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Evaluating Interoperability in EV Wireless Charging Systems: A Framework-Based Comparative Approach

Panji Narputro[1]*, Anang Suryana[1,2]

[1] *Electrical Engineering Department, Faculty of Engineer, Computer and Design Universitas Nusa Putra, Jl. Raya Cibolang Cisaat No.21, Kabupaten Sukabumi, West Java 43152, INDONESIA*
[2] *Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat, Johor, MALAYSIA*

*Corresponding Author: panji.narputro@nusaputra.ac.id
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Abstract

Wireless Power Transfer (WPT) technology has emerged as a promising solution for convenient and safe Electric Vehicle (EV) charging. However, the lack of interoperability between wireless charging systems developed by different manufacturers due to the diversity of international standards such as SAE J2954, IEC 61980, and ISO 15118 poses significant barriers to large-scale adoption. This paper presents a comprehensive review of the current WPT standard and its technical specifications, and is followed by an analysis of interoperability challenges in EV charging systems. Based on these identified gaps, we propose a conceptual framework to evaluate technical interoperability across various WPT implementations. This framework certainly also considers key parameters such as frequency alignment, coil compatibility, power level, communication protocol, and safety features. The results of this study provide insights for developers, manufacturers, and regulators in aligning the WPT system to support EV charging infrastructure that can be operated in the future.

1. Introduction

The global push toward sustainable mobility has led to an accelerated adoption of electric vehicles (EVs) worldwide. As this trend continues, the need for efficient, safe, and user-friendly charging systems has become increasingly critical. Among the emerging technologies, WPT has shown significant promise by enabling contactless charging of EVs, eliminating physical connectors, and supporting both static and dynamic charging modes [1], [2].

WPT systems are typically based on inductive coupling or magnetic resonance, operating at high frequencies to optimize power transfer efficiency [3]. To support their development and deployment, several international standards have been established, including SAE J2954 in the United States, IEC 61980 at the global level, and ISO 15118 for communication between EVs and the grid [4], [5]. Despite these efforts, the lack of interoperability between WPT systems from different vendors remains a major technical barrier, especially in public or shared charging environments.

Previous studies have mainly focused on technical aspects such as coil design, misalignment compensation, and system efficiency. However, the issue of interoperability has not been sufficiently addressed as a holistic and multi-dimensional engineering challenge. The existence of multiple standards, each with different design parameters and communication protocols, contributes to fragmentation across the WPT ecosystem [2], making integration between EVs and charging infrastructure difficult in multi-vendor scenarios.

Recent deployment reports highlight interoperability issues in real-world WPT applications, including communication mismatches and non-uniform power transfer capabilities between systems developed by different manufacturers. These problems are especially critical in countries with growing EV adoption, such as Indonesia, where early infrastructure decisions can significantly impact long-term scalability and vendor neutrality [2].

This paper aims to address these challenges by presenting a comprehensive review of current WPT standards and evaluating interoperability issues across the physical, electrical, and protocol layers. A structured framework is proposed for assessing system compatibility and standard alignment, with the objective of supporting the development of a more interoperable, scalable, and open WPT ecosystem.

2. WPT System Overview

WPT systems for Electric Vehicles (EVs) are designed to deliver electrical energy from a fixed power source to either a stationary or moving vehicle without requiring direct physical contact. The operating principle is typically based on either Inductive Power Transfer (IPT) or Magnetic Resonant Coupling (MRC). These systems offer significant advantages, including enhanced user convenience, support for automated charging, and improved system durability resulting from the absence of mechanical connectors [2], [6], [7].

2.1 System Architecture

A typical WPT system consists of several essential components (see Fig. 1) [6], [8]:

- Power Supply Unit – Converts the AC input from the grid to the appropriate DC level.
- Inverter – Converts DC power to high-frequency AC, typically in the range of tens to hundreds of kilohertz.
- Primary Coil (Transmitter) – Installed in the ground or charging pad, it generates a time-varying magnetic field.
- Secondary Coil (Receiver) – Mounted on the underside of the vehicle to receive the magnetic field and induce an electric current.
- Rectifier and Filter – Convert the induced AC to DC for battery charging.
- Communication Module – Enables bidirectional data exchange for safety, alignment, and control, often implementing standards such as ISO 15118.

