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Executive Summary

This deliverable presents the current status of the doctoral research work carried out within the framework of the Ph.D. program in Electromagnetic Compatibility (EMC) applied to railway electrification systems. The research commenced in October 2023 and is structured around a comprehensive state-of-the-art review, complemented by practical validation activities and methodological development.

The initial phase focused on a systematic literature review covering simulation methodologies for both AC and DC railway power feeding systems. Key aspects addressed include the modelling of moving loads, dynamic network topologies, multi-voltage domains, and long distributed conductors requiring frequency-dependent and distributed-parameter representations. The review examined co-simulation approaches integrating traffic timetables with electrical solvers (e.g., OpenTrack–OpenPowerNet), advanced substation technologies such as bidirectional converters (BCD), energy storage systems (ESS), and energy feedback systems (EFS), as well as demand modelling techniques for planning studies. For AC systems, emphasis was placed on wideband impedance modelling up to several kilohertz, harmonic interactions, signalling compatibility (per EN 50388), and real-time simulation frameworks including Power Hardware-in-the-Loop (PHIL) validation. Emerging architectures, such as three-phase traction networks, were also analysed, particularly regarding impedance unbalance and compliance with negative-sequence limits.

Concurrently, the EMC dimension of railway electrification was investigated, focusing on conducted and radiated emissions, resonant voltage distortion, electromagnetic coupling to adjacent infrastructure, and human exposure. The analysis integrates relevant European and international standards: EN 50121, EN 50122, EN 50388, EN 50500, and IEC 62236, to ensure alignment with regulatory requirements for emissions, immunity, and safety. Field measurement campaigns were conducted using standardized EMC instrumentation to gather empirical data for model validation and compliance assessment against EN limits, thereby reinforcing links with industrial practice.

A software tool has been developed by consolidating and harmonizing legacy simulation scripts, enabling integrated analysis of power flow and EMC phenomena. This tool constitutes a core technical output of the ongoing work.

Mandatory complementary training requirements have been fulfilled through coursework totalling 101 hours, covering scientific research methodology and intellectual property fundamentals.

Regarding dissemination, while the planned outputs (two conference contributions and one journal publication) have experienced minor delays due to the intensive technical workload associated with Work Package 3, concrete progress includes an accepted abstract for TRA 2026, a state-of-the-art conference paper under preparation (target completion: end of 2025), and a journal manuscript (targeting Q1–Q2 ranking) describing the developed methodology and simulation framework.

The research employs a PRISMA-guided systematic review methodology, organized into two thematic clusters: (A) railway power system modelling and (B) EMC interactions with surrounding environments. Both academic and grey literature sources were considered to ensure technical completeness and operational relevance.

In summary, this deliverable confirms that the foundational research phase has been successfully completed, establishing a robust technical basis for the subsequent development of advanced simulation and validation capabilities. The work is positioned to contribute novel methodologies for EMC assessment in railway systems, with direct applicability to interoperability, safety, and compliance engineering.

1 Status of research work of the PhD candidate

Mr. Javier Gómez Fernández, Ph.D. candidate, was appointed as an Assistant Professor at the Universidad Politécnica de Madrid (UPM) in April 2024 following a competitive selection process. Prior to this appointment, he had enrolled in the Ph.D. program in October 2023.

Before beginning his doctoral studies, Mr. Gómez Fernández served as a postgraduate researcher at the same institution.

The initial phase of his doctoral research involved conducting a comprehensive state-of-the-art review. This review encompassed an examination of all relevant research and activities carried out within his research group and across the university in the field of electromagnetic compatibility, as well as his own prior contributions to the discipline.

After having cleared out everything produced in the institution, the state of the art review past to a wholesome state of the art on several topics mainly related to:

- Electromagnetic compatibility
- Grounding and bonding of railway electrical feeding lines
- Affections on tractor chain
- Affections on high frequencies signals

In parallel, after the internal state of the art review, the candidate has been programming the software tool by converging different scripts and works done in the past on the topic to make a working tool.

