so maintenance is triggered only when genuine degradation patterns emerge. Equally important is integrating these predictive insights with existing maintenance workflows, ensuring that threshold breaches automatically generate work orders through decision boards and updated standards that bridge the gap between ICT tools and managerial practice. Another key aspect is domain knowledge and customization: algorithms must be tuned to the failure modes and operating contexts of each asset so alarm thresholds reflect real risk. Finally, an effective balance between online and offline analytics is essential; real-time edge protection must be complemented by periodic cloud or offline mining of historical data to refine models without overwhelming bandwidth or compromising cybersecurity. Altogether, CBM success hinges as much on organizational alignment as on technical sophistication, turning predictive maintenance from promise into operational reality.

In summary, the literature indicates that CBM implementation is a socio-technical endeavor: it involves deploying the right sensor and analytics technology and also ensuring organizational readiness. Implementations in other industries have proven the concept’s value by extending asset life and preventing failures of various machine elements. The latest global trends point to increasing use of AI and IoT for automated, real-time condition monitoring, moving maintenance towards a truly predictive model. At the same time, case studies show that critical challenges like data integration, change management, and aligning maintenance policies must be addressed to realize CBM’s full potential [2,33]. When these challenges are met, CBM systems can effectively solve many maintenance problems even for auxiliary equipment like fans or secondary motors: sensors can catch early signs of degradation (e.g. rising vibration indicating a fan bearing fault), AI models can forecast the time to failure, and maintenance crews can replace or repair the part at a scheduled opportunity before any disruption occurs. Such proactive solutions, documented increasingly in research, highlight that the key to CBM is not just technology itself, but how it is applied within an ecosystem of people, processes, and tools to ensure safer and more reliable operations.

The reviewed literature demonstrates that although CBM in railways has been widely explored at the conceptual and experimental levels, its operational implementation remains limited. The main barriers include insufficient integration with MMS, fragmented organizational responsibilities, limited use of collected data and the absence of clear procedures for documentation and risk management. These challenges are particularly visible in Central and Eastern European railway operators, where maintenance strategies remain largely preventive and documentation-driven, as highlighted in studies such as Smoczyński et al. These gaps indicate that achieving operational CBM requires not only sensing and algorithms, but also a structured implementation process – which is the central focus of this article.

3. Traction motor cooling fans – object of study

As highlighted in the literature review, research and industrial practice largely concentrate on CBM solutions for primary rolling-stock components such as wheels, bearings, bogies and pantographs, whereas auxiliary systems receive considerably less attention. To demonstrate the feasibility of a practical and implementable CBM framework, this study focuses on one such subsystem – the traction motor cooling fans used in EMUs. These fans constitute a technically important yet diagnostically overlooked component whose condition directly affects traction motor reliability and operational safety.

Traction motor cooling fans ensure adequate thermal management of traction motors by delivering a continuous stream of cooling air across the motor casing and associated components. In EMUs, they are typically mounted beneath the vehicle body (Figure 1) or in side equipment compartments, where they operate in a demanding environment rich in dust, sand, moisture and contaminants lifted from the track bed. The combination of underframe positioning (Figure 2), continuous exposure to airflow from the track and sustained vibration results in rapid accumulation of dirt on impeller blades and inside the housing.

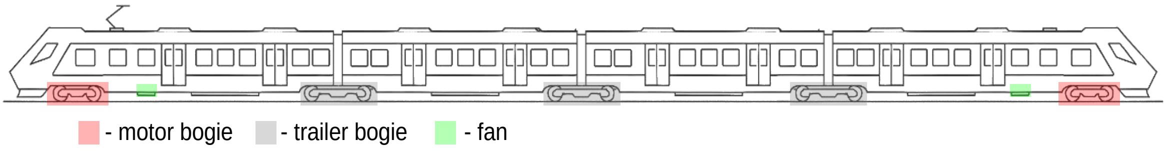

Figure 1. Location of cooling fans relative to the powered bogies in an EMU.

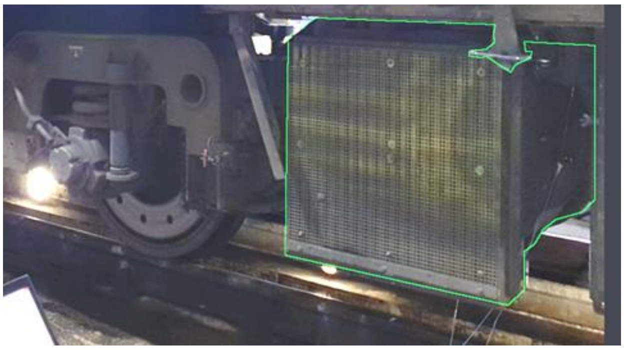

Figure 2. Example of cooling fan with protective filtration cover.

Therefore, the cooling fans are exposed to several degradation mechanisms that develop progressively during normal service. The most common issue is impeller fouling, where accumulated dirt causes mass imbalance, increased vibration and reduced airflow efficiency. Over time, mechanical loads generated by imbalance accelerate bearing wear, including pitting, cage degradation and surface damage, which may evolve into elevated noise, vibration and eventually shaft seizure. Contaminants and mechanical resistance may also lead to a reduction in rotational speed, lowering the volume of delivered air and impairing traction motor cooling capacity. In some cases, foreign objects or impacts can deform the impeller blades or housing, further amplifying imbalance and causing abrupt airflow loss.

These degradation processes have direct operational implications. Reduced cooling efficiency leads to elevated traction motor temperatures, thermal derating, diminished torque availability and-in severe cases-train withdrawal or emergency procedures. Prolonged overheating accelerates insulation wear, increases energy consumption and raises the likelihood of traction motor failures. As a result, even partial deterioration of the cooling fans can significantly affect train reliability and maintenance costs.

According to feedback from operating personnel, the fans require substantially more frequent cleaning than prescribed in the MMS documentation or recommended by the manufacturer. This discrepancy indicates that real-world operating conditions are more severe than assumed in planned-maintenance strategies, further reinforcing the need for a condition-based approach.

