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A LIFE-CYCLE APPROACH TO SAFETY IN MAGLEV DERIVED RAILWAY TECHNOLOGIES

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Abstract

The developments in European railway systems nowadays require a careful analysis of how safety, technological innovation, and interoperability can coexist. In this context, Maglev Derived Systems (MDS) represent a frontier of research that combines the principle of magnetic levitation and linear motor propulsion with traditional railway infrastructure, generating hybrid solutions with high performance potential accompanied by increasing technical complexity. The aim of this study is to propose a renewed approach to risk analysis and management for MDS, capable of overcoming the limitations arising for innovative solutions constraining consolidated models in the railway sector. The work adopts a flexible methodological approach, integrating European standards with dynamic analytical tools and a systemic lifecycle perspective for the applied emerging technologies.

Keywords: risk analysis, risk assessment, safety, maglev derived system, interoperability

1 Introduction

The growing demands for speed, efficiency, and sustainability are driving a time of rapid technical innovation in the European railway industry. Maglev Derived Systems (MDS), a modern system, are notable for integrating magnetic levitation and linear motor propulsion into the current railway infrastructure. Improved operational performance and less of an impact on the environment are promised by this hybridization. Nevertheless, these technologies also bring with them previously unheard-of levels of technological complexity and safety issues that are difficult for conventional risk management frameworks to adequately handle. Traditional railway methods, which are frequently based on historical precedent and prescriptive rules, might not be adequate for cutting-edge hybrid systems. The development of modern risk analysis techniques that are adaptable, lifecycle-oriented, and compliant with European interoperability standards is therefore essential. Maglev Derived Systems (MDS) represent one of the most promising and complex innovations in this scenario. By integrating principles of magnetic levitation and linear motor propulsion into railway-compatible architectures, MDS create hybrid transport solutions that combine elements of conventional wheel–rail systems with advanced electromagnetic technologies. While these systems offer potential benefits in terms of speed, reduced mechanical wear, enhanced performance on gradients, and improved passenger comfort, they also introduce new safety-critical interfaces, operational scenarios, and system interdependencies. Traditional railway risk assessment methodologies, largely developed for mature and standardized technologies, may not be fully adequate to address the hybrid and dynamic nature of MDS. This paper therefore proposes a renewed approach to risk analysis and management tailored to Maglev Derived Systems within the European regulatory and operational context.

2 Safety and risk management in the european railway framework

The main goal of transportation is to offer a high-quality service to passengers for safety and service availability. Safety in railway systems is traditionally addressed through the RAMS paradigm, Reliability, Availability, Maintainability, and Safety, as defined in European standards such as EN 50126 [1], Within this framework, safety is understood as freedom from unacceptable risk, and risk management is embedded throughout the entire system lifecycle. The Common Safety Method for Risk Evaluation and Assessment (CSM-RA), established by Commission Implementing Regulation (EU) No 402/2013, provides a harmonized process for identifying hazards, evaluating risks, and defining appropriate mitigation measures. This approach ensures consistency across Member States and supports interoperability within the European railway area. However, MDS challenge some of the implicit assumptions embedded in conventional railway safety models. In Europe, risk analysis for challenges is regulated by the following standards:

- EN 50126-1/2 (RAMS lifecycle process) [1]
- Commission Implementing Regulation (EU) No 402/2013 (Common Safety Method – CSM-RA) [2]
- Directive (EU) 2016/798 on railway safety [3].

The EN 50126 dictated that safety must be ensured throughout the entire system life cycle. Moreover, RAMS process defines a structured methodology for:

- system definition
- hazard identification
- risk evaluation and acceptance
- definition and verification of risk control measures.

3 Maglev derived systems: architecture and complexity

Maglev Derived Systems (MDS), investigated within the MaDe4Rail project, aim to bridge this gap by integrating Maglev technologies into traditional railway systems. These systems may be classified into:

- full MDS, based entirely on magnetic suspension and propulsion, typically require specialized infrastructure that is incompatible with the current railway infrastructure.
- hybrid MDS, combining conventional wheel-rail systems with maglev-based levitation or propulsion (e.g., magnetic induction sliders or air cushion systems); By interacting a slider with a ferromagnetic rail, they can use the principle of magnetic induction between materials with different permeabilities
- conventional systems upgraded with MDS technologies, maintaining wheel-rail contact while introducing alternative propulsion or assistance systems; they offer benefits such as increased permissible track gradient, elimination of traction limitations due to wheel-rail adhesion, reduction of rotating components.

