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Condition-Based Maintenance (CBM) of Railway Safety-Related Systems

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Railway accidents often result from a combination of factors, including human errors, inadequate maintenance, and system design flaws, leading to the realization of risks inherent in identified hazards. This paper investigates selected accidents in Europe, identifying the underlying causes—whether they come from human factors, technical deficiencies, or inadequate design.

To enhance proactive safety management, we propose a systematic approach to risk mitigation starting from the system design phase. This approach combines advanced safety management techniques, including hazard identification, condition monitoring, and failure prediction, with accident analysis to design more resilient systems. Condition-Based Maintenance (CBM) is a key part of this approach, not only as a cost-reduction tool but also as a critical method for detecting potential failures early, allowing timely interventions to prevent hazards from escalating into accidents. To support the approach, we build on the results of the PRAMS group within System Pillar project by Europe's Rail.

By analyzing accidents and categorizing them as realized hazards, we establish a framework that integrates CBM and hazard identification tools to propose common design measures, including strategies to mitigate human factors. These measures aim to reduce the likelihood of accidents by addressing risks before they can evolve into dangerous situations, ultimately contributing to the development of safer, more resilient railway systems.

Keywords: Railway Safety, System Design, Condition-Based Maintenance (CBM), Rail Accidents, Risk Mitigation

1. Introduction

Every human-made system is inevitably burdened with human errors, whether in design, manufacturing processes, in operation, or even within or after its disposal. These errors are often hidden and may not manifest immediately but only under certain conditions, revealing the primary risks inherent in systems. These risks are defined by the level of hazards introduced by the systems due to their potential to fail, which consequences could be harming people or destroying another system. Reducing the criticality of systems, i.e., increasing their safety, is a fundamental prerequisite for a sustainable future for a safe and secure human society.

For systems that have been in operation for several decades or even centuries, we rely on reactive safety principles, ad hoc: accident – investigation – implementation of countermeasures. In complex systems and when introducing new technologies, this safety process is complicated by the natural lack of knowledge about the behavior of new technologies in practice under unpredictable conditions, beyond the considered design conditions. For these cases, proactive safety management needs to be introduced. When considering the possible introduction of errors into the system at any stage of its life cycle, it is essential to combine reactive and proactive measures.

The railway sector, a prime example of a complex system, has been operational since the 19th century. Over the years, numerous reactive measures have been implemented across Europe, often addressing similar hazards but through different protection systems and interlocking mechanisms, while the fundamental principles of rail operation remain mostly consistent. As the railway system evolves with increasing tracks, capacities, speeds, and modes of transportation, it also incorporates newer IT technologies, technical principles, and environmental considerations. This evolution necessitates a systematic approach to risk mitigation starting from the system design phase. Advanced safety management techniques, including hazard identification, condition monitoring, and failure prediction, must be combined with accident analysis to design more resilient systems.

Furthermore, the financial perspective drives the system towards greater economic prosperity, necessitating the maintenance of safety at certain or higher limits. Safety, often invisible under normal conditions, becomes apparent only when lapses in safety procedures lead to accidents. Therefore, it is imperative to integrate feedback from operational experiences into the design of newer system versions and to develop ad hoc solutions in response to dangerous faults, ensuring continuous improvement in safety management.

To create a common European railway system, initiatives such as interoperability standards and the European Railway Agency (ERA) with the 4th Railway Package have been established, alongside EU-funded programs like Europe's Rail Joint Undertaking (EU-Rail). We participate in the System Pillar PRAMS group of EU-Rail program to address these topics at the European level, dealing with hazards, modularization of the railway system, and managing the evolution of the complex system with critical safety assessments, mainly in terms of continuous increasing of grade of automation.

In this paper, we mainly focus on Condition-Based Maintenance (CBM) of safety-related systems, which may play a crucial role in this approach, not only as a cost-reduction tool but also as a critical method for early detection of potential failures, allowing timely interventions to prevent hazards from escalating into accidents. The work based on the current experience of modern railway accidents, we aim to identify areas that can be easily improved by techniques under development (risk-driven design, hazard database, CBM, or processes in safe evolution management). We will critically assess the CBM technique to improve safety in these selected areas, not only as a tool for cost reduction but also to enhance safety. The results will not only be valuable for European railways but, given our involvement in global projects, they have the potential to be applied as valuable insights in railway projects worldwide.

2. Railway Safety in Europe

The railway system in Europe was historically managed separately by each national country. Although there was some sharing of experience about the rail system, each country had its own independent rules. There were international technical standards, but their use was not generally mandated. With the growing number of EU member states and the opening of borders across Europe in the 1990s, it became necessary to address common railway infrastructure, interoperability of rail systems, and a unified approach to safety.