To sum up, cooling fans constitute a subsystem that is both operationally critical and diagnostically neglected. Unlike wheels or bearings, which benefit from extensive monitoring technologies, cooling fans are maintained almost exclusively based on periodic schedules, despite producing clear and measurable indicators of degradation such as vibration increase, noise, shaft-speed reduction and airflow imbalance. At the same time, they exhibit relatively simple failure modes whose symptoms are easily detectable using straightforward measurement techniques. Combined with the observed mismatch between MMS-recommended and actual cleaning intervals, this makes traction-motor cooling fans an excellent object for demonstrating a practical, low-intrusion and implementable CBM strategy in operational railway conditions. This provides a natural motivation for next sections, where the proposed CBM concept and the measurement-based evaluation of fan condition are presented.

4. Proposed CBM concept and feasibility

The previous chapter characterised the operational role, degradation mechanisms and measurable symptoms observed in traction motor cooling fans. Building upon this understanding, the present section introduces a practical and operationally feasible concept of CBM designed specifically for this subsystem. The aim of the proposed framework is to replace schedule-driven inspection and cleaning routines with a data-informed procedure carried out during standard maintenance activities of the P1 and P2 type, without altering the established maintenance workflow of the operator.

Figure 3. View of the fan during testing (view after removing the filter cover).

The proposed CBM concept relies on short vibration measurements performed directly on the fan housing using a single accelerometer (Figure 3). Each measurement lasts approximately five seconds and captures the mechanical response of the fan during normal operation. Vibration monitoring was selected as the primary diagnostic method because the dominant degradation mechanisms of cooling fans generate clear physical symptoms that manifest directly in the vibration signal. These include mass imbalance arising from impeller fouling, characteristic frequency components associated with bearing wear and sideband patterns linked to a reduction in rotational speed. As a result, even a short time record is sufficient to detect the presence of early-stage degradation.

The diagnostic framework integrates three complementary indicators derived from the acquired vibration signal. The first indicator is the root mean square value (RMS) of vibration velocity evaluated in the frequency range from 10 to 1000 Hz. The second indicator is the vibration amplitude extracted from the frequency spectrum at the rotational frequency of the fan and its harmonics, which is particularly sensitive to imbalance and mechanical looseness. The third indicator is based on impulse related components and sidebands associated with rolling bearing defects, identified using envelope analysis and aggregated through an RSS parameter.

4.1. Measurement methodology and reference criteria

The technical condition of 42 cooling fans was assessed using RMS vibration velocity measured radially on the fan housing. This measurement location is consistent with ISO 20816 [34] recommendations and represents a rational compromise between diagnostic sensitivity and practical accessibility. Direct measurements on the fan motor would require partial disassembly, including removal of rear covers, extending inspection time by several minutes per fan, which would contradict the assumptions of fast and low intrusion diagnostics required for routine maintenance.

Two reference levels were adopted for RMS vibration velocity. The first was based on ISO 20816 criteria [34], with an alarm threshold of 4.5 mm/s and a critical limit of 7.1 mm/s. The second reference level was taken from the operator's MMS documentation, where the manufacturer defined critical RMS limit for the analysed fan type is set at 11 mm/s. This value is significantly higher than normative limits and serves as a useful benchmark for evaluating the sensitivity of schedule based criteria.

RMS results were compared with vibration acceleration amplitudes extracted from the FFT spectrum at the fan rotational frequency and its second harmonic. FFT spectra were calculated with a frequency resolution of 0.5 Hz, using 50 percent overlap and RMS linear averaging. Because no normative thresholds exist for FFT based amplitudes at specific frequencies, diagnostic limits were determined using the statistical method proposed by Cempel [35]. This approach allows adaptive diagnostic thresholds to be defined based on the statistical distribution of measurement data within a given population of machines [36,37]. The method is grounded in probabilistic decision theory and explicitly accounts for acceptable false alarm rates [35,36]. In this study, the critical threshold was calculated assuming a false alarm probability of 10 percent, while the alarm threshold corresponded to early warning detection with a higher tolerance for false positives. A technical readiness probability of 0.97 was adopted.

4.2. Results and diagnostic interpretation

Figure 4 compares RMS vibration velocity with FFT acceleration amplitudes at the rotational frequency and its second harmonic. The left diagram therefore represents the relationship between global RMS velocity and the fundamental rotational component, while the right diagram illustrates the corresponding relationship for the second harmonic component, which is often associated with mechanical asymmetry or developing imbalance effects. RMS velocity values are expressed in mm/s in accordance with ISO 10816, whereas FFT amplitudes are presented in m/s², reflecting acceleration-based spectral indicators. The vertical dashed lines represent RMS-based thresholds (ISO alarm, ISO critical, and the manufacturer's permissible limit), while the horizontal solid lines correspond to statistically derived alarm and critical levels calculated using Cempel's method for the respective spectral components.

A representative example is fan number 9 (highlighted in red), which had previously been indicated by the operator as potentially faulty. In this case, RMS vibration velocity exceeded the alarm threshold but remained below the critical ISO limit [34]. At the same time, the FFT amplitude at the rotational frequency exceeded the statistically derived critical threshold, clearly indicating abnormal operation. This situation illustrates a diagnostically relevant discrepancy, where spectral analysis reveals early-stage degradation not yet fully reflected in RMS-based assessment. Two additional fans exhibited similar behaviour, where FFT based indicators revealed significant deviations that remained below RMS alarm levels. These cases demonstrate that frequency-domain indicators may provide higher sensitivity to emerging imbalance or bearing-related faults compared to global RMS velocity criteria. Overall, the agreement between normative and statistical classifications reached 92.9%, corresponding to 78 consistent decisions out of 84 comparisons based on the rotational component and its second harmonic. Importantly, the most diagnostically relevant discrepancies occurred for fans later confirmed as degraded.