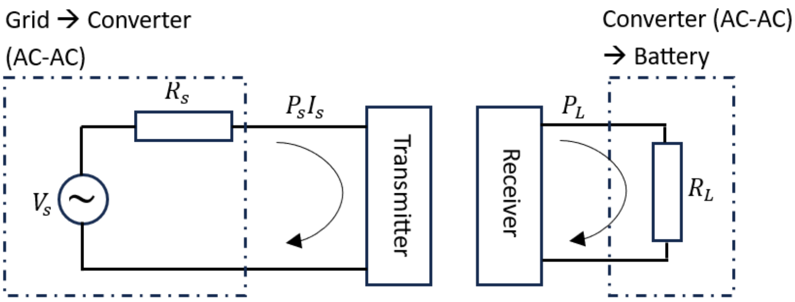

Fig. 1 *Wireless Power Transfer (WPT) system*

2.2 Key Technical Parameter

The performance and interoperability of WPT systems depend on several critical parameters:

- Operating Frequency – Standards such as SAE J2954 define a frequency band around 85 kHz to ensure efficiency and minimize electromagnetic interference (EMI) [9], [10].
- Coupling Coefficient (k) – A function of the spatial relationship between coils, typically ranging from 0.1 to 0.5 depending on design constraints [11].
- Power Transfer Rate – Usually categorized into power classes (e.g., 3.7 kW, 7.7 kW, 11 kW) according to SAE J2954 [9], [10].
- Coil Alignment Tolerance – Determines system robustness under misalignment during real-world parking conditions [12].
- Efficiency – Often targeted above 85%, achievable through compensation topologies such as LCC and CLC networks [13].

2.3 Static vs. Dynamic Charging

Static charging refers to scenarios in which the vehicle remains stationary during energy transfer. This method is the most mature and widely piloted globally. Dynamic charging allows vehicles to be charged while in motion over road segments embedded with transmitter coils. Although dynamic systems offer continuous energy supply, they face significant challenges in cost, infrastructure complexity, and interoperability [14]

2.4 Safety and Electromagnetic Compatibility

Safety is a primary concern due to the emission of high-frequency electromagnetic fields. Exposure limits are governed by standards from organizations such as the International Commission on Non-Ionizing Radiation Protection (ICNIRP) and IEEE C95.1 [15]. Ensuring compliance involves shielding, controlled field shaping, and dynamic object detection systems.

2.5 Communication and Control

Effective coordination between the EV and the charging infrastructure is necessary for authentication, alignment detection, and charging control. Standards such as ISO 15118 and SAE J2847 specify communication interfaces, which are commonly implemented using Power Line Communication (PLC) or wireless modules [16].

3. International Standards Landscape

As the deployment of Electric Vehicle (EV) wireless charging systems expands, the role of international standardization is becoming increasingly important to ensure safety, efficiency, and most importantly interoperability. Several organizations have developed WPT-related standards, each addressing a specific layer of the system architecture.

This section reviews three major international standards: SAE J2954, IEC 61980, and ISO 15118, highlighting their scope, technical parameters, and implications for cross-vendor compatibility.

3.1 SAE J2954

The SAE J2954 standard, developed by the Society of Automotive Engineers (SAE), defines wireless charging interfaces and performance requirements for light-duty electric vehicles. It is currently considered one of the most mature and globally adopted WPT standards. SAE J2954 standardizes the operational parameters of frequency, coil class, alignment tolerance, power transfer level, and also supports compatibility with ISO 15118 for its communication [17].

3.1.1 Frequency and Power Classes

SAE J2954 uses a general operating frequency centered around 85 kHz with a tolerance of ±1 kHz[5], [18], [19]. This standard defines four classes of WPT that are divided by power level:

- WPT1: 3.7 kW
- WPT2: 7.7 kW
- WPT3: 11.0 kW
- WPT9 (under development): ≥22.0 kW (high-power application)

This classification ensures scalability by maintaining backward compatibility.

3.1.2 Z-Class Coil Alignment and Compatibility

A key element of the SAE J2954 standard is the use of "Z-Class" coils (e.g., circular or double-D shapes) with a specified alignment tolerance[5], [9], [20], [21], [22]:

- Lateral misalignment: ±75 mm
- Axial (vertical) tolerance: ±50 mm
- Angular deviation: up to 10 degrees

This parameter is intended to ensure reliable charging even in imperfect vehicle parking conditions.

3.1.3 Communication and Control Integration

Although SAE J2954 does not directly define its own communication standards, SAE J2954 is designed to be operated with ISO 15118 and SAE J2847 communication standards [23], [24]. It includes provisions for:

- Automatic charging session initiation,
- Charging status monitoring,
- Foreign Object Detection (FOD),
- Protection of Living Property (LOP).