The work previously done in the mechanical engineering simulation research group has been enhanced to study different configurations of victim wires for induced voltage.

Single copper wire placed along the infrastructure could be analysed and now it has been enhanced to multiconductors, quad, single, pair, screened or unscreened while before it was made with a simplistic reduction of the reduction factor of the wire

Critical inputs are many, since the configured line needs to have defined the value of the wire´s section, magnetic permeability, position, frequency of the system, location of TTSS, location of trains-bonds-consumers, data of the victim (multiconductor, quad,pair…).

The potential limitations would be that the tool does not solve for a train mesh, punctual consumers on different K.P.s are to be used, grounding is parametrized with the same value at a fixed distance throughout the whole disturbing line. Victim line must be DC, transitions between electrical feeding systems are not considered.

At the moment of development, the following EMC effects can be calculated with the tool:

EMC Effect	Description	Typical Victim Infrastructure	Calculated Output
Conductive coupling	Transfer of disturbance through galvanic or grounding connections	Shield grounding systems, bonded metallic structures	Current and voltage distributions
Inductive coupling	Voltage induced by magnetic fields generated by traction currents	Signaling cables, telecom cables	Induced voltage and induced current
Capacitive coupling	Voltage transfer caused by electric-field interaction between conductors	Shielded and unshielded cables	Core-to-screen voltage, conductor voltages
Common-mode interference	Disturbance affecting all conductors with respect to ground	Signaling and telecom systems	Vcm
Differential-mode interference	Disturbance appearing between conductors of a pair	Track circuits, communication pairs	Vdm
Shield transfer effects	Coupling through cable screens and bonding arrangements	Shielded signaling cables	Screen voltage, screen current, core voltage
Inter-pair crosstalk	Coupling between circuits within multicore or star-quad cables	Multicore signaling cables	Induced voltages on neighboring pairs
Electromagnetic field exposure	Electric and magnetic field levels around the railway infrastructure	Any nearby installation	E-field and H-field maps

The developed tool evaluates the main electromagnetic compatibility (EMC) effects associated with AC railway electrification systems. Rather than focusing exclusively on induced voltages, the methodology quantifies the different coupling mechanisms responsible for electromagnetic disturbances in nearby infrastructures.

These include inductive coupling generated by traction return currents, capacitive coupling between conductors, common-mode and differential-mode interference affecting signalling systems, shield transfer effects in screened cables, and inter-pair crosstalk in multicore and star-quad cable configurations.

In addition, the tool provides spatial distributions of electric and magnetic field intensity around the railway corridor, enabling the assessment of electromagnetic exposure levels and coupling mechanisms under different electrification system configurations.

As well as that, several data gathering campaigns have been carried out (Figure 1):

Figure 1 Equipment used in the different EMC measuring campaigns

This also fortifies the links with the industry, since this data gathering campaigns are also meant to check the limit values for compliance with standards EN-50121 and EN 50122.

The measurements used for 50122 validation in collaboration with industry reports measure different things depending on if we are also checking IEC 60364 or just 50122.

For 50122, the measured variables are the following: between track voltages, voltage rail-track, Accessible element voltage, grounding voltage, rail currents.

For wire measuring, these variables are voltage between wire and earth in common and differential mode, same for current and an accessible element inside the technical cabin.

Within the Ph.D. programs, students are required to complete a mandatory component of complementary training. As a general university requirement, a minimum of 60 hours of coursework must be undertaken in various subjects.

The candidate has enrolled in the courses listed in the following Table 1.

Table 1 – A summary of hours in the study plan of the PhD candidate

COURSE TITLE	Hours	Completed Date
Bases Metodológicas y de Documentación para la Investigación Científica (Methodological Foundations and Documentation for Scientific Research)	56	30-10-2025
Patentes y Derechos de Autor: Lo que todo investigador debería saber (Patents and Copyright: What Every Researcher Should Know)	45	24-10-2025

2 SoA analysed during first steps of the PhD program

3.1 State of the art: simulation of railway electrical feeding systems (AC and DC)

In the initial phase of the state-of-the-art study, an analysis of simulation techniques for railway electrical feeding lines was conducted, with the aim of comparing and informing the work developed at the university with current international trends. This ensured that the research remained aligned with the most recent methodologies applied to this type of study.