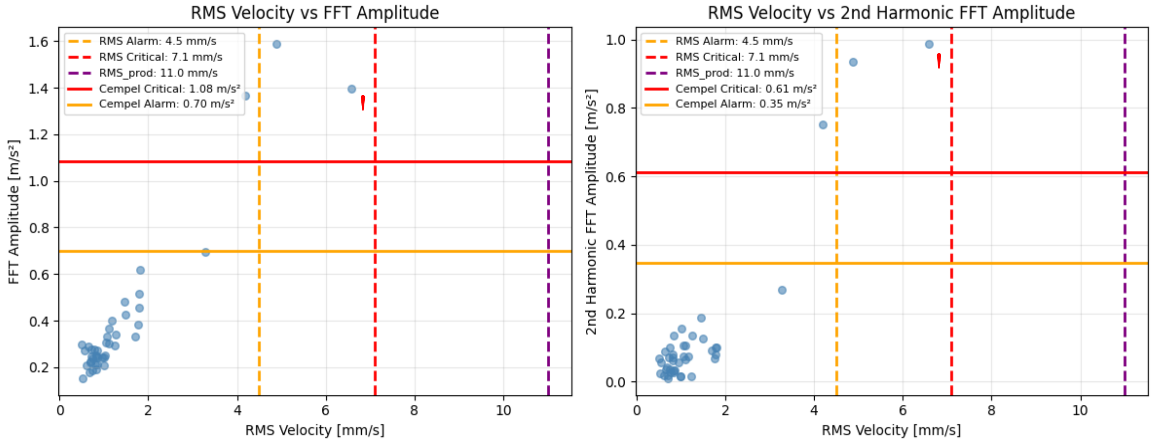

Figure 4. Comparison of RMS-based normative criteria and statistically derived FFT acceleration thresholds for the fundamental (left) and second harmonic rotational components (right).

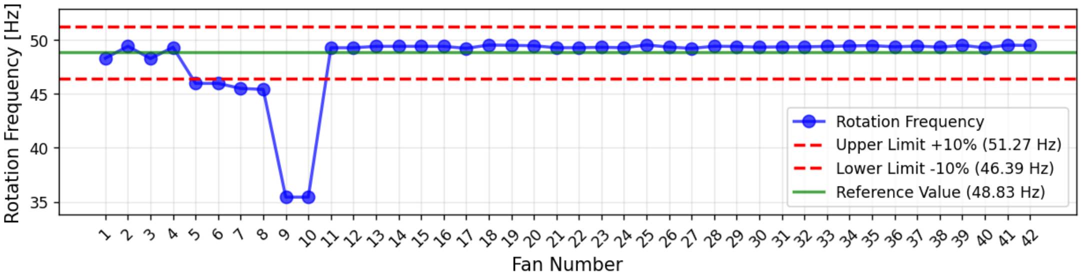

Figure 5. View Identification of fan rotational frequency based on FFT analysis.

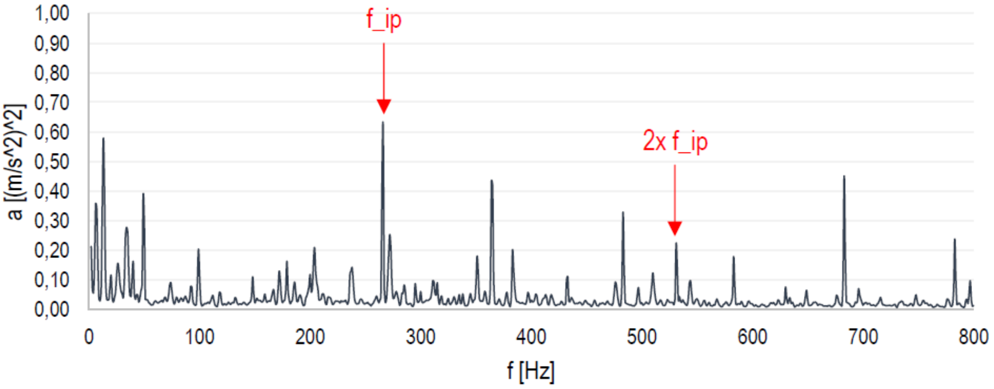

Figure 6. Example FFT spectrum showing rotational frequency and harmonics.

Furthermore, Figure 5 presents the rotational frequencies identified for all analysed fans using FFT based spectral analysis. The nominal rotational frequency of 48.8 Hz is shown together with an acceptance band of plus and minus 10 percent. While the majority of fans operate close to the nominal value, a distinct group of fans exhibits a significantly reduced rotational frequency, falling below the lower tolerance limit. This behaviour indicates increased mechanical resistance, contamination related drag or control related anomalies. FFT based identification of rotational speed therefore provides an additional diagnostic dimension, enabling early detection of operational irregularities that are not captured by RMS vibration levels alone.

The last but not least, Figure 6 shows a representative vibration acceleration spectrum for a degraded fan no. 9, with clearly visible components at the rotational frequency and its second harmonic. The elevated amplitude at the fundamental frequency is characteristic of mass imbalance caused by impeller fouling, while the presence of harmonics indicates nonlinear mechanical effects and increased structural excitation. These spectral features provide direct physical insight into the degradation mechanism and allow reliable discrimination between imbalance related faults and other vibration sources.

In addition, rolling bearing condition was assessed using envelope analysis, with characteristic defect frequencies calculated individually for each fan based on its measured rotational speed and bearing geometry. Envelope spectra enabled detection of low energy impulse components associated with defects of the inner race, outer race and rolling elements. This approach allowed identification of subtle bearing anomalies that were not visible in broadband vibration spectra, confirming the usefulness of envelope based indicators as a complementary diagnostic tool within the CBM framework.

4.3. Operational feasibility and decision logic

The complete diagnostic procedure for a single vehicle required approximately 19 minutes, including sensor mounting, measurements on all fans, relocation between measurement points and data handling. The reported duration was derived from direct time observations of consecutive operator activities under industrial workshop conditions. Although the vibration signal acquisition for a single fan lasts approximately 5 seconds, the total operational time per individual fan is approximately 2-3 minutes, including sensor placement, signal verification and relocation between measurement points. The accelerometer is mounted using a neodymium magnetic base at predefined and repeatable locations on the fan housing, ensuring measurement consistency while keeping positioning time minimal. The accelerometer used in the procedure is calibrated in accordance with the manufacturer’s recommendations and standard metrological practice, typically at least once per year, independently of routine maintenance measurements. The estimation included equipment preparation, access to the vehicle, measurements on 4 fans and return to the workstation, ensuring that the reported value reflects realistic operating conditions rather than an idealised scenario. The procedure fits naturally within the time window allocated for routine P1 and P2 maintenance activities and does not interfere with other servicing tasks. To support decision making, diagnostic indicators were integrated into a simple three stage intervention logic aligned with existing maintenance practice. Elevated vibration levels associated with contamination trigger cleaning, persistent imbalance signatures lead to balancing and confirmed bearing related impulses indicate the need for bearing replacement or fan refurbishment. This sequence corresponds directly to observed degradation mechanisms and does not require organisational changes in the maintenance workflow.

