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Interoperability of electric vehicle charging: fault diagnosis and compliance.

Interoperability of electric vehicle charging: fault diagnosis and compliance

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Summary

The interoperability of electric vehicle charging depends on technical layers ranging from the connector to the network *software .* This article proposes a four-layer conceptual framework: (i) physical connectors and contacts (IEC 62196 family, *International Electrotechnical Commission),* (ii) signaling and control of the conductive charging system (IEC/ABNT NBR 61851 family, *Brazilian Association of Technical Standards),* (iii) high-level communication between vehicle and station *(ISO* 15118, *International Organization for Standardization,* including *Plug & Charge* and certificate chain), and (iv) operational *backend* of the charging point *(OCPP, Open Charge Point Protocol).* Based on literature up to 2023, we developed a layer-specific fault taxonomy and a replicable diagnostic tool *(design-science)* that combines physical inspection, CP/PP *(Control Pilot/ Proximity Pilot)* measurements , *AC/ DC log* analysis , and network event analysis. Key performance indicators (KPIs) were defined for evaluation (rate of completed sessions, time to *handshake,* interruptions per 100 sessions, pin temperature, *OCPP categories).* Case studies show that seemingly "identical" symptoms derive from distinct mechanisms: thermal *derating* due to contact resistance (physical layer), *duty cycle.*

Inconsistent (signaling), expired certificates in *PnC* (communication), and remote policies *(backend).* The implications encompass *conformance testing,* the design of academic test benches, and data standardization for reproducibility. The article contributes a unified normative model, a low-cost diagnostic *pipeline ,* and a research agenda focused on the robustness of *AC/ DC recharging.*

Keywords: interoperability; IEC 62196; IEC/ABNT NBR 61851; ISO 15118; OCPP; AC/DC recharging; layered diagnostics.

Abstract

Charging interoperability in electric vehicles hinges on multiple technical layers, from hardware contacts to networked software. This paper advances a four-layer conceptual framework—(i) physical connectors and contacts *(IEC* 62196, International Electrotechnical Commission), (ii) signaling and control for conductive charging systems (IEC/ABNT NBR 61851, *Associação Brasileira de Normas Técnicas),* (iii) high-level communication between vehicle and charger *(ISO* 15118, *International Organization for Standardization,* including *Plug & Charge* and certificate chains), and (iv) *backend*

operations of the charge point *(OCPP, Open Charge Point Protocol).* Drawing on literature up to 2023, we develop a failure taxonomy per layer and a replicable diagnostic instrument (design-science) that combines physical inspection, *CP/ PP* measurements (Control/Proximity Pilot), and structured analysis of *AC/ DC* session logs and network events. We define KPIs—successful session rate, time-to-handshake, interruptions per 100 sessions, pin temperature, and *OCPP* event classes. Case studies demonstrate that similar symptoms stem from distinct mechanisms: thermal derating due to contact resistance (physical), inconsistent duty cycle (signaling), expired Plug & Charge certificates (communication), and remote policies (backend). Implications include conformance testing, the design of academic test benches, and standardized datasets for reproducibility. The paper contributes a unified normative model, a low-cost diagnostic pipeline, and a research agenda for *AC/ DC* charging robustness.

Keywords: interoperability; IEC 62196; IEC/ABNT NBR 61851; ISO 15118; OCPP; AC/DC charging; layered diagnostics.

Chapter 1 — Problem, gaps, and research questions

Charging electric vehicles is a technical phenomenon that may seem trivial from a purely technical point of view.

of the user — "touch, plug and charge" — but which, in practice, depends on layers of

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Compatibility ranges from the metal of the connector to the *software* that communicates with a remote server. When any of these layers fails, the experience degrades: the session doesn't start, it's... Interrupted, limited power without apparent cause, or works on one operator and fails on another. In Instead of attributing the problem to a "generic defect" in the car, the field of study on Interoperability of the recharge proposes viewing the EV–EVSE–network interface as a system. sociotechnical framework comprised of normative standards, protocols, and measurable criteria for conformity.