2.1.1 Why railway feeding simulation is distinct from conventional power-system studies

Railway feeding systems present specific characteristics that distinguish them from conventional power system analyses. They combine: (i) moving loads, as train positions change the network topology continuously; (ii) rapid load dynamics associated with traction and braking cycles; (iii) multiple voltage domains, such as high-voltage three-phase utility networks supplying single-phase traction transformers and onboard converters, or AC–DC substations in metro systems; and (iv) long distributed conductors (catenary, rails, and return paths), which are relevant for both power quality and electromagnetic compatibility (Iliev et al., 2024; Ogunsola & Mariscotti, 2013)..

2.1.2 Co-simulation with traffic/operation models (timetable-driven power supply)

A consolidated state-of-practice approach is the co-simulation between a railway operations simulator (covering train movements, timetables, and gradients) and an electrical network solver responsible for power supply calculations (Stephan, 2008). In this context, Alnuman (2024) describes an OpenTrack–OpenPowerNet workflow in which the operations module provides train mechanical demands and trajectories, while the power supply module computes the corresponding electrical variables, with trains frequently represented as current sources within the network solver. The study details the required network data (substation type and location, feeding scheme, conductor cross-sections, return cables) and highlights discretization strategies (such as longitudinal segmentation of lines) that balance accuracy and computational speed, including the distributed modeling of rail-to-earth leakage along the track (Alnuman, 2024). OpenPowerNet is further documented as a co-simulation module interfaced with OpenTrack, capable of representing typical AC and DC railway power supply systems for analysis and optimization purposes (Stephan, 2008). Within this paradigm, the approach is particularly suitable for energy assessments, voltage profile evaluation, substation loading analysis, and infrastructure planning under realistic operating conditions (timetables and gradients), providing sufficient fidelity for many DC and low-frequency studies (Alnuman, 2024)..

2.1.3 DC traction power flow and advanced substation devices (EFS/ESS/BCD)

Urban direct-current (DC) railway systems increasingly incorporate energy recovery technologies, including energy storage systems (ESS), energy feedback systems (EFS), and bidirectional converter devices (BCD), which motivates the development of simulation models that extend beyond traditional passive rectifier representations (Zhang et al., 2022).

Zhang et al. (2022) introduce a unified AC/DC power flow framework, based on graph theory, to manage topological changes arising from train movements and to analyze configurations in which BCDs interconnect the AC and DC sides (Zhang et al., 2022). They highlight that conventional AC/DC power flow techniques, such as Newton–Raphson formulations used for VSC-HVDC systems, are not directly applicable to railway systems with moving loads and dynamically varying DC network topology (Zhang et al., 2022).

The reported results show that substations equipped with power electronic converters can reduce rail potential and voltage fluctuations while enhancing energy recovery, thereby demonstrating the growing importance of detailed converter models in feeding-system simulations, not only for energy performance assessment but also for the evaluation of safety-related voltages (Zhang et al., 2022)

2.1.4 Demand modeling and “diversified demand” for planning studies

For planning purposes and for the interaction with distribution systems, simplified yet operationally meaningful demand models remain essential. (Ríos and García, 2010) present a physical–mathematical framework and a MATLAB-based computational model for estimating the instantaneous power demand of electrified mass-transit lines (tram and metro), incorporating parameters such as network length, acceleration and braking profiles, number of trains, passenger load, and rectifier substation spacing. They also apply “demanda diversificada” (diversified demand curves) at the substation level, which is directly applicable to sizing studies and grid impact assessments

2.1.5 AC feeding: wideband impedance, harmonics, and interaction-aware simulation

In AC mainline systems, simulation fidelity must extend into the harmonic range relevant to signalling constraints and to converter switching sidebands. Stackler et al. (2016) provide a concise state-of-the-art overview for 25 kV–50 Hz systems up to 5 kHz, in which line sections are represented by cascaded quadripoles (π-sections) with distributed parameters, resistance is modeled as frequency-dependent via ladder networks to capture skin effect, and a state-space formulation is derived to enable efficient multi-train interaction analyses through transfer functions between train currents and voltages at multiple locations. This modeling approach directly supports CENELEC EN 50388-type coordination questions, including harmonic amplification, overvoltage limits, and the protection of no-harmonic bands reserved for signalling.