At a system level, MDS can be decomposed into four fundamental subsystems. The complexity of these architectures lies not only in individual subsystem innovations but in their interactions. The presence of electromagnetic forces, advanced control logic, and new operational modes generate non-linear dependencies that may amplify failure propagation mechanisms. This systemic complexity requires a risk assessment approach capable of integrating technical, operational, and organizational perspectives.

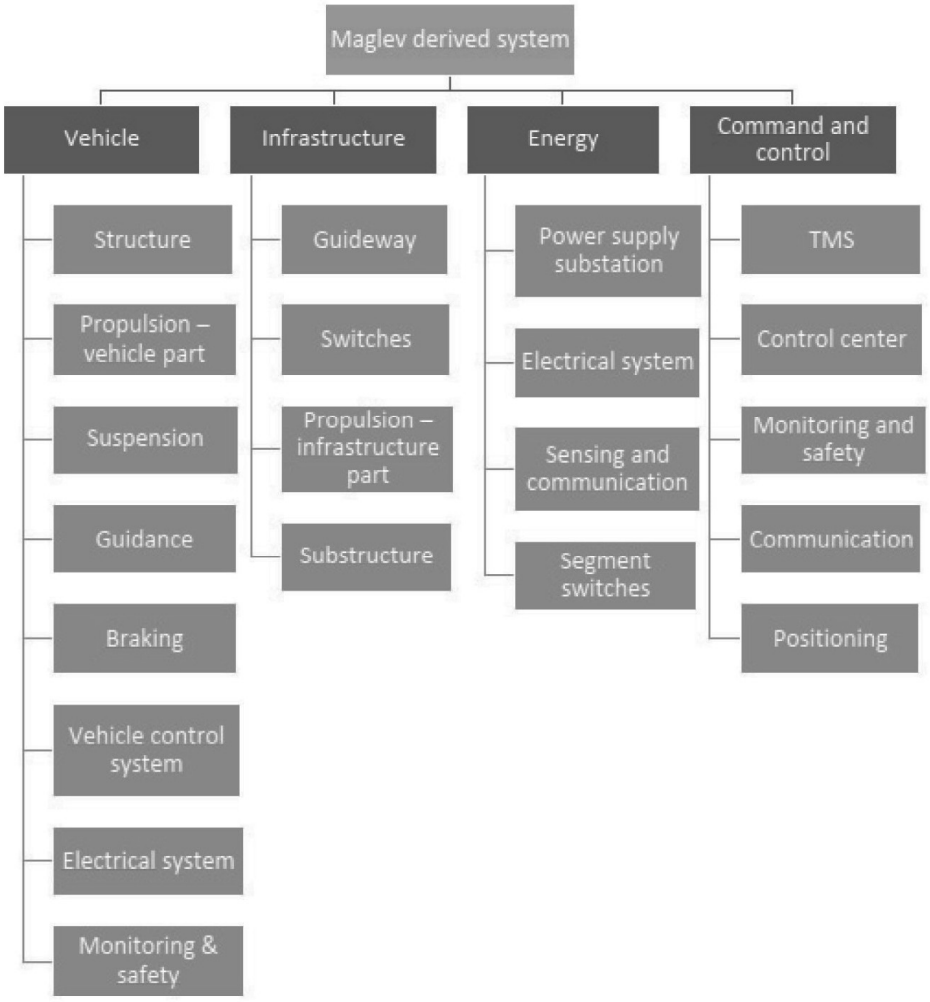

Figure 1 MDS breakdown subsystems

4 A renewed approach to risk analysis for MDS

The traditional system for risk analysis in railways includes three main steps:
- system definition
- hazard identification
- risk evaluation and acceptance.

While this structure remains valid, however its application for MDS must evolve from a static to a continuous lifecycle process. Risk assessment should accompany system conception, development, validation, operational changes and interoperability extensions.

Integration of european standards with dynamic analytical tools
The proposed framework does not replace existing European standards but complements them with advanced and dynamic analytical tools capable of modeling complex behaviors.