3.1.4 Resonant Topology and Compensation

SAE J2954 recommends the use of LCC compensation networks, which offer better current and voltage control in a wide range of load conditions. This standard allows for flexibility in primary/secondary compensation matching, as long as the overall system is compliant with performance and safety metrics [20], [25], [26], [27].

3.1.5 Safety and EMC Compliance

The safety aspects of SAE J2954 are in line with IEEE C95.1-2005 for human electromagnetic field (EMF) exposure. The system must also comply with CISPR 11 Class B limits for its electromagnetic compatibility [15], [22], [28], [29]. These constraints are to ensure that the WPT system meets public health and EMI emission requirements during real-world operation.

3.1.6 Vehicle Alignment Detection (VAD) and Positioning

This standard supports Vehicle Alignment Detection (VAD) using a magnetic or RF-based localization system to guide the vehicle's position over the charging pad [30]. The system improves the overall efficiency and safety of the clutch, reducing user dependency and allowing for automatic parking integration.

3.1.7 Adoption and Use Cases

The SAE J2954 standard has been successfully piloted to several OEM platforms and infrastructure providers, including BMW, WiTricity, and others. Several automotive Tier-1 suppliers are developing suitable pads (bearings) and in-drive systems, and paving the way for mass production [22], [30], [31].

3.2 IEC 61980 Series

The IEC 61980 series, developed by the International Electrotechnical Commission, provides a comprehensive and globally applicable standard for WPT systems intended for electric vehicle charging systems. The standard is modular and is organized into sections, each focusing on a different vehicle category and aspect of the system[32]. With structure and scope:

- IEC 61980-1: General requirements and definitions
- IEC 61980-2: Specific requirements for light-duty vehicles
- IEC 61980-3: Specific requirements for heavy-duty vehicles, published in 2022

IEC 61980-3:2022 (latest edition) expands the standard coverage of high-power WPT systems (up to 200 kW or more) for buses, trucks, and commercial fleets [33], [34]. This marks a fairly significant evolution of the SAE J2954 and SAE J2954/2 light-duty scopes with technical features:

3.2.1 Power Classes and Application Context

IEC 61980-3 specifies a power category of up to 200 kW, which supports a fast recharge process for large capacity batteries. This standard is generally applied to vehicles such as city electric buses, distribution trucks, as well as charging facilities at depots or business locations located on certain transportation routes[32], [34], [35].

3.2.2 Operating Frequency and Resonant Behavior

The system operates in the frequency range of 81.39 to 90 kHz, which allows for certain compatibility with the SAE J2954 standard. This standard supports the use of magnetic resonance systems with less tight couplings, to accommodate greater distances between the transmission coil (Tx) and receiver (Rx), such as ground clearance of up to 300 mm [5], [19], [21], [22].

3.2.3 Misalignment and Alignment Guidance

IEC 61980-3 permits dynamic alignment tolerances for heavy vehicles, with the following limits: lateral deviations of up to ±100 mm, vertical clearances of 150 to 300 mm, and angular misalignment of up to ±10° [27], [32], [36]. To maintain clutch efficiency despite these variations, the use of VAD systems, such as camera-based or magnetic sensors, is essential.

3.2.4 Thermal and EMC Constraints

Due to higher power usage, this standard sets stricter provisions regarding temperature monitoring, cooling systems, and electromagnetic compatibility (EMC) emissions. Exposure limits to magnetic fields refer to ICNIRP

2020 guidelines, and include multi-zone field shape settings to protect pedestrians and maintenance personnel [32], [37], [38], [39], [40], [41], [42].

3.2.5 Foreign Object Detection (FOD) and Protection

IEC 61980-3 requires the implementation of a multi-layered Foreign Object Detection (FOD) system, which includes both passive and active scanning methods. For systems with power above 50 kW, integration with the Living Object Protection (LOP) mechanism is mandatory, to ensure automatic shut-off when the presence of humans or animals is detected [32], [43], [44], [45].

3.2.6 Interoperability and Communication

While IEC 61980-3 primarily regulates the power transfer aspect, it is designed to work interoperable with ISO 15118-20, including features such as Plug & Charge, Vehicle-to-Grid (V2G) readiness, and secure communication via TLS encryption. In addition, this standard supports over-the-air (OTA) system updates to communication controllers, reflecting its compatibility with the smart grid concept [16], [32], [46].

The IEC 61980-3 standard positions itself as the cornerstone of global high-power WPT infrastructure, especially in regions that prioritize the electrification of public transportation and zero-emission logistics. Its alignment with the previous section (61980-1/2) and external communication standards (ISO 15118) ensures scalability and potential vendor-agnostic deployment [32].