2.1.6 Real-time simulation, PHIL, and validation of converter–network interactions

A prominent recent trend is the shift from purely offline studies toward real-time emulation and power-hardware-in-the-loop (PHIL) techniques to validate converter control under realistic network impedance and resonance conditions. Stackler et al. (2019) extend the 0–5 kHz infrastructure modeling into a PHIL-oriented workflow in which a state-space representation of the infrastructure is obtained in MATLAB/Simulink, subjected to model order reduction (using balanced realization and removal of weakly controllable/observable states while preserving the target frequency range), discretized for real-time execution, and finally connected to hardware through established PHIL transformer models. Their results show that converter harmonics close to a network resonance (for example, around 3.6 kHz in their test case) can be strongly amplified by the emulated infrastructure, and that degraded converter operation shifts harmonic clusters and may reduce amplification, thereby closing the loop between impedance-accurate network modeling and experimental validation of converter behavior in resonant grids, which is critical for both electromagnetic compatibility and stability assurancegrids—critical for both EMC and stability assurance (Stackler et al., 2019).

2.1.7 Emerging architectures: three-phase traction networks and impedance unbalance

Emerging concepts, such as three-phase traction distribution at power frequency (for example, at 3 kV), introduce new simulation challenges, including unbalanced phase impedance matrices, ferromagnetic effects in conductors with irregular cross-sections, and compliance with negative-sequence limits. Xiong et al. (2023) derive phase impedance matrices and propose conductor impedance formulations that are frequency- and current-dependent through equivalent tubular conductor modeling, and they construct an equivalent 50 Hz circuit to evaluate receiving-end voltage and the negative-sequence voltage unbalance factor. This work illustrates how railway feeding system simulation is expanding beyond conventional single-phase AC and DC schemes toward novel multi-phase architectures that require new impedance and unbalance metrics.

2.1.8 Integrated utility-grid + traction substation modeling (large-scale, unbalanced, non-sinusoidal)

Lliev et al. (2024) represent a complementary line of research focused on large-scale modeling of the supplying electric power system that feeds both DC and AC traction substations, explicitly considering asymmetry through sequence components, harmonics up to the 40th order, and resonant phenomena and their consequences. Their emphasis on system-level asymmetry and harmonic behavior is closely aligned with practical grid-interface concerns, including unbalance limits, transformer thermal stress, and resonance issues.

3 SoA: ElectroMagnetic Compatibility (EMC) and "affections" of AC traction feeding on the surroundings

EMC problem framing in AC railway electrification

Alternating-current (AC) traction feeding systems, such as 25 kV–50 Hz schemes, inherently act as wideband electromagnetic compatibility (EMC) sources because traction converters draw non-sinusoidal currents and inject harmonics and interharmonics into a supply network whose impedance is strongly frequency-dependent and spatially distributed. The resulting conducted disturbances give rise to voltage distortion, including resonant overvoltages, which can couple into signalling and telecommunications systems, adjacent metallic structures, and the public environment in the form of electromagnetic field exposure.

A central EMC challenge is that railway supply lines behave as electrically long structures in which propagation and resonances already become significant in the kilohertz range, as line-section lengths become comparable to the corresponding wavelengths. As a consequence, lumped-parameter approximations lose validity with increasing frequency, and distributed-parameter modeling becomes necessary to obtain credible EMC assessments.