Directive 96/48/EC of 23 July 1996 on the interoperability of the trans-European high-speed rail system introduced interoperability requirements, the Technical Specifications for Interoperability (TSI), and defined essential safety requirements, for which each Member State is responsible. In the need for the liberalization of European railways, the EU Commission adopted three Directives known as the ***"rail infrastructure package"*** (first railway package in 2001) to ensure operators' access to the trans-European network. It included directives on the development of the Community's railways, licensing of railway undertakings, allocation of railway infrastructure capacity, and the levying of charges for the use of railway infrastructure and safety certification (ERA 2025a).

The second railway package in 2004 established the European Union Agency for Railways (ERA) to devise the technical and legal framework for creating a Single European Railway Area (SERA) as mandated under European Union law. In terms of safety, Directive 2004/49/EC defined the division of responsibilities on safety among operators and Member States and set requirements for the continuous development of safety through Common Safety Targets (CST), Common Safety Methods (CSM), and Common Safety Indicators (CSI).

The third railway package in 2007 aimed to complete the European regulatory framework for the rail sector, regulating passengers' rights, rail services, and the certification of train crews.

The fourth railway package in 2016 was a significant change in railway safety and rail authorization. The Technical Specifications for Interoperability (TSI) and CSM, CST, and CSI came into force, changing safety responsibilities. Each operator is responsible for system safety and must require their suppliers to follow safety directives, mitigating all risks in their systems and communicating issues, mainly in maintenance, but also with all sub-suppliers in the railway industry. It splits responsibilities among industry, operators, infrastructure managers, national railway authorities, and ERA. New regulations released include:

- REGULATION (EU) 2016/796, on the European Union Agency for Railways and repealing Regulation (EC) No 881/2004.
- Directive (EU) 2016/798, on railway safety demanding the Common Safety Methods (CSM).
- Directive (EU) 2016/797, on the interoperability of the rail system within the European Union.

The common safety methods currently are:

- on Safety Level and Safety Performance (ASLP)
- for Monitoring
- in Supervision
- for Conformity Assessment (CA)
- for Risk Evaluation and Assessment (RA)
- on Safety Management System Requirements (SMS)
- on Common Safety Targets (CST)

each with its own regulation.

In addition to the European directives, the CENELEC standards on safety, e.g., EN 50126, which is already harmonized with CSM RA, and other standardization organizations (ISA, UIC, IEEE, etc.) have released and continuously update standards and norms for ensuring safety, both technical and functional, reactive and proactive, in general or in specific technical areas. These standards are applicable if mandated by the EU Directive, national law, or required by the project contract. They may also be used as Codes of Practice as a risk acceptance principle based on CSM RA or in areas where the CSM is not mandated (light rail, metro).

3. Europe's Rail Joint Undertaking

Europe's Rail Joint Undertaking (EU-Rail) is established by Council Regulation (EU) 2021/2085 of 19 November 2021. It is the new European partnership on rail research and innovation established under the Horizon Europe program (2020-2027) and the universal successor of the Shift2Rail Joint Undertaking. (EU-Rail 2025a).

EU-Rail's programs are grouped into two main pillars (System Pillar, Innovation Pillar) and deployment group. Deployment group accelerates the deployment of outcomes from the pillars. Innovation Pillar provides the multi-annual work program framework in seven flag ship areas: EU rail traffic management, digital and automated train operations, sustainable and digital assets, competitive digital green rail freight, smart solutions for low density traffic lines, transversal topics: data and digital enablers, explanatory research and paradigm shifts. The System Pillar provides governance, resource, and outputs to support a coherent and coordinated approach to the evolution of the rail system and the development of the system view, based on a formal functional system architecture approach to speed innovation and deployment (EU-Rail 2025b).

The Performance, Reliability, Availability, Maintenance, and Safety (PRAMS) team has been established within the System

Pillar to define the non-functional requirements, strategy, policies, methods, and principles based on current and potentially future issues in the railway market and operation and coordinate them within the System Pillar. In addition to other important domain topics, such as safety planning, human and organizational factors, and PRAM key performance indicators, the PRAMS team has identified the following areas relevant to this paper, which are being addressed within the program:

- Evolution management of safety-related systems
- European Rail Hazard Database (ERHD) and Risk Assessment (methodology, templates and tools)
- Condition Based Maintenance (CBM)

Evolution management deals with the evolution of the railway systems within the scope of the System Pillar, defining the common manner for changes to allow faster and cheaper evolutions of the safety-related systems (adaptation, modularity, and safety authorization during and after the changes). It includes the processes triggering changes in the system, i.e., evolution from the overall system point of view, and criteria for assessing and approaching each change/adaptation in its category (Spanneut et al., 2024).