3.3 ISO 15118

The ISO 15118 standard developed by the International Organization for Standardization is the most important component in the architecture of smart electric vehicle (EV) charging systems, including wired and wireless interfaces. Although initially focused on plug-in charging, ISO 15118-20:2022 introduces broader support for WPT and enables other advanced features such as Plug and Charge (PnC) and V2G operation [16], [47], [48].

3.3.1 Evolution of the ISO 15118 Standard

ISO 15118 is structured into several sections:

- Sections 1–2: Common architecture and basic communication
- Sections 3–4: Physical link and data layers
- Sections 8–20: Application layers and advanced features

ISO 15118-20, released in 2022, replaces ISO 15118-2 and introduces a next-generation communication protocol with enhanced WPT-specific security, extensibility, and provisions [47].

3.3.2 Relevance to Wireless Charging Systems

A. WPT Session Management

ISO 15118-20 defines the specific sequence of communications for wireless charging, including [47]:

- Message WPTStart, WPTStop, and WPTStatus,
- Support for power alignment negotiation, coil positioning, and efficiency monitoring,
- Real-time control between EV and Electric Vehicle Supply Equipment (EVSE) for frequency adjustment and dynamic power adaptation.

B. Alignment with SAE and IEC Standards

ISO 15118-20 is designed to operate with [47]:

- SAE J2954 for coil alignment and safety features,
- IEC 61980-3 for power transfer management and protection mechanisms.

This enables unified communication behavior across a wide range of hardware implementations.

3.3.3 Plug & Charge and Auto-Authentication

One of the distinctive features of ISO 15118 is that PnC allows vehicles to authenticate and start charging sessions automatically without user interaction. In wireless scenarios, this increases usability and aligns with the integration of autonomous vehicles [47], [49].

- Digital certificates are exchanged using Public Key Infrastructure (PKI).
- This standard supports TLS 1.3 encryption and mutual authentication.

3.3.4 Vehicle-to-Grid (V2G) and Bidirectional Charging

ISO 15118-20 introduces full support for bidirectional energy transfer, making it a support for V2G and Grid-to-Vehicle (G2V) operations [47], [50], [51].

- Energy trading, load balancing, and demand response can be coordinated.
- WPT systems can participate in dynamic grid control, especially if integrated with smart inverters.

3.3.5 Support for Future Mobility Scenarios

ISO 15118-20 incorporates capabilities beyond traditional charging, such as [47], [48], [52], [53]:

- Wireless Payment Integration (ISO/IEC 14443 interface),
- OTA updates for firmware and certificates,
- Smart Home and IoT interconnectivity through an interface to a home energy management system (HEMS).

3.3.6 Challenges in Real-World Implementation

Although ISO 15118-20 provides a strong communication backbone, real-world implementation faces challenges including:

- Inconsistent stack implementation across OEMs and charging networks,
- High complexity in the management and provision of certificates,
- Latency constraints in high-speed wireless charging, especially under dynamic conditions.

These issues underscore the importance of an interoperability testing and conformity certification framework, as proposed in the evaluation framework section of this paper [16], [47], [54].

3.4 Comparative Analysis of Standards

The following Table 1 summarizes and compares the key technical attributes of the three main standards discussed.

Table 1 *Comparison of key wireless charging standards for EVs*

Aspect	SAE J2954	IEC 61980 (1–3)	ISO 15118-20
Organization	Society of Automotive Engineers (USA)	International Electrotechnical Commission (Global)	International Organization for Standardization (Global)
Primary Focus	Hardware & system requirements for WPT in light-duty EVs	Modular technical framework for WPT (light-duty to heavy-duty)	Communication protocol between EV and EVSE
Latest Version	SAE J2954-2020	IEC 61980-3:2022	ISO 15118-20:2022
Vehicle Category Support	Light-duty vehicles	Light-duty (Part 2), Heavy-duty (Part 3), future support for dynamic charging	All categories, including bidirectional & dynamic charging
Power Classes	WPT1: 3.7 kWWPT2: 7.7 kWWPT3: 11 kWWPT9: ≥22 kW (future)	Up to ≥200 kW for heavy-duty (flexible)	Defined through energy contracts, no fixed class
Operating Frequency	Centered at 85 kHz (Z-Class coils, ±1 kHz tolerance)	81.39–90 kHz (flexible across coil types)	Protocol-agnostic, supports frequency negotiation at application level
Coil Geometry Standardization	Z-Class defined (circular, Double-D)	Flexible coil topology (IPT, resonant, loosely coupled)	N/A
Alignment Tolerance	±75 mm lateral, ±50 mm vertical (light-duty)	±100 mm lateral, 150–300 mm vertical (heavy-duty)	Supports VAD integration, not defined at physical level
Communication Stack Integration	Supports ISO 15118 & SAE J2847	Interfaces with ISO 15118, partial implementation guidance	Full protocol stack (PnC, TLS 1.3, V2G)
WPT Session Management	Indirect support via higher-layer protocols	Abstracted through EVSE control layer	WPTStart, WPTStop, WPTStatus defined in protocol
Plug & Charge	Supported via ISO 15118	Supported via ISO 15118	Fully defined (certificate-