To give the reader some context, it is helpful to clarify the key acronyms. *ISO* stands for *International Organization for Standardization,* which publishes, among others, the *ISO* 15118 family, responsible for high-level communication between the vehicle and the infrastructure, including features such as authentication and *Plug & Charge.* In simple terms, *ISO* 15118 describes the digital “dialogue” between car and charger, especially relevant for direct current (DC) charging, even though it has extensions. for other cases; its part 2 details the set of messages in application, focusing on energy transfer and the vehicle detection requirements by the charging station. This dialogue It is the foundation upon which to "increase power," negotiate profiles, and safely close a session. Reproducible actions, provided that the implementation is compliant.

IEC stands for International *Electrotechnical Commission.* The *IEC* 61851 family includes the "wire" "Land" of interoperability: the requirements of the conductive charging system and the signaling logic. electrical safety measures that precede any digital transaction. In *AC,* before the messages of At a high level, the vehicle and the EVSE "talk" through two analog circuits — *Control Pilot* (CP) and *Proximity Pilot* (PP) — which discriminate vehicle presence, relay activation, permissible cable current, and grounding conditions. *IEC* 61851 defines, for example, the Voltages and *duty cycles* that indicate "can be energized," "reduce current," or "turn off." Without this basis, The recharging process shouldn't even begin. Part 1 establishes the general system requirements and limits. operating voltage of the charging equipment; the parts dedicated to *DC,* such as 61851-23 and 61851-24, specify the role of the *EVSE* and the digital control communication when the transfer occurs. at high power.

The physical layer of the coupling — the “hardware” of pins, contacts, and latches — is standardized by the *IEC* 62196 family , which defines connectors, *inlets* and sockets (for example, Type 2). in Europe and parts of the world, and the *CCS arrangements).* This family is not just about the format: it establishes Rated current and voltage, thermal limits, and mechanical details determine when a cable... It is "telling the truth" about the current it supports and when the integrity of the contact is lost because wear or oxidation. Thus, a section that limits to 6–8 A, even though the installation allows for more, This could be the effect of a PP signal indicating an undersized cable according to *IEC* 62196.

Finally, there is the network dimension. *OCPP (Open Charge Point Protocol),* maintained by *Open Charge Alliance* is the de facto standard for communication between charging stations and the central system.

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The *OCPP* does not represent the conversation between the car and the charger, but rather the charger's conversation with the operator. Your server: user authorization, reservations, *firmware update, smart charging,* registration of Events and failures. Version 2.0.1, introduced in 2020 and established as the successor to version 1.6, It reorganized the specification into profiles and test cases, reinforcing the path to certification. In In terms of phenomena, this means that a session can fail "due to policies or remote states". Even if *CP/ PP* and the *handshake* with the vehicle are correct — isolating this layer is crucial. for consistent diagnoses and causality studies.

This normative mosaic is not merely ornamental: it forms part of the layered conceptual model. which the literature and standardization suggest as a lens. Interoperability, therefore, is not binary. (“works” / “doesn’t work”), but probabilistic and multifactorial: it depends on effective adherence to standards, implemented versions, any errata, and *firmware* maturity among stakeholders. ecosystem. In the field, identical symptoms often have different causes. "Connects and drops" can This is due to: localized heating at the connector pin, which triggers *derating* for safety and cuts off the connection. session (physical layer/62196); inconsistent duty *cycle* in the *CP,* which makes the vehicle respect a ceiling of Current and, under higher demand, abort (signaling/61851); *Plug & Charge* authentication failures due to an expired certificate chain (communication/ISO 15118); or *OCPP* events that terminate the Transaction by operator policy *(backend).* On the surface, everything "looks the same"; under the microscope normative, they are distinct mechanisms, with different relationships to risk, compliance and remediation.