The European Rail Hazard Database (ERHD) aims to create a common database by provisioning from various well-known national databases such as the technical safety plan (TeSiP) by EBA, or CHAMOIS by RSSB. This will help standardize across System Pillar domains to better understand the specific hazards of each technical topic – from cause to hazard and, on the other hand, the accident. Understanding the difference between hazard and accident, it also carefully works with CSM ASLP, the list of accident categories, and their causes to manage hazards in new design solutions during the risk analysis phase (Bois et al. 2024).

The PRAMS working group defined the basic requirements on the Condition Based Maintenance (CBM) detailed in next chapter (Perletto et al. 2024).

An important output of the System Pillar EU-Rail program is the EU-Rail Standardisation and TSI Input Plan that transfers the research and innovation results to the EU standardization and regulation process.

4. Condition Based Maintenance

Condition based maintenance (CBM) in the railway industry, particularly for rolling stock, has evolved significantly over the years. Here is a brief overview of its history and development. Early beginnings of CBM:

- Reactive maintenance: Initially, railway maintenance was primarily reactive, focusing on corrective actions after failures occurred. This approach often led to unexpected downtimes and higher costs.
- Preventive maintenance: over time, the industry shifted towards preventive maintenance, where regular inspection and scheduler maintenance were performed to prevent failures. This method, while more effective, still involved replacing parts based on time, kilometers, intervals rather than actual condition.

The concept of CBM began to gain traction in the late 20th century. CBM focuses on monitoring the actual condition of assets to determine maintenance needs, aiming to perform maintenance only when necessary. The evolution of CBM and its integration with Industry 4.0, along with the associated benefits, are discussed in detail in the work of Di Nardo et al. (2024).

The development of advanced sensors, data analytics, and diagnostic tools has been crucial in the adoption of CBM. These technologies enable continuous monitoring and accurate assessment of rolling stock components. For example, SNCF has integrated digitalization and predictive analytics, utilizing IoT sensors for real-time monitoring and maintenance optimization (SNCF 2024).

Implementing CBM for rolling stock involves several advanced techniques and methodologies. For example, are here some key approaches (Caviglia 2016):

Data Collecting and Monitoring. Modern CBM relies heavily on Sensors and internet of Things (IoT) devices to continuously monitor the condition of rolling stock components. These sensors collect data on various parameters such as temperature, vibration, pressure, and wear. Furthermore, Automatic Vehicle Inspection System (AVIS) provides comprehensive monitoring solutions by integrating multiple sensors and diagnostic tools to assess the condition of rolling stock.

Data Analysis and Diagnostic. Analysis software is used to collect, store, and analyze operational and condition data. Software like the OSI PI system helps in processing large volumes of data to identify patterns and anomalies. Other options are used machine learning and AI. Advanced algorithms and machine learning models are employed to predict failures and optimize maintenance schedules. These models analyze historical and real-time data to forecast potential issues before the occur.

Predictive maintenance. By using predictive analytics, maintenance teams can forecast potential failures and schedule maintenance activities accordingly. This approach minimizes unscheduled downtimes and extends the lifespan of components. Condition monitoring system continuously evaluates the condition of rolling stock and provides real-time alerts for any deviations from normal operating conditions. This allows for timely interventions and maintenance actions.

Integration with Maintenance Management Systems. Integrating CBM data with Computerized Maintenance Management Systems (CMMS) helps in planning, scheduling and tracking maintenance activities. This integration ensures that maintenance actions are based on the actual condition of assets rather than predefined schedules.

Implementation strategies. Implementing CBM often starts with pilot projects to test and validate the methodologies and technologies. These projects help in fine-tuning the approach before full-scale deployment. Training and skill development ensuring that maintenance personnel are trained in using CBM tools and interpreting data is crucial for successful implementation. Continuous training and skill development programs are essential.

Collaboration and Research. Collaboration with industry partners, research institutions, and technology providers can accelerate the development and implementation of CBM solutions. Joint research projects and knowledge sharing are vital for advancing CBM practices. Continuous improvement of CBM is an evolving field, and continuous improvement through feedback, research, and technological advancements is necessary to keep up with changing demands and challenges.

CBM helps in predicting and addressing potential failures before they occur, significantly reducing unexpected breakdowns. This leads to higher reliability and availability of rolling stock, ensuring that trains run more consistently and efficiently.