Aspect	SAE J2954	IEC 61980 (1–3)	ISO 15118-20
(PnC)	integration	integration	based authentication)
Vehicle-to-Grid (V2G) Support	Optional, emerging	Supported via ISO 15118 interface	Full bidirectional control, load balancing, energy trading
Safety and EMC	EMF limits (IEEE C95.1), CISPR 11 Class B	EMF: ICNIRP 2020, advanced shielding & thermal safety for high-power	Secure communication, digital signatures, authentication handshake
Dynamic Charging Readiness	Limited (under study via J2954/2)	Supported for heavy-duty/dynamic bus applications	Session continuity and roaming support for DWPT
Certification & Test Protocols	Benchmarked via conformance testing (OEM-specific)	Under development (flexible testing strategy)	ISO 15118 Conformance Test System (CTS), PKI infrastructure
Global Adoption	North America, BMW pilot deployments	EU & Asia (public transport, commercial fleet pilots)	Used globally across CCS and wireless platforms

3.5 Implications for Interoperability

Although the goals overlap, these standards differ in their scope and technical definition, leading to fragmentation in their implementation in the real world. For example, vehicles designed under SAE J2954 may not operate seamlessly with infrastructure that strictly complies with IEC 61980 if coil geometry or control protocols are not suitable. In addition, cross-standard harmonization remains voluntary, without global regulatory enforcement.

This lack of harmonization underscores the need for a technical interoperability evaluation framework to systematically identify compatibility bottlenecks and guide cross-vendor development efforts.

4. Interoperability Challenges in Wireless Charging Systems

While WPT offers a promising path for scalable EV infrastructure, interoperability between charging systems and vehicles remains a major barrier to widespread adoption. In contrast to conventional plug-in chargers, where there are standard connectors and protocols the WPT system currently faces significant heterogeneity in design, specification, and control, especially when crossing standard boundaries [2], [55].

4.1 Physical Misalignment and Coil Compatibility

WPT performance is highly sensitive to coil alignment and geometric compatibility between transmitter (Tx) and receiver (Rx). Standards such as SAE J2954 define acceptable tolerances of lateral and axial misalignment; However, the shape, size, and configuration of coil resonance still vary across implementations [56]. Vehicles designed with Z-class Rx coils may experience decreased clutch efficiency when placed on top of unmatched Tx coils, even in the same power class.

Additionally, manufacturers can use proprietary ferrite settings, protective techniques, or compensation topologies (e.g., LCC vs. CLC), which further reduces cross-system compatibility.

4.2 Variation in Resonant Frequency and Power Class

Even within the 85 kHz range recommended by SAE J2954, slight resonance frequency deviations due to component tolerances or control algorithms may result in suboptimal or failed power transfer [19], [57]. In addition, some IEC 61980-based systems target higher power classes (e.g., 22 kW) [32], [34], [35], making them incompatible with vehicles that only support lower-end receivers unless adaptive control and negotiation mechanisms are implemented.

4.3 Communication Protocol Mismatch

Interoperability also relies on vehicle-to-charger communication protocols, especially for starting and setting up charging sessions [58], [59], [60], [61]. ISO 15118 provides a common language for identification, energy transfer coordination, and payment. However, variations in implementation accuracy, software stack versions, and encryption schemes can lead to handshake failures or require manual intervention [62].

In some deployments, hybrid implementations combine ISO 15118 with proprietary extensions, further complicating interoperability between systems from different OEMs or suppliers [63].

4.4 Electromagnetic Compatibility (EMC) and Safety Constraints

Differences in compliance with electromagnetic field exposure limits, protective methods, and biological safety regulations can prevent one system from operating safely in the physical environment of another. Charging bearings designed with certain protective assumptions in mind may fail EMC tests when interacting with non-native vehicle receivers, especially in high-density urban environments [64].