Taken together, the results demonstrate that combining short vibration measurements with FFT based indicators and adaptive statistical thresholds provides a significantly more sensitive and informative diagnostic basis for CBM of cooling fans than RMS based criteria alone. At the same time, the method remains fast, non intrusive and fully compatible with routine maintenance activities. These findings provide a solid technical foundation for the next section, which focuses on the practical implementation of the proposed CBM approach within the operator’s MMS and the Polish railway maintenance framework. Similar thoughts are declared in the Predict-Maintenance project, which is still ongoing [38].

5. Implementation in the polish maintenance system (case study)

5.1. Organisational background

The majority of railway maintenance systems currently applied in Europe are based on a time- or mileage-driven PM philosophy, with predefined maintenance levels and fixed resource intervals. In Poland, the most common approach is a five-level maintenance cycle, which constitutes the organisational and procedural background for the case study presented in this article. In this paper, the labels P1–P5 are used to denote the commonly applied Polish maintenance levels, ranging from routine inspections to general overhaul.

The first maintenance level (P1) consists of daily or short-interval inspections, typically performed without disassembly, and includes basic visual checks, replenishment of operating fluids and verification of the technical condition of essential components. The second level (P2) involves technical inspections with partial disassembly, enabling a more detailed assessment of component condition and the execution of basic adjustments. The third level (P3) covers extended technical inspections, often including partial refurbishment of running gear, braking or traction components. The fourth level (P4), commonly referred to as an overhaul, involves substantial disassembly of the vehicle for replacement or regeneration of major subsystems and verification of structural elements. The fifth level (P5), known as the general overhaul, represents a comprehensive renewal of the vehicle, often combined with modernisation measures, aimed at restoring or improving its original design parameters.

In this maintenance framework, vehicles are withdrawn from service at fixed intervals determined by time or accumulated mileage and subjected to all activities prescribed for a given maintenance level. Higher-level overhauls are generally scheduled as multiples of lower-level intervals; however, each maintenance level has its own independent limits. Consequently, unplanned events such as long-term failures or accidents do not shift the timing of higher-level overhauls, meaning that the maintenance levels do not form a strictly sequential chain. Depending on vehicle type and operational profile, the complete maintenance cycle from commissioning to P5 overhaul typically spans between 18 and 40 years, during which a vehicle may undergo between one and seven P4 overhauls.

The prevalence of PM in railway systems is largely rooted in historical operational practice. Early railway technologies did not allow reliable assessment of technical condition using diagnostic methods, which led to the adoption of rigid time-based inspection intervals. Over time, this philosophy was extended to entire vehicles and remains deeply embedded in maintenance practice. Despite substantial advances in vehicle design, sensing technologies and diagnostic methods, similar preventive approaches continue to be applied even to newly introduced rolling stock [39].

Recent regulatory changes at both national and European levels have created opportunities for greater flexibility in railway maintenance systems and for the introduction of condition-based elements. However, the practical implementation of such changes remains limited, with organisational inertia and established procedures often representing a greater barrier than technical feasibility. This context provides the background for the legal and regulatory considerations discussed in the following section.

5.2. Legal and regulatory requirements for implementing CBM

Any modification to an existing railway maintenance system that may potentially affect safety must be formally assessed within the applicable legal and regulatory framework. In the European railway system, such changes are governed by the requirements of the ECM framework and CSM RA [10]. Consequently, the introduction of CBM elements into an established PM regime cannot be treated solely as a technical improvement but must be addressed as a regulated change to the maintenance system.

Depending on the organisational setup, the responsibility for initiating and managing such a change may lie either with a railway undertaking acting as its own ECM or with an external ECM contracted by the operator. In both cases, the procedure for introducing changes is defined within the MMS and, where applicable, the SMS. While the internal workflows may differ between organisations, the process must always comply with the requirements of Regulation (EU) No 402/2013 on the CSM RA [10].

The first step in this process is the assessment of the significance of the proposed change. According to CSM RA, a change is considered significant if at least one of several predefined criteria is met. These criteria include the potential consequences of system failure, the novelty of the solution, the complexity of the change, the possibility of monitoring its effects during operation, the reversibility of the change and the interaction with other concurrent changes. If the assessment indicates that the change is significant, a full risk management process must be conducted.

In the context of introducing CBM for traction motor cooling fans, the modification concerns the replacement of selected manual inspection and servicing activities with a diagnostic procedure based on vibration measurements and data-driven decision rules. Although the change does not alter the vehicle structure, it directly affects maintenance decision-making for a safety-relevant subsystem. As such, it falls within the scope of changes that require formal evaluation under CSM RA.

A full risk management process must address several key elements. These include a clear specification of the change, covering its objectives, functional scope, system boundaries and interfaces, as well as the identification of existing safety measures. Furthermore, potential hazards associated with the change must be identified and evaluated, and appropriate risk control measures must be defined where necessary. The process must also document all assumptions relevant to system integration, operation and maintenance that are made during the definition and assessment of the change.

The outcome of the risk management process is documented in a structured risk assessment report, which is subsequently subject to independent evaluation by an Assessment Body. The role of the Assessment Body is not to verify the technical design of the solution itself, but to assess whether the applied process, argumentation and evidence are consistent, transparent and compliant with the requirements of Regulation (EU) No 402/2013 [10]. A positive independent assessment constitutes a formal prerequisite for approval of the modified maintenance system by the National Safety Authority.

This regulatory framework defines the boundary conditions within which the proposed CBM solution must be implemented. The following sections therefore focus on how the change associated with introducing CBM for cooling fans was specified, assessed and integrated into the existing maintenance system in a manner compliant with these legal and regulatory requirements.

5.3. Assessment of change for CBM implementation

The introduction of CBM for traction motor cooling fans required a formal assessment of change within the existing maintenance system. The assessment focused on identifying which maintenance activities would be affected by the proposed modification and determining whether the change should be classified as significant in accordance with the CSM RA.