Standardization landscape that drives "state-of-practice"

Contemporary railway EMC assessment is largely organized around four pillars: limits and measurement methods for emissions to the external environment, rolling stock emission and immunity, signalling and telecommunications equipment immunity, and fixed power-supply installations, as codified in the EN 50121 and IEC 62236 standards families. Within the EN 50121 series, Part 2 specifies the emission limits of the overall railway system towards the outside world, while the IEC 62236-2 standard provides the corresponding international framework, including measurement concepts and typical field cartography for emissions evaluation.

EN 50388 and EN 50388-1 define the technical coordination criteria between traction power supply and rolling stock, with direct relevance to harmonic and dynamic effects in AC traction systems and interoperability requirements. EN 50500 establishes procedures for the measurement and calculation of electric and magnetic fields in the railway environment with respect to human exposure, whereas, for DC systems, EN 50122-2 addresses stray-current corrosion and mitigation, reflecting the historically lower criticality of AC stray-current corrosion in long-term operation.

Mechanisms: how AC feeding affects its surroundings

(a) Conducted emissions and resonant voltage distortion

Pulse-width-modulated front-end converters generate harmonic components whose interaction with the frequency-dependent infrastructure impedance may produce substantial voltage distortion, particularly in the vicinity of resonance frequencies. Stackler et al. show that harmonics injected by onboard rectifiers can be significantly amplified by infrastructure resonances and become detrimental for signalling systems or other trains within the same electrical section, underlining the importance of interoperability constraints set out in EN 50388.

Their work includes a concrete example in which a resonance around approximately 680 Hz allows a harmonic current of only 1 A to induce voltage distortion of the order of several kilovolts (around 7 kV) at another train's terminals, illustrating the strong system-level amplification potential of seemingly small harmonic injections.

(b) Non-sinusoidal, unbalanced operation and equipment stress

Lliev et al. model complex asymmetric and non-sinusoidal operating modes in extensive feeding networks and summarize practical consequences of harmonic distortion, including increased losses and heating, reduced equipment lifetime, metering inaccuracies, neutral conductor overheating due to triplen harmonics, and resonant phenomena around higher-order harmonics. Reported resonances around the 21st–23rd harmonics, whose frequencies shift with section length and network configuration, exemplify how harmonic distortion can interact with infrastructure characteristics to create reliability and performance risks.

(c) Electromagnetic influence on adjacent infrastructures

Beyond internal equipment impacts, Iliev et al. emphasize the electromagnetic influence of traction networks on adjacent transmission and communication lines and on extended metallic structures along the route, highlighting the broader environmental footprint of unbalanced traction operation. Significant electromagnetic fields generated by such networks may thus affect infrastructure beyond the strict boundaries of the traction system itself.

(d) Radiated fields and human exposure

For public and worker exposure, standards such as EN 50500 provide structured procedures for field measurement and calculation in railway environments, while IEC 62236-2 and EN 50121-2 define system-level emission frameworks, including limits and standardized measurement setups at specified distances from tracks and substations. In parallel, ICNIRP guidelines from 2010 and 2020 establish reference levels and limits for human exposure to low-frequency electric and magnetic fields that are applicable to railway-generated fields

Modeling approaches used in EMC studies for AC traction feeding

Distributed transmission-line and multiconductor models

For EMC-relevant frequency ranges, distributed modeling based on transmission-line and multiconductor transmission-line theory is required to accurately represent overhead lines and return paths, particularly once propagation effects become non-negligible. This approach, underpinned by canonical multiconductor analysis references such as Paul's work, supports the evaluation of frequency-dependent coupling and resonant behaviour in complex railway infrastructures.

Frequency-dependent resistance in time-domain simulations

A key state-of-the-art aspect for kilohertz-range EMC studies is the inclusion of skin and proximity effects in conductors and transformers, which shape both impedance magnitude and resonance damping. Stackler et al. propose ladder-circuit realizations to reproduce frequency-dependent resistance in the time domain, enabling accurate time-domain simulations up to several kilohertz for 25 kV systems.