In addition, differences in the sensitivity of foreign object detection (FOD) and living body protection mechanisms (LOP) can lead to operational failures or inconsistent safety behavior between systems [44], [65], [66], [67].

4.5 Dynamic Charging Complexity

For dynamic WPTs where vehicles are charged while in motion conditions raises a new interoperability problem. Variations in time synchronization, communication latency, and position tracking are becoming very important. Currently, there is no unified standard that fully defines the interoperability framework for dynamic WPT, and the initial pilot remains largely proprietary [68].

4.6 Lack of Unified Certification and Test Frameworks

Currently, there is no global certification program that guarantees cross-standard interoperability between WPT systems. This results in a reliance on vendor-specific compatibility testing or closed ecosystems. Without standard interoperability test procedures, EV manufacturers and infrastructure providers risk costly integration efforts and market fragmentation [2], [68], [69].

4.7 Summary of Interoperability Issues

The key interoperability challenges across WPT systems can be summarized in Table 2 below:

Table 2 *Summary of key interoperability challenges in EV wireless charging*

Challenge Area	Description
Coil Misalignment	Performance degradation due to shape/position mismatches
Frequency and Power Disparity	Incompatibility across power classes and tuning variances
Communication Protocol Mismatch	Handshake failure due to mixed or partial protocol support
Safety and EMC Differences	Inconsistent shielding, FOD/LOP behavior across systems
Dynamic Charging Timing	Control and synchronization issues in mobile environments
Lack of Certification	No global validation system for multi-vendor compatibility

These interoperability issues highlight the urgent need for a standard evaluation framework that can assess and validate cross-system compatibility under realistic operational conditions. The next section discusses the gaps in current research and sets the stage for proposing such a framework.

5. Research Gaps and Opportunities

While there has been considerable progress in the development of WPT technology for EVs, interoperability remains an underexplored dimension. While international standards provide basic guidance on system design, communication, and safety, there is no integrated approach to evaluating and ensuring seamless compatibility between various WPT implementations. This section identifies critical gaps in current research and outlines future opportunities.

5.1 Lack of Systematic Interoperability Frameworks

Current standards define the technical parameters for each WPT system, but do not specify how these systems should interact across vendors or configurations. Most studies have focused on intra-system performance such as coil efficiency or alignment tolerance without exploring the effects of combining different system components developed under different standard interpretations.

This presents a gap to the main research: There is no standard, modular, and replica interoperability framework that can be evaluated under realistic operational conditions.

5.2 Limited Cross-Standard Comparative Studies

Several studies provide quantitative comparisons between WPT systems designed under SAE J2954 and IEC 61980. Differences in frequency control, compensation topology, or signal modulation methods are often handled separately, lacking comprehensive equivalence or difference mapping. In addition, practical studies of the tolerance of misalignment across different coil geometries are rare, especially in simulated or experimental mixed standard environments.

5.3 Inadequate Integration of Communication and Power Transfer Protocols

The integration between the communication layer (ISO 15118) and the power transfer layer (SAE/IEC) is not handled consistently. In many deployments, communication protocols are implemented partially or dependent on the middleware owner, creating an additional point of failure in interoperability.

There is an opportunity for research on integrated control architectures that can negotiate parameters such as power levels, frequencies, and coil alignment while maintaining strong communication between EVs and infrastructure.

5.4 Dynamic Charging Underrepresented in Interoperability Context

Although dynamic WPT (DWPT) has been explored as a fairly promising extension of stationary systems, its interoperability challenges remain largely unaddressed. Issues such as handover between transmitter coils, synchronization latency, and continuous authentication during motion are largely limited to proprietary studies. The general evaluation framework applicable to dynamic scenarios is currently missing.

5.5 Absence of Interoperability-Focused Simulation Models

Most simulation studies on WPT focus on coil design or electromagnetic field behavior, rather than on system-level interoperability. There are drawbacks:

- Multi-standard simulation environment,
- Scenarios that model cross-standard communication,
- Evaluation of metrics specific to interoperability (e.g., compatibility index, error rate during handshake, loss of efficiency due to mismatch misalignment).

Developing this kind of simulation model will allow researchers and developers to validate the system design in advance and reduce risks during integration.

5.6 Certification and Validation Gaps

There are currently no global organizations that offer a formal certification process for WPT interoperability, unlike plug-in EV chargers (e.g., CCS or CHAdeMO). Research on test protocols, in-loop hardware validation methods, and third-party verification procedures could pave the way for future interoperability certification ecosystems.