CBM contributes to sustainability by reducing waste and energy consumption. By accurately assessing the condition of components, rail operators can avoid premature replacements, extending the life of critical parts and minimizing the environmental footprint associated with manufacturing and disposing of components. Additionally, targeted maintenance efforts result in fewer overall maintenance activities, reducing the energy consumption associated with large-scale overhauls and replacements.

Higher reliability and fewer breakdowns lead to more consistent and dependable train services, improving customer satisfaction. Proactive maintenance ensures that trains are in optimal condition, reducing delays and cancellations

Beyond the purposes influenced by Reliability, Availability, and Maintainability (RAM), preventive maintenance, automation and improvement of some non-safety related processes (reference), CBM can significantly enhance the safety level of maintained systems by timely revealing dangerous failures through continuous monitoring.

Suppliers of safety-related systems also require periodic safety-related maintenance (Safety Related Application Conditions - SRAC), such as periodic checks or replacements within a certain period due to the components' lifetime. The potential of CBM lies in its ability to help cover these SRAC requirements if performed safely and with high assurance, while also providing cost benefits. However, CBM is recently not widespread for safety-related systems onboard rolling stock, because it is necessary to demonstrate that the SRAC can be covered by CBM. CBM has been implemented for safety-related systems mainly by major railway undertaking on existing rolling stock, and not by suppliers during the design phase. This is even more challenging for command and control systems with high safety integrity levels.

5. Data

This chapter presents the data collected for this study, including accident investigation reports, empirical experience on maintenance requirements of railway vehicles, and statistical data on railway operations.

Thanks to the Common Safety Indicators (CSI) introduced in Chapter 2, each member state is mandated to report accidents along with the investigation results. National Railway Authorities (NSA) or other designated investigation bodies publish the investigation reports and statistics and submit them to the database managed by the European Railway Agency (ERA) and also outside of Europe. We accessed detailed reports of railway accidents from the past year, which included information on causes, circumstances, and outcomes:

(i) CSI data (ERA 2024)
(ii) Accident investigation, 3781 records of train accidents of various causes (ERA 2025b)
(iii) United Kingdom Railway Accident Investigation Branch (RAIB)
(iv) United States National Transportation Safety Board (NTSB)

Additionally, we utilized previous work on the analysis of investigation reports and statistics from the Czech Republic covering the years 2006 to 2021 (Kertis et al. 2022). We compare our results with empirical experience based on data from commercial projects, including standard SRACs and maintenance requirements. However, due to confidentiality agreements, we cannot officially report or database this internal data. We leverage general hazard database knowledge as discussed in previous chapters on railway safety in Europe and the System Pillar.

6. Methodology

This chapter outlines the methodology used to evaluate the applicability and efficiency of Condition-Based Maintenance (CBM) in railway operations. The methodology is divided into five main steps: data collection, evaluation of railway accidents, identification of CBM applicability, evaluation of CBM efficiency, and critical judgement of the results in conclusion.

The methodology is based on techniques of data comparison, research in investigation reports, data collection, case studies, implementing risk-based design principles in the system design approach (such as required in CSM RA), and critical judgement of the results.

A collection of incidents and accidents was chosen based on the root cause, specifically those caused by human error during maintenance works, maintenance checking or maintenance preparation. Each accident report, from data provided in previous chapter, was systematically analyzed to extract root causes, contributing factors, and the context surrounding the failures. By leveraging this data, a comprehensive understanding of recurring vulnerabilities was established.

7. Evaluation of Railway Accidents

The foundation of Condition Based Maintenance recommendations provided in this paper is an extensive analysis process of multiple resources that collect and report on previous accidents, detailed in Part 3 Data. Two examples of the case studies developed as part of this work are:

The Eschede Train Disaster: a tragic high-speed rail accident in 1998, resulted in 101 deaths and 88 injuries. The train derailed near Eschede, Germany, due to a wheel failure caused by an undetected fatigue crack. The wheel lodged in a track switch, causing it to reposition, causing multiple carriages to collide and a road bridge to collapse onto the train. This event remains one of the deadliest rail accidents in history.

The Eschede disaster resulted in significant loss of life and injuries, exposed vulnerabilities in **maintenance** practices and high-speed rail system design, strained emergency response efforts, and led to widespread scrutiny of rail safety standards. The train's carriages, designed with lightweight materials for speed and efficiency, crumpled under the collapsed bridge, further contributing to the high casualty count.

The wheel failure was preventable due to a manufacturing defect in the wheel's composition, which went undetected during routine **maintenance** and **inspection**. Factors contributing to this failure included insufficient visual inspections and the absence of condition-based monitoring systems capable of identifying early signs of fatigue in critical components like wheels and axles.