State-space and transfer-function formulations for multi-train interaction

To analyse how harmonic injections from one train affect voltages at other trains and infrastructure nodes, state-space representations of the traction network can be constructed and used to derive transfer functions between current sources and remote voltage points. This framework supports systematic multi-train interaction studies, including the identification of frequencies at which small injected currents may cause large voltage perturbations elsewhere in the system.

Impedance-based stability and interaction analysis

Beyond strict compliance checks, impedance- and admittance-based modelling is increasingly employed to assess harmonic resonance, harmonic instability, and low-frequency oscillations in train–network interactions. Hu et al., for example, apply an impedance-based method to evaluate harmonic instability in high-speed railway systems with multiple trains, demonstrating how network and control parameters influence resonance build-up and potential mitigation strategies

Research trends and gaps (EMC + surroundings)

Several research and engineering trends can be identified in the EMC treatment of AC railway electrification systems: higher-frequency extensions of models are becoming necessary as new converter topologies, including solid-state transformer concepts, shift emission spectra to higher frequency bands and demand more detailed representations of transformers, lines, and return paths, including proximity effects and soil-return characteristics. Coupled multi-domain EMC remains a challenge, particularly the integrated modeling that links traction-feeding harmonics, signalling susceptibility bands (no-harmonic zones), and real operational variability such as train positions and degraded operating modes.

Furthermore, system-level compliance evidence, as required by EN 50121-2 and IEC 62236-2, calls for robust methodologies that bridge detailed converter and network simulations with standardized measurement points and acceptance criteria used in practice. Addressing these aspects over the full duration of the project is expected to be essential for developing a comprehensive and credible EMC assessment framework for AC railway electrification and its interaction with surrounding environments.

4 Consolidated reference list

- Alnuman, A. (2024). Modelling a DC Electric Railway System and Determining the Optimal Location of Wayside Energy Storage (Energies).
- Lliev, I. et al. (2024). Modeling the Operating Conditions of Electric Power Systems Feeding DC and AC Traction Substations (Energies).
- Ríos y García (2010). Modelo de cálculo de demanda de potencia eléctrica en sistemas de tracción tipo metro, tren y tranvía.
- Stackler, C. et al. (2016). 25 kV–50 Hz railway supply modelling for medium frequencies (0–5 kHz).
- Stackler, C. et al. (2019). 25 kV–50 Hz railway power supply system emulation for power-hardware-in-the-loop testings (IET Electrical Systems in Transportation).
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- Zhang, J. et al. (2022). Modelling, simulating and parameter designing for traction power system with bidirectional converter devices (IET Generation, Transmission & Distribution).
- CENELEC. EN 50121-2: Railway applications – EMC – Part 2: Emission of the whole railway system to the outside world (e.g., UNE listing). (UNE)
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- Hu, H., Tao, H., Blaabjerg, F., Wang, X., He, Z., & Gao, S. (2018). Train–Network Interactions and Stability Evaluation in High-Speed Railways—Part I: Phenomena and Modeling. IEEE TPEL, 33(6), 4627–4642. DOI: 10.1109/TPEL.2017.2781880. (Aalborg Universitets forskningsportal)
- Paul, C. R. (2007). Analysis of Multiconductor Transmission Lines (2nd ed.). Wiley-IEEE Press. (wiley.com)
- Stephan, A. (2008). Simulation of Railway Power Supply Systems (OpenPowerNet/OpenTrack co-simulation; COMPRAIL / WIT). (witpress.com)

5 Papers submitted by the PhD candidate

The publication plan for the candidate specifies that, by this stage, two papers should have been presented at international conferences and one paper should have been published in an international journal. These objectives have not yet been met by the PhD candidate, as the work carried out within Work Package 3, together with certain personal circumstances, has delayed the preparation of the planned manuscripts; however, it is expected that this situation will be remedied and the planned outputs achieved in the near future.

What has been achieved are:

- One conference abstract submitted and accepted by TRA 2026.
- One conference paper on state of the art ongoing preparation for before end of the year 2025.