5.7 Opportunities for Future Work

The gaps identified highlight several high-impact research directions:

- Development of an integrated interoperability evaluation framework, integrating the physical layer and communication aspects.
- Simulation-based testing platform to validate multi-standard system configurations.
- Proposal for a modular certification scheme that aligns with existing SAE/IEC/ISO standards.
- Research on AI-assisted interoperability tuning, in which machine learning algorithms dynamically adjust coil alignment, frequency, or communication time to ensure compatibility.

This gap forms the basis for the next section, which proposes a new framework for the evaluation of interoperability in wireless EV charging systems.

6. Proposed Interoperability Evaluation Framework

To address the interoperability challenges outlined in the previous chapter, we propose a technical evaluation framework that allows for a systematic assessment of compatibility between wireless charging systems based on different international standards. The framework is designed to guide manufacturers, researchers, and regulators in testing cross-system functionality while identifying points of failure at the WPT implementation layer.

6.1 Framework Overview

The proposed interoperability framework is structured around three core dimensions:

- Physical Layer Compatibility
- Communication Protocol Interoperability
- System-Level Performance Consistency

Each dimension includes key parameters, validation procedures, and interoperability indicators that collectively make up the Compatibility Evaluation Matrix (CEM).

6.2 Physical Layer Compatibility

This layer focuses on the alignment of hardware-level specifications and electromagnetic performance between the transmitter (Tx) and receiver (Rx) systems.

The main parameters include:

- Operating frequency and accuracy of resonance tuning (e.g., tolerance ±3 kHz from 85 kHz)
- Power transfer rate and class match (e.g., 3.7 kW vs. 11 kW mismatch)
- Coil geometry (circular, Double-D, DDQ) and misalignment tolerance
- Protective characteristics and magnetic leakage limits
- Compensation network type (e.g., LCC, CLC, S-S)

Evaluation Method:

- Electromagnetic simulation using software such as COMSOL or ANSYS Maxwell
- Testing of coil misalignment under different lateral and axial offsets
- Efficiency measurement under mixed hardware configuration

6.3 Communication Layer Interoperability

This dimension ensures that EVs and EVSEs can successfully exchange control and authentication signals, regardless of protocol origin.

The main parameters include:

- Protocol standard support (ISO 15118-2, SAE J2847)
- Communication media (PLC, RF)
- Handshakes latency and error rates
- Secure authentication success rate
- Data model compatibility (e.g., EVCC vs. SECC structure)

Evaluation Method:

- Simulated communication testing using hardware-in-the-loop settings
- Software stack suitability check
- Validation of data exchange between mixed firmware versions

6.4 System-Level Performance Consistency

Beyond the individual layers, these dimensions assess how the entire system performs when EV components and chargers come from different standard bases.

Key metrics include:

- Net power transfer efficiency in mixed configurations
- System startup time and charging stability
- Safe behavior fails during miscommunication or misalignment
- Error recovery mechanism and try again

Evaluation Method:
- Full system simulation with integrated communication and power model
- Benchmark testing in a multi-standard lab setting
- Scenario-based testing: cold start, load variation, moving platform

6.5 Compatibility Evaluation Matrix (CEM)

Table 3 illustrates a simplified version of the proposed Compatibility Evaluation Matrix, combining parameters across all three layers to assess interoperability scores.

Table 3 *Compatibility evaluation matrix*

Layer	Parameter	Test Method	Interoperability Score
Physical	Resonant Frequency Tolerance	Spectrum Analyzer	Pass / Fail
	Misalignment Efficiency Drop	Lab Bench Test	High / Medium / Low
Communication	ISO 15118 Handshake Time	Comm Stack Emulation	Pass / Timeout / Error
	Secure Authentication Success	Protocol Analyzer	% Success Rate
System-Level	Combined Efficiency (Tx–Rx)	End-to-End Simulation	% Power Retention
	System Restart Capability	Failure Injection Test	Pass / Fail

Each parameter can be graded at a normalized scale (e.g., 0–1), allowing indexing of the overall interoperability for a given system pair.

6.6 Implementation Considerations

- The framework can be adapted to both static and dynamic WPT scenarios.
- The modular design allows future extensions to include V2G, two-way charging, and integration with renewable energy.
- Can support certification bodies or testing laboratories in establishing reproducible procedures.

7. Discussion and Implications

The proposed interoperability evaluation framework addresses a critical gap in the current wireless charging ecosystem by offering a structured layered method for assessing cross-system compatibility. This section discusses the practical implications, implementation, and strategic value of the framework for various stakeholders, as well as its limitations and implementation pathways.