The starting point for the assessment was a detailed review of the maintenance activities related to the traction motor ventilation system as defined in the current maintenance documentation. These activities include a set of repetitive manual inspections performed at short intervals, such as visual checks for damage, contamination and leaks, verification of smooth running and noise, as well as selected electrical checks of the fan motor conducted at longer intervals (Table 1). Most of these activities are performed during P1 and P2 maintenance levels and rely primarily on subjective assessment by maintenance personnel rather than on quantitative condition indicators.

Table 1. List of maintenance activities conducted on the traction motors' ventilation system (baseline state).

No.	Activity	Criteria	Frequency
1.	**Traction motors' fans – assembly**		
1.1	Visual inspection of the fan for damage	No mechanical damage affecting the correct operation of the fan	30 000 km or 60 days
1.2	Inspection of the fan for smooth running	The device must not emit excessive noise during operation (in relation to other fans built on the vehicle)	30 000 km or 60 days
1.3	Visual inspection of the fan for leaks	Pay special attention to the tightness of the inspection hatch	30 000 km or 60 days
1.4	Visual inspection of the fan for contamination	Remove corrosion and any extraneous matter; pay special attention to the condition of the covers	30 000 km or 60 days
1.5	Removal of condensate	Remove excess condensate from the fan using the dedicated valve	30 000 km or 60 days
2.	**Fan motors**		
2.1	Visual inspection of motors	No leaks from around the bearings when the motor is at a standstill; no smoke or sparks during operation	30 000 km or 60 days
2.2	Measurement of nominal current flow	Values ≤ 6 A	400 000 km or 2 years
2.3	Inspection of motor's freedom of movement	Rotor must rotate freely; bearings must have no play; no noisy operation	400 000 km or 2 years
2.4	Measurement of motor's insulation resistance	$R \geq 5$ MΩ at 500 V DC	400 000 km or 2 years
2.5	Replacement of motor's bearings	Replace with new bearings of the same type	600 000 km or 3 years

Table 2. Modified maintenance activity for traction motors' ventilation system incorporating CBM.

No.	Activity	Criteria	Frequency
2.1	Vibration measurement of fan assembly	Verify technical condition based on diagnostic parameters defined in the measurement protocol. If thresholds related to contamination or imbalance are exceeded, corrective balancing shall be performed and the measurement repeated. If results still exceed defined thresholds, further actions shall be determined based on the identified degradation mechanism. This may include increased monitoring frequency, bearing replacement, corrective maintenance or fan or motor replacement during the next higher-level maintenance activity.	30 000 km or 60 days

Table 3. Analysis of the criteria for assessing the significance of change.

Criteria	Description	Analysis result
Failure consequence	Malfunction of the traction motors' ventilation system may lead to motor overheating, causing significant operational disruptions, financial losses or potential fire resulting in human casualties	Due to serious consequences, the change must be considered significant
Novelty in change	No condition-based diagnostic system for the ventilation system was previously implemented	As this is the first application of such a solution, the change must be considered significant
Complexity of the change	The modification does not affect the structure of the vehicle or other maintenance system components	The change affects only one subsystem and is therefore insignificant
Monitoring possibility	Errors in testing procedures can be detected through maintenance records, staff qualifications and internal reporting procedures	Monitoring is possible using the MMS; the change may be considered insignificant
Reversibility	The change can be fully reversed by restoring the previous maintenance activities	Full reversibility indicates the change to be insignificant
Additionality	No parallel changes affecting the same system	Not applicable

The activities listed above include several manual inspections that assess similar degradation phenomena, such as contamination, imbalance and bearing condition, using different subjective criteria. As part of the proposed CBM implementation, selected manual inspection tasks are replaced by a single diagnostic activity based on vibration measurement of the fan assembly (Table 2).

Importantly, the introduction of this diagnostic activity does not change the frequency of inspections, ensuring that the overall maintenance schedule remains unaffected. The modification therefore replaces multiple manual and subjective inspections with a single quantitative assessment procedure aligned with CBM principles.

Following the identification of affected maintenance activities, the significance of the change was evaluated using the criteria defined by CSM RA (Table 3). The assessment considered the potential consequences of system failure, the novelty of the proposed solution, the complexity and scope of the modification, the possibility of monitoring its effects during operation, its reversibility and its interaction with other changes introduced within the maintenance system.

The analysis indicates that although the modification affects only a single subsystem and does not introduce changes to the physical structure of the vehicle, it alters the decision-making process for assessing the technical condition of a safety-relevant function. Malfunction of the traction motor ventilation system may lead to traction motor overheating, resulting in operational disruptions and significant financial losses, and therefore cannot be considered negligible.

At the same time, the assessment shows that the change is limited in scope, fully reversible and monitorable within the existing MMS. Despite these mitigating factors, the combination of potential failure consequences and the novelty of introducing a diagnostic-based decision process led to the classification of the change as significant. Consequently, a full risk management process in accordance with CSM RA was required. This assessment provides the formal basis for proceeding with the detailed specification of the change, hazard identification and risk evaluation, which are presented in the following sections.

5.4. Assessment of change for CBM implementation

In accordance with the CSM RA, a formal specification of the proposed change was developed prior to hazard identification and risk evaluation. The purpose of this specification is to define the scope and objectives of introducing CBM for traction motor cooling fans, as well as to identify the system boundaries, interfaces and existing safety measures relevant to the modification.

The objective of the change is to modify maintenance activities related to the traction motor ventilation system by introducing a diagnostic-based decision process that reduces the number and time consumption of repetitive manual inspections and limits unnecessary preventive replacement of components that remain in acceptable technical condition. The change is confined to the maintenance domain and consists exclusively of modifications to maintenance documentation and procedures implemented within the MMS. No changes are introduced to the physical design of the vehicle, the fan assemblies or the traction motors themselves. Selected manual inspection tasks are replaced by a vibration-based diagnostic procedure, while other safety-critical inspections and preventive measures remain unchanged.