Methodology

Thematic Clustering

The systematic literature review (SLR) on railway EMC compatibility was structured around two thematic clusters: Group A and Group B. Group A focused on technical and operational aspects of railway energy feeding systems for modelling Group B Relation with electromagnetic compatibility

Literature Sources

The review incorporated both academic and grey literature. Academic sources included peer-reviewed journal articles, conference proceedings, and theses. Grey literature comprised government reports, industry publications, and policy documents. This dual approach ensured a holistic understanding of the current state of railway sustainability research and practice.

Search Strategy and Screening

The search strategy involved querying multiple databases using keywords related to railway modelling, human exposure, EMC. The PRISMA methodology was employed to guide the screening process (Figure 2). Initial searches yielded a large number of records, which were then filtered through title and abstract screening, followed by full-text review. Inclusion criteria focused on relevance to the thematic clusters and methodological rigor.

PRISMA-style Diagram for Railway Systems Literature Review

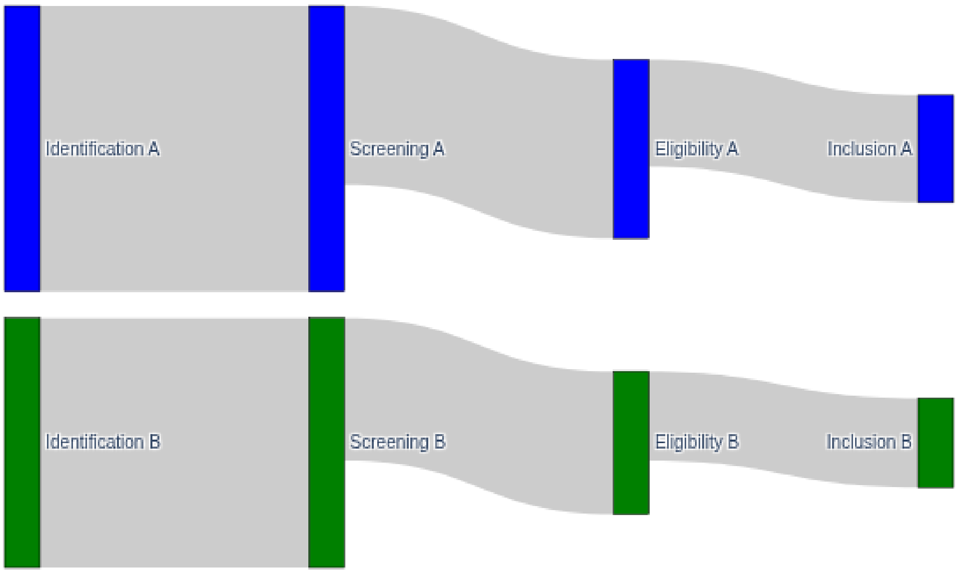

Figure 2 PRISMA diagram illustrating the systematic review process.

Evaluation and Categorization

Each selected study was evaluated based on its contribution to the thematic clusters, methodological quality, and practical implications. Studies were categorized according to their alignment with the core areas of the research. This categorization facilitated the mapping of literature to EMC and modeling and highlighted areas for future research.

Outcomes

The SLR revealed significant insights into the integration of EMC evaluation in railway systems. Key outcomes included the identification of best practices, modelling recommendations, and innovative technologies. The analysis also underscored the importance of interdisciplinary collaboration and stakeholder engagement in advancing railway simulations.

- One article for an international journal JCR Q1-Q2 rated

One article describing the tool and methodology of the same which is the main result for the PhD.