The Eschede disaster highlighted the need for condition-based maintenance in high-speed rail systems. Advanced technologies like acoustic emission sensors and vibration monitoring could have detected wheel microcracks before failure. Integrating these with Internet of Things (IoT) platforms would enable real-time condition tracking and predictive analytics. The disaster also highlighted the need for improved rolling stock design to improve crashworthiness and safety standards.

The Eschede disaster highlights the limitations of traditional maintenance methods and the transformative potential of Continuous Maintenance (CBM). By utilizing real-time data, operators can identify and address vulnerabilities, reducing catastrophic failure risks, protecting passenger safety, and improving high-speed rail system reliability. This highlights the urgent need for innovation in rail safety practices.

The Fire on Paddington to Swansea Train Near Maidenhead: in 1995 demonstrated the disastrous consequences of inadequate maintenance and inspection practices for critical components. The fire started when a fuel tank on a high-speed train ruptured, spilling diesel fuel onto the track. The fire engulfed the first three carriages. The tank's securing arrangements had deteriorated over time, with significant wear on bolts and brackets that was not addressed during routine maintenance inspections. This led to the tank's detachment due to vibrations and dynamic forces generated during high-speed operation.

A train fire caused extensive damage and disrupted services on the Great Western Main Line, causing six passengers to suffer smoke inhalation and one passenger to be killed by a passing train. The incident highlighted the severe consequences of failures in safety, operational efficiency, and public trust in rail transportation.

The case study highlights the potential of condition-based maintenance (CBM) to prevent fuel tank failures. It suggests that advanced vibration sensors, thermal imaging systems, and IoT-enabled monitoring systems could have detected signs of wear and potential leaks in real-time. The study also highlights the need for improved design standards for fuel tanks, requiring greater resilience to vibrations and dynamic forces, and stricter inspection protocols for safety-critical components.

8. Areas of CBM Applicability

Following a cross-examination of multiple railway safety agency accident databased, a collection of recommendations for mitigation that are based on CBM is presented to prevent the most common critical failures and assure that human error and/or negligence is accounted for.

Most common errors made during the maintenance process include inadequate inspection, installation or identification of a problem. These errors can all be mitigated if condition-based maintenance is used.

Track Geometry Monitoring: Geometry monitoring systems are utilized to make informed decisions about replacing and maintaining track sections, focusing on those under the most stress or most likely to cause derailment, thereby allocating time and effort accordingly.

Brake Wear Monitoring: Implementing brake pad and disc wear sensors in a smart software solution can enable railway vehicle maintainers to analyze brake condition, make informed decisions about brake replacement frequency, and ensure proper stopping functionality is available when needed.

Smart Pantograph Systems: Smart pantograph systems detect real-time irregularities in the pantograph system, such as wire wear, cable misalignments, and hotspots, to stop trains and implement necessary mitigations and control measures to contain OCS-related hazards during railway operation.

Thermal Imaging and Temperature Sensors: Thermal imaging and temperature sensors enable early detection of electronic equipment overheating, enabling maintenance to take precautionary measures to prevent fires or equipment failures.

Embankment Faults: Strategic application of inclinometers along the embankment allows for detection of embankment issues and misalignments

Door Sensors: Door performance can be monitored, and most anomalies can be tracked using a door diagnostic solution.

Bogie Health Monitoring: Bogie health monitoring systems that include vibration sensors and monitor critical bogie data such as bogie performance, system health and areas in need of maintenance.

Genset and Fuel Monitoring: Regular monitoring of genset performance and fuel systems can identify fuel leaks immediately and ensure all systems are functioning optimally.

Detection of a faulty trackside balise by the onboard ETCS.

9. Conclusion

The investigation reports and their analyses show us that lack in maintenance significantly contributes to the big railway accidents.

Next to the proactive safety management based on risk design approach of railway assets, with the critical hazard analysis the continuous monitoring is necessary. The benefits of applying such systems into the railway maintenance process are prominent. CBM applications in the railway industry promise a safe railway experience through early failure detection and proactive risk mitigation. CBM also facilitates a more efficient maintenance process, only doing maintenance activities when needed, this increases system availability and decreases running costs by minimizing down time through optimized maintenance scheduling and faster problem diagnosis and avoid replacing components too early.

Disadvantages of the CBM remains in the complexity and costs of safe implementation of the techniques. These disadvantages may be reduced by taking account the CBM during the design phase, and implementation of modularized safe platforms, which application scope is still limited in the practice. Such platform would allow the continuous development and evolution of the rolling stock maintenance for more safety-related functions and a reduced cost. Therefore, future research should focus on the modularity of software and quantitative approaches, to allow frequent evolutions of the maintenance functions, without impacting the functional safety.

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