The boundaries of the change are defined by the maintenance documentation and procedures governed by the MMS. The modified maintenance process interfaces with the rolling stock through the acquisition and interpretation of condition data that directly influence maintenance decisions and the technical condition of the vehicle. It also interfaces with workshop infrastructure through the use of vibration measurement equipment, diagnostic software and standard maintenance tools, as well as with maintenance personnel through qualification requirements, training and defined responsibilities necessary for the correct execution and interpretation of diagnostic measurements. The integration of CBM into the existing MMS is procedural rather than IT-based and does not require a dedicated data interface or real-time transmission system. Diagnostic results obtained during scheduled P1 and P2 maintenance are recorded in the standard maintenance documentation. Defined alarm and critical thresholds serve as formal decision triggers within the MMS, initiating corrective actions such as cleaning, balancing, increased monitoring or component replacement in accordance with established procedures. The operational environment of the change includes the SMS of the railway undertaking and the MMS of the ECM of maintenance responsible for vehicle upkeep.

Existing safety measures consist primarily of the established maintenance procedures defined in the current maintenance documentation, including periodic inspections, preventive bearing replacement and functional checks performed at higher maintenance levels. These measures remain valid and provide a baseline level of safety throughout the implementation of the change. The associated risk assessment is conducted from the perspective of the Entity in Charge of Maintenance and therefore does not address hazards related to the original design or manufacturing processes of the vehicle, which are already covered by existing conformity and certification procedures. Instead, the assessment focuses on risks introduced by changes to maintenance decision-making and diagnostic processes. This specification defines the framework for the hazard identification and risk evaluation steps presented in the following sections.

5.5. Assessment of change for CBM implementation

Based on the specification of the change presented in the previous section, a structured hazard identification process was conducted in accordance with the principles of the CSM RA. The purpose of this step was to identify potential hazardous situations that could arise as a result of replacing selected manual maintenance activities with diagnostic-based condition assessment supported by an advanced measurement system.

The replacement of manual inspections with a measurement-driven diagnostic process may introduce new operational risks related to the reliability of diagnostic information, the correctness of its interpretation and the interaction between the diagnostic system and maintenance personnel. Through the analysis of potential adverse events associated with the modified maintenance process, a set of representative hazards was identified. These hazards reflect the main failure modes and organisational risks relevant to the implementation of CBM for traction motor cooling fans.

The implementation of CBM requires appropriate qualification of maintenance personnel performing vibration diagnostics. Training includes basic principles of vibration analysis relevant to cooling fan degradation mechanisms, interpretation of RMS and FFT-based indicators and correct application of predefined decision thresholds. Competence is verified through supervised practical sessions and periodic internal evaluation in accordance with existing MMS procedures. The introduction of CBM therefore extends existing maintenance competencies rather than creating a separate diagnostic function.

The identified hazards cover both technical and human-factor-related aspects of the proposed change. They are not associated with the original design or manufacturing of the vehicle or its components, which are already addressed by existing certification and approval processes, but arise specifically from the modification of maintenance decision-making and diagnostic workflows.

The hazard list presented in Table 4 constitutes the basis for the subsequent risk evaluation and acceptance process. In the following section, each identified hazard is assessed using a quantitative risk evaluation method, and appropriate risk control measures are defined to ensure that the resulting risk levels remain acceptable within the framework of the MMS.

Table 4. Identified hazards related to the introduction of CBM for traction motor cooling fans.

Hazard ID	Hazard description
H.1	Failure to detect progressive degradation of the cooling fan due to overly conservative diagnostic thresholds or unreliable measurements, potentially resulting in continued operation of a degraded component
H.2	Excessive number of maintenance interventions caused by overly restrictive diagnostic criteria, leading to unnecessary maintenance costs and workload without proportional safety benefits
H.3	Incorrect interpretation of diagnostic results by maintenance personnel, resulting in inappropriate maintenance decisions
H.4	Failure or malfunction of measurement transducers or diagnostic software, leading to incorrect or misleading diagnostic outputs
H.5	Improper execution of the measurement procedure by maintenance personnel, resulting in unreliable or invalid measurement results

5.6. Risk evaluation and acceptance

Following the hazard identification presented in the previous section, a quantitative risk evaluation was conducted in accordance with the Failure Mode and Effects Analysis (FMEA) methodology. The assessment was performed using risk evaluation measures applied in the MMS of a Polish railway operator responsible for the vehicles analysed in this study. The adopted approach is consistent with commonly applied railway safety management practices and fulfils the requirements of the CSM RA.

Risk was evaluated as the product of three parameters [40,41]; the probability of occurrence (*P*), the severity of consequences (*C*) and the probability of detection (*D*), resulting in a risk index expressed as (1):

$$R = P \cdot C \cdot D \tag{1}$$

The qualitative interpretation of the parameters *P*, *C* and *D* was based on ordinal scales reflecting typical railway operational conditions, very similar to scales in [40]. In practical terms, the values of individual parameters are determined by a team of safety experts based on historical records of component damage (*P*), expert assessment of potential consequences (*C* – for the worst-case scenario for the activation of a hazard is always taken into account), and verification of whether existing safety systems or codes of conduct will allow for early detection of the problem and, ultimately, reduction of the final risk value (*D*). For clarity and conciseness, only a condensed description of the adopted scales is provided below (Table 5-7), as the detailed definitions are organisation-specific and not essential for understanding the comparative risk assessment results.

Table 5. Probability of occurrence (*P*) – condensed scale.

Rank	Qualitative description
1–3	Very low probability, rare or exceptional occurrence
4–6	Medium probability, sporadic occurrence
7–8	High probability, regular occurrence
9–10	Very high probability, frequent or almost certain occurrence

Table 6. Severity of consequences (*C*) – condensed scale.

Rank	Qualitative description
1–3	Minor impact on operation and safety
4–6	Significant operational consequences, potential safety impact
7–8	Serious safety consequences
9–10	Very serious safety consequences, including potential fatalities

Table 7. Probability of detection (*D*) – condensed scale.

Rank	Qualitative description
1–3	High probability of detecting the cause before failure
4–6	Moderate probability of detection
7–8	Low probability of detection
9–10	Very low or negligible probability of detection

Based on the calculated risk index, three risk acceptance classes were defined in Table 8.

Table 8. Risk acceptance criteria.

Risk class	Risk index (***R***)	Interpretation
1	$R \leq 120$	Risk acceptable
2	$120 < R \leq 150$	Risk tolerable; mitigation measures should be considered
3	$R > 150$	Risk unacceptable; mitigation measures required

The identified hazards H.1–H.5 were evaluated using the above criteria. For hazards exceeding the acceptable risk level, additional safety measures were defined to reduce the resulting risk. The complete risk evaluation results are summarised in Table 9.