6 Conclusions

The comprehensive state-of-the-art review constitutes a pivotal milestone in the doctoral research, establishing a rigorous foundation for the analysis of railway electrical feeding systems (both AC and DC) and their associated electromagnetic compatibility (EMC) challenges. This review systematically addresses the distinctive characteristics of railway power systems, including moving loads, time-varying network topologies, wideband impedance behavior, and resonant phenomena across the kHz range. It integrates advanced methodological approaches such as co-simulation with operational traffic models, modeling of energy recovery technologies (e.g., ESS, EFS, BCD), and emerging multi-phase traction architectures. The work also critically examines relevant standardization frameworks, including EN 50121, IEC 62236, EN 50388, and EN 50500, and incorporates state-of-the-art modeling techniques such as distributed-parameter transmission line models, state-space formulations for multi-train interaction, and impedance-based stability assessments. These elements collectively position the research at the forefront of current EMC and power system simulation practices while identifying key gaps related to high-frequency emissions, coupled multi-domain interactions, and compliance validation under real-world variability.

Current EN EMC standards demonstrate electromagnetic robustness of products, but they do not always fully demonstrate interoperable behavior at railway system interfaces, especially for train detection, traction power interaction, and route-specific CCS coexistence.

You could then turn that into recommended improvement areas:

- Stronger harmonized requirements for non-axle-counter train detection interfaces,
- Better coverage of low-frequency conducted interference and return-current effects,
- **a more explicit bridge between type testing and route compatibility assessment,**
- Updates for FRMCS and modern radio coexistence.

The core of the PhD is stablished on that highlighted in bold area, trying to push forward if time makes it possible, to have final compatibility with track circuits regarding EN 50238

In collaboration with industry, we are studying implementation of EN 50122 on DC lines through the installation of VLD-F in Spain.

Although the initial dissemination plan, targeting two international conference contributions and one journal publication by this stage, has not yet been fully realized, the delay is attributable to the intensive technical workload associated with Work Package 3 and external personal circumstances, not to any deficiency in research progress or scientific rigor. Complementary training requirements have been fulfilled, and the integration of empirical measurement campaigns with simulation development has reinforced both methodological coherence and industrial relevance. With the foundational phase now complete, the timely submission of planned publications is expected, focusing on the developed simulation tool, EMC assessment methodology, and field validation results.

The research trajectory remains aligned with its core objectives, with upcoming activities directed toward real-time PHIL validation and integrated multi-physics simulations. These efforts are anticipated to yield substantive advancements in ensuring interoperability, safety, and efficiency in modern railway electrification systems at systems interface. The doctoral work thus holds significant potential for scientific contribution and practical impact in the domains of sustainable rail infrastructure and smart grid integration.

Annex: Abstract submission TRA 2026

Submission 967	
Title	Tool for evaluation on electrical affections and EMC on railway enviroments
Paper	
Track	TRA 2026
Author keywords	EMC Railway electrification Affections Disturbances CMS
Topics	Resilient Transport Systems, Transport Safety
Abstract	This newly developed software provides an integrated environment for assessing electromagnetic compatibility (EMC) disturbances and human exposure to electromagnetic fields (EMFs) in electrified railway systems. It enables simulation of induced voltages on nearby conductors and calculation of electric and magnetic field distributions generated by high-voltage AC traction systems. Its modular design allows users to configure detailed electrical scenarios, including electrification schemes, substation and autotransformer locations, grounding conditions, and specific train or load setups. A key feature is the ability to define victim wires near the electrified infrastructure, supporting both parallel and crossing geometries. The interactive user interface simplifies the definition of complex parameters while offering precise control over simulation settings. Results can be visualised through automatically generated graphs, contour plots, and 3D field maps. The tool also incorporates exposure assessment functions aligned with international safety standards, allowing users to evaluate compliance with recommended limits. Its capabilities support the analysis of impacts on safety-related installations—particularly command and signalling—technology compatibility between systems, and effects on electrical safety. This practical and versatile tool is intended for engineers, researchers, and infrastructure planners involved in the analysis of EMC phenomena and EMF exposure in railway environments, aiding both design optimisation and regulatory evaluation.
Submitted	Jun 27, 06:10
Last update	
Transport modes	Rail
Proceedings	yes
Special issue	no
Visions young researcher award	yes
Visions senior researcher award	no
Word count	

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Annex 2 Main State of the art references for PhD development

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