7.1 Relevance to Manufacturers and Developers

For EV manufacturers and WPT system developers, the framework serves as a design validation tool for pre-market interoperability assessments. By testing compatibility against systems designed based on other standards, developers can:
- Improve cross-brand compatibility,
- Reduce integration failures during deployment,
- Minimize the need for costly post-deployment updates or withdrawals.

In addition, the Compatibility Evaluation Matrix (CEM) can be adapted as a diagnostic tool during the prototyping and pilot testing phases, guiding engineers towards parameter tuning (e.g., frequency offset thresholds, misalignment handling).

7.2 Support for Regulatory Bodies and Standardization Committees

The absence of unified global certification for wireless charging systems limits consumer confidence and slows down the deployment of infrastructure. This framework provides a basis for regulators and standardization bodies (e.g., IEC, SAE, ISO) to:
- Determine the level of interoperability suitability,
- Establish a technology-agnostic certification protocol,
- Promoting the adoption of open modular standards across the EV industry.

In addition, the ability to measure interoperability provides data-driven justification for regulatory policies and safety guidelines related to electromagnetic compatibility and the implementation of dynamic WPT.

7.3 Interoperability as a Strategic Enabler for Smart Mobility

As cities move towards a smart mobility ecosystem, unlimited charging is becoming essential. An operable WPT system will allow:

- Shared infrastructure among multiple EV brands,
- Integration with V2G operations,
- Dynamic energy pricing and load management through ISO 15118-based communication.

The framework can also be extended to support bidirectional power transfer, further increasing the value of EVs as grid assets.

7.4 Integration with Simulation and Digital Twin Platforms

The modularity of the framework supports implementation in digital twin environments, where real-time interaction between physical systems and virtual models allows:

- Continuous monitoring of system compatibility,
- Predictive analytics on fault tolerance,
- Optimized configuration planning for infrastructure launches.

Integration with platforms such as MATLAB/Simulink, Modelica, or shared simulation tools will improve accessibility for researchers and system integrators.

7.5 Limitations and Future Development Needs

Although the proposed framework establishes a solid foundation, some limitations remain:

- It currently focuses on technical interoperability, excluding economic, legal, and user experience dimensions.
- The use cases of dynamic charging require further expansion, especially regarding real-time communication and position synchronization.
- The lack of public datasets and testbeds limits reproducibility; Future work should aim to develop shared repositories and open access simulators.

In addition, scoring systems in the CEM matrix may require tuning based on the application context (e.g., passenger cars vs. logistics fleets), which paves the way for developing domain-specific profiles.

8. Conclusion and Future Work

WPT is a critical technology in the evolution of EV infrastructure, offering convenience, automation, and integration with smart energy systems. However, interoperability between diverse WPT systems remains a significant barrier to widespread adoption and operational scalability.

This paper has presented a comprehensive review of the current international standards governing WPT for EVs, including SAE J2954, IEC 61980, and ISO 15118. Through a detailed comparative analysis, we identified key technical differences in physical specifications, power levels, communication protocols, and safety mechanisms that contribute to fragmentation and compatibility issues in the WPT landscape.

To address these challenges, we propose a structured interoperability evaluation framework that integrates assessments on three core layers: physical hardware compatibility, communication protocol alignment, and system-level performance stability. The framework introduces the Compatibility Evaluation Matrix (CEM) as a tool to compare cross-system interactions and diagnose potential points of failure.

This contribution provides practical value for:

- EV manufacturers and developers of WPT systems, as a tool for pre-deployment testing.
- Standardization of bodies, as the basis for harmonized certification.
- Researchers, as a basis for future simulation, validation, and extension into the context of intelligent mobility.

Future Work

Several promising directions emerged from this study:

- Dynamic Wireless Charging Extension: Incorporates interoperability scenarios involving mobile vehicles and multi-zone transmitter coordination.
- Integration with AI-based Controls: Leverages machine learning for adaptive parameter tuning and error recovery in real time.

- Open Access Testbed Development: Building a shared simulation environment and experimental dataset for reproducible research.
- User-Centered Interoperability Metrics: Extends the framework to include human factors, usability, and behavioral responses during cross-system deployment.

Ultimately, building a globally recognized and technically robust interoperability framework will play a key role in accelerating the deployment of cross-compatible universal wireless charging infrastructure and realizing the full potential of electric transportation.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Panji Narputro;* ***data collection:*** *Panji Narputro;* ***analysis and interpretation of results:*** *Panji Narputro, Anang Suryana;* ***draft manuscript preparation:*** *Anang Suryana. All authors reviewed the results and approved the final version of the manuscript.*

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