Table 9. Risk assessment for changes in the maintenance system.

Hazard	Original values (***P***, C, ***D***)	***R***	Safety measure	Values after mitigation (***P***, ***C***, ***D***)	***R***
H.1	4, 10, 4	160	Application of measurement system calibration procedures	2, 10, 4	80
H.2	4, 2, 4	32	–	–	32
H.3	6, 10, 5	300	Introduction of measurement instructions, training for ECM personnel, reference measures embedded in the diagnostic system	2, 10, 3	60
H.4	2, 10, 4	80	–	–	80
H.5	4, 10, 4	160	Introduction of measurement instructions, training for ECM personnel, reference measures embedded in the diagnostic system	2, 10, 2	40

The results indicate that two hazards (H.1 and H.5) initially exceeded the acceptable risk threshold, while one hazard (H.3) reached a critical risk level. After the introduction of targeted mitigation measures, all identified hazards were reduced to acceptable risk levels in accordance with the adopted criteria. Hazards H.2 and H.4 were classified as acceptable without additional mitigation.

Overall, the conducted risk evaluation confirms that the introduction of CBM for traction motor cooling fans can be implemented within the existing MMS without compromising railway safety, provided that appropriate procedural and organisational safeguards are applied. The results complete the formal risk management process required for implementing the proposed CBM solution.

6. Discussion – integration of the CBM concept with the MMS framework

The diagram presented in Figure 7 provides a structured comparison of two fundamentally different maintenance philosophies applied to rolling stock auxiliary systems, namely preventive maintenance (PM) and condition-based maintenance (CBM). Rather than focusing on specific diagnostic techniques, the figure highlights system level characteristics of both approaches by juxtaposing their entry conditions, dominant risks, mitigation mechanisms and long-term strategic effects. In this sense, it forms a direct conceptual bridge between the technical feasibility of simplified vibration-based diagnostics demonstrated in Section 4 and the formal and regulatory implementation within the MMS discussed in Section 5.

The left side of the diagram represents the PM approach that still dominates many railway maintenance organisations. Its low entry conditions, including a simple MMS, basic staff qualifications and low entry costs for the ECM, explain its widespread and persistent use, particularly in small fleets and legacy vehicle platforms. At the same time, the diagram clearly exposes the structural risks associated with this strategy. PM is labour-intensive, prone to unnecessary component replacements and highly dependent on human judgement. Most critically, progressive degradation may remain undetected between scheduled interventions. As indicated in the risk mitigation block, these weaknesses are not addressed through technical means but instead managed through procedures, inspections and organisational discipline, without objective feedback from the actual technical condition of the component.

These limitations translate directly into the strategic effects associated with PM. While operating costs may remain moderate for small fleets of relatively simple vehicles, diagnostic effectiveness is inherently limited and system safety depends largely on human factors rather than on measurable condition indicators. In the case of auxiliary systems such as traction motor cooling fans, this results in maintenance actions that are frequently either premature or delayed, with limited capability to adapt interventions to real degradation mechanisms.

The right side of the diagram illustrates CBM approach as a contrasting system logic. Its entry conditions are substantially more demanding, requiring integrated measurement systems, data-driven MMS and highly qualified personnel. Correspondingly, the key risks include high initial investment, implementation complexity and organisational barriers. Importantly, these challenges are explicitly acknowledged rather than concealed. However, the diagram also shows that the mitigation mechanisms for CBM differ fundamentally from those of PM. Risks are reduced through fleet size effects enabling amortisation, maintenance decision processes supported by diagnostics and a reduction in labour demand through targeted interventions. In this model, diagnostics do not merely document compliance but actively reduce uncertainty in maintenance decision making.

From an economic perspective, the short duration of the proposed diagnostic procedure (19 minutes per vehicle) also has significant economic implications in the context of avoiding unplanned rolling stock downtime. According to value-of-information (VoI) estimation models, the cost of corrective maintenance following a failure can reach approximately €10,000, whereas a planned condition-based intervention may cost around €500, which corresponds to approximately 95% cost savings for each avoided critical failure [42]. This aspect is particularly relevant in the Polish railway market, where over a typical 25–30 year operational cycle the total maintenance cost of rolling stock is comparable to its initial acquisition cost [43]. Furthermore, early detection of cooling fan degradation helps prevent in-service failures and service interruptions, which in European railway systems may lead to delay penalties estimated at approximately £40–£100 per minute [44].

As a consequence, the strategic effects of CBM emerge at a different scale. For large fleets of complex rolling stock, CBM enables lower operational costs, higher diagnostic effectiveness and improved safety and reliability. These benefits do not arise from individual measurements alone but from the systematic integration of diagnostic information into MMS processes, as demonstrated by the implementation pathway described in Section 5.