The following methodologies remain foundational:

- failure modes and effects analysis (FMEA) that is a commonly used, methodical approach of examining an item to determine its possible failure modes, their probability of occurring, and their impact on the system's and the items' performances, can be for systematic identification of subsystem-level failure modes
- fault tree analysis (FTA) that is a methodology for system reliability and availability analysis, as well as safety analysis can be used for modeling causal chains leading to undesired top events
- event tree analysis (ETA), a method that begins with an initiating event and explores the various mutually exclusive can be used for analyzing possible consequence sequences following initiating events
- bowtie analysis a method used to assist in the identification and management of risk can be used for visual integration of causes, consequences, preventive and mitigative barriers
- decision tree analysis (DTA) that is used to organize choices according to anticipated utility or, more generally, projected financial gain or loss, can be used for supporting strategic and investment-related safety decisions.

However, for MDS applications, these tools should be extended through:

- dynamic fault tree analysis (DFTA) to model time-dependent and sequential failures
- probabilistic risk assessment (PRA) to quantify complex system interactions
- fuzzy logic and uncertainty-based models to address incomplete or non-statistical data
- bayesian networks for representing probabilistic dependencies among subsystems
- scenario-based simulation models for hybrid operational environments.

Such integration allows for a more accurate representation of the interactions between vehicle dynamics, electromagnetic forces, software-driven control systems, and infrastructure interfaces.

5 Subsystem hazard identification and interoperability

The difference between levitating MDS and Maglev systems is most likely negligible at this level of abstraction. It implies that there won't be any changes to the hazard list. Furthermore, there is no discernible difference in high-level risks across the subcategories that result from different levitation and traction mechanisms. Evaluating the functional break-out supplied by deliverable D2.1 [4] is now the first stage. The methodology makes use of the knowledge that is currently available and can be consulted in two ways. The first step is about the examining of the current accident and incident history. A summary was completed, yielding the initial unstructured list of risks. This information can be used to ensure that no counterexamples can be found. The second step is for discussion with current Maglev system experts, as this industrial system has been in operation for many years. The experts in the maglev system create a prior list of threats to verify the functioning break-out. Attempting to match the functional breakout with the list of dangers is the second stage. Three different interpretations can be made when the list of hazards is different. The break-out hide a functional area such a way that a hazard disappears. In this instance, a portion of reality is obviously being concealed by the functional break-out analysis. When the level of abstraction is not the same, several hazards may belong to a single class of hazards. As the break-out does not consider the diversity of the technological solution providing a given function, several kind-off technological hazards may produce the same misfunctioning. From a formal point of view, the question is: Is the first experts list a refinement of the list produced while aligning with the functional break-out?

Endly, when a given hazard does not take place in the first hazard list, it may come from a different definition of “maglev specific hazards”. In this case, the concerned hazard can be suppressed with the agreement of the system experts. An example of this class of hazard proposal is “fire in the control room”. The same process is applied with the hazard list of MDS solution technology providers and with the hazard list of given technology like electromagnetic compatibility. A discussion technical try to align hazard classification with system functional frameworks. It provides insights into the systematic breakdown and its consistency with state-of-the-art systems. A critical aspect of MDS deployment in Europe is interoperability with the existing railway network. Hybrid systems must comply with Technical Specifications for Interoperability (TSIs) while ensuring that innovative technologies do not compromise safety integrity levels or operational compatibility. Risk assessment therefore becomes not only a technical exercise but also a strategic instrument for:

- demonstrating regulatory compliance
- supporting certification processes
- facilitating stakeholder acceptance
- enabling gradual technological integration into the European railway ecosystem.

By adopting a flexible, systemic, and lifecycle-based approach, safety management can act as an enabler of innovation rather than a limiting constraint.

6 Conclusion

Interoperability, safety, and technical innovation must all be carefully balanced as European railway networks develop. By fusing magnetic levitation principles with traditional railway infrastructure, Maglev Derived Systems offer a cutting-edge area of innovation that produces hybrid designs with substantial performance potential but higher technological complexity. By combining dynamic analytical techniques, a systemic lifecycle perspective, and European safety requirements, this study suggests a novel method for risk analysis and management for MDS. The unique difficulties presented by hybrid maglev–rail systems can be addressed by combining probabilistic, dynamic, and uncertainty-based models with conventional approaches like FMEA, FTA, ETA, Bowtie, and DTA. Ultimately, effective risk management for MDS should be regarded not as a limitation on innovation, but as a systematic and flexible framework that facilitates the secure and sustainable integration of developing technologies into the European railway system.

References

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