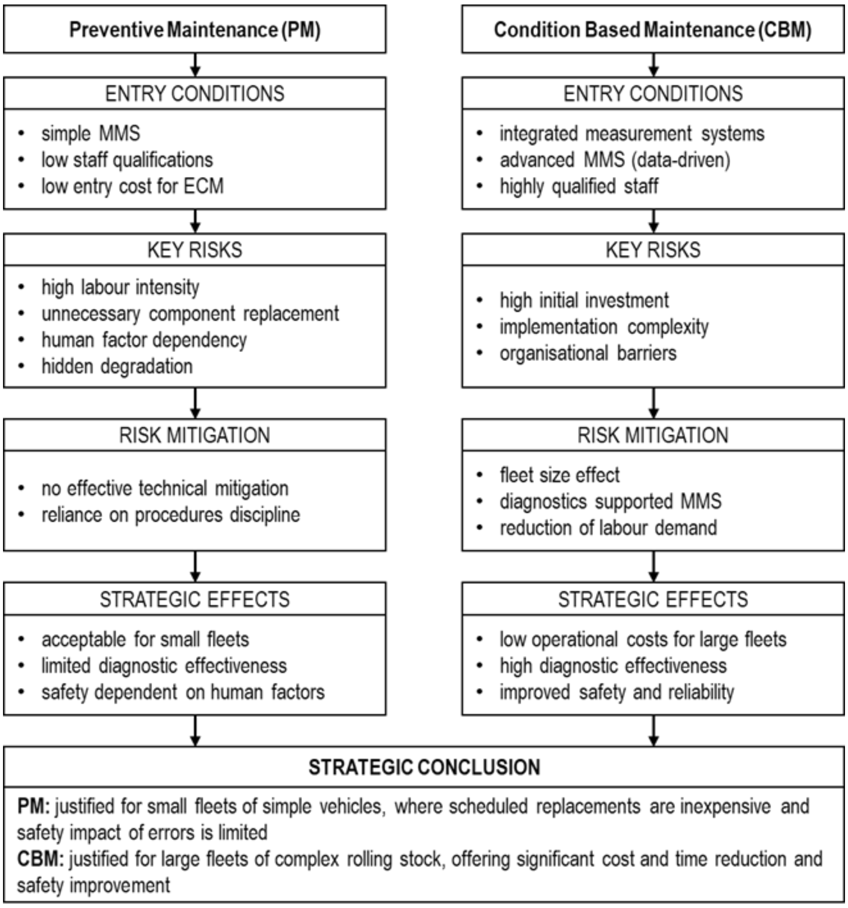

Figure 7. Diagram of the strategic comparison between PM and CBM.

The strategic conclusion formulated at the bottom of the diagram explicitly defines the boundary conditions under which each maintenance philosophy is justified. PM is appropriate only for small fleets of simple vehicles, where scheduled replacements are inexpensive and the safety impact of diagnostic uncertainty remains limited. CBM, in contrast, is not economically justified for small fleets but offers substantial cost reduction and safety improvement for large fleets of complex rolling stock.

Interpreted in the context of the case study presented in this article, the diagram acquires an additional meaning. The proposed CBM concept for traction motor cooling fans deliberately challenges the assumption that condition-based strategies necessarily require high initial investment. By employing simplified vibration-based diagnostics within existing P1 and P2 maintenance windows and embedding the resulting decisions into the MMS, the approach presented here retains the strategic advantages of CBM while significantly lowering its entry barriers. In this way, it extends the applicability of CBM to subsystems and fleet sizes that are traditionally considered unsuitable for such strategies.

7. Summary and conclusions

This article examined the feasibility of implementing CBM for traction motor cooling fans in EMUs under real operational and regulatory conditions. The study combined vibration-based diagnostics, field measurements performed on an operating fleet and a structured implementation process aligned with the European railway maintenance framework. The results demonstrate that CBM for this auxiliary subsystem is technically achievable, operationally feasible and compatible with existing maintenance systems, provided that organisational and practical constraints are properly addressed.

From the perspective of system implementation and safety management discussed in section 5, the study confirms that the introduction of CBM constitutes a regulated modification of the maintenance system and must therefore be assessed in accordance with CSM RA. Although the proposed change is limited in scope, fully reversible and does not affect vehicle design or maintenance intervals, it modifies the decision-making process for a safety-relevant function and must be classified as significant. The conducted hazard identification and FMEA-based risk evaluation showed that all identified risks can be reduced to acceptable levels through relatively simple procedural and organisational measures implemented within the MMS, confirming that CBM can be formally integrated into an existing maintenance framework without compromising safety or regulatory compliance.

From the technical perspective presented in section 4, the study demonstrates that short vibration measurements performed on the fan housing provide sufficient information to reliably assess the technical condition of traction motor cooling fans. RMS vibration velocity remains a useful global indicator but is insufficient as a standalone diagnostic criterion, whereas the inclusion of FFT-based indicators at the rotational frequency and its harmonics, combined with statistically derived diagnostic thresholds, significantly improves sensitivity to early-stage degradation. Envelope analysis further enables detection of bearing-related defects that are not visible in broadband indicators, allowing reliable differentiation between contamination-related imbalance, bearing degradation and normal operating conditions within routine P1 and P2 maintenance activities.

The results also indicate that the main challenges associated with CBM implementation are not technical but organisational and human-related. Convincing decision-makers that simplified vibration-based diagnostic methods provide sufficiently reliable information to support maintenance decisions remains a key barrier in organisations accustomed to strictly schedule-based strategies. A second challenge concerns the practical use of measurement equipment by maintenance personnel, which requires diagnostic tools tailored to workshop conditions and focused on essential decision-support information. The study therefore recommends the use of simple measurement devices providing clear indications of fan condition with respect to imbalance, bearing condition and the need for cleaning, as this approach supports consistent application, reduces training effort and facilitates effective adoption of CBM in everyday maintenance practice.

In line with the strategic comparison discussed in Section 6, the benefits of CBM should be interpreted in relation to fleet size, system complexity and organisational maturity, rather than as a universally optimal replacement for PM. The proposed solution deliberately lowers the typical entry barriers associated with CBM by combining simplified diagnostics with formal integration into the MMS, thereby extending the applicability of condition-based strategies to auxiliary subsystems and operational contexts that are traditionally considered unsuitable for such approaches. The study is based on a specific fleet and fan design, therefore, the quantitative thresholds presented here should be interpreted as case-specific. However, the diagnostic logic and implementation framework remain applicable to other radial cooling fan systems, provided that statistical recalibration is performed for the target population.

Although a comprehensive life-cycle cost model was not the primary focus of this study, the reduction of unnecessary interventions and the shortened diagnostic procedure already indicate a clear potential for operational savings. The proposed method, demonstrating 92.9% agreement with normative classification while simultaneously enabling early fault identification, represents a practical tool supporting the objectives formulated in international research initiatives such as the INNOTRACK project, which target a 30% reduction in total LCC of railway infrastructure and rolling stock through the application of CBM strategies [45]. The implementation of periodic vibration diagnostics allows optimisation of component replacement thresholds, thereby minimising the long-term maintenance cost rate while maintaining full operational safety [46].

Overall, the study demonstrates that a carefully scoped, low-intrusion CBM concept can provide tangible technical and organisational benefits without requiring extensive investment in advanced monitoring infrastructure. By aligning diagnostic methods with existing maintenance processes and regulatory requirements, the proposed approach offers a pragmatic pathway for the gradual introduction of CBM elements into established railway maintenance systems.

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