The state of the art up to 2023 offers sufficient material for an academic effort that unites Theory, norm, and method. However, there are clear gaps. The first, of an epistemological nature, This relates to the terminology and delimitation of the layers. Some of the technical literature uses the term "Interoperability" to refer to user experience or network coverage, ceasing to One aspect is the engineering of the layers that make the session possible. The second, methodological aspect, refers to... absence of standardized diagnostic instruments that can be replicated in academic testing environments and, when possible, reproducible under controlled conditions with descriptive event *logs .* A The third, empirical, problem lies in the scarcity of datasets (even anonymized ones) with granularity. sufficient to map faults by layer, protocol version, and thermal or electrical conditions, especially in *AC* scenarios with varying power quality and in high-power *DC .*

This article starts from these gaps and proposes three complementary movements. The first is normative-conceptual: organize a layered framework that aligns with *IEC* 61851 (signaling and control). safety, *AC* and DC), *IEC* 62196 (connectors and rated currents), *ISO* 15118 (communication of high-level authentication and services) and OCPP (telemetry, remote control and backend policies) in a minimal ontology, avoiding overlaps. The second is taxonomic: to derive, from this Ontology, a taxonomy of faults with mechanisms, signals, and testable hypotheses at each layer.

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The third is methodological: to propose and validate a diagnostic instrument — a layered *pipeline .* — capable of isolating hypotheses with realistic, low-cost tools and *log* collection structured, allowing for replicable and comparable analyses between studies.

From this, the research questions that guide the study emerge:

What mechanisms explain the most frequent layer-by-layer interoperability failures, and how? How can we distinguish between them empirically when the symptoms are similar?

How to operationalize, based on standards up to 2023, a diagnostic method by layers that are reproducible and useful for *conformance studies,* without relying on equipment. Owners?

Which metrics (time to *handshake,* session completion rate, interruptions per 100 sessions, Pin temperature, OCPP events by category) best predict the success and stability of sessions?

What implications do these findings have for the evolution of interoperability standards and testing? including certification pathways and interlaboratory testing events?

The scientific contribution of this work is twofold. On the theoretical-normative level, we propose a A layered model explicitly anchored in reference documents, which clarifies the roles and The boundaries of the *IEC* 61851, *IEC* 62196, *ISO* 15118 and *OCPP* standards are being broadened, reducing ambiguities that currently exist. Comparisons between studies and field reports are difficult. From a methodological-empirical standpoint, We present a data-driven diagnostic tool, with metrics and a *logging* scheme. which allow us to reconstruct the life cycle of a session and assign causality sparingly to each layer. An important consequence is making recurring hypotheses refutable ("the cable is "bad", "the charger is to blame", "the car is limited") through procedures that point to the This is a normative document for the underlying technical event, not for vague narratives.

There is also a dimension of disciplinary impact. The interoperability of recharging is not just An applied engineering agenda: it involves system reliability, machine-to-machine communication. Machine, information security (in *Plug & Charge* and certificates), compatibility Electromagnetic and embedded software engineering. Placing these aspects under the same framework. allows academia to contribute to more robust conformance testing, for test batteries that They should bridge the gap between layers and contribute to open databases that overcome current fragmentation. If Safe and convenient electric transportation depends on sessions that "simply work". The scientific path involves defining what "functioning" means — in normative terms, measurable and reproducible.

In the following chapters, we develop the theoretical and normative framework, proposing the Taxonomy of faults, we describe the method and instrument for diagnosis, and report the results. We use empirical data and analyses, and discuss scientific and normative implications. The premise is simple: how much

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best for our common language — the map of layers, events, and metrics. —, more quickly We will move from "works/doesn't work" to the science of applicable, auditable, and interoperability. cumulative. Along this path, the regulations up to 2023 are not barriers, but alliances: they provide the Steps so that hypotheses can be tested, failures explained, and improvements verified.

Chapter 2 — Theoretical and normative framework (acronyms explained and roles of each layer)

The academic debate on recharge interoperability only gains rigor when... The terminology is standardized and the roles of each standardization body are clearly defined. delimited. *ISO (International Organization for Standardization)* and *IEC (International The Electrotechnical Commission* publishes the standards that structure communication and safety in Electrical coupling between vehicle and infrastructure. In Brazil, ABNT *(Brazilian Association of Technical Standards) Technical Standards)* adopts and harmonizes, like ABNT NBR, parts of *IEC* and *ISO,* facilitating the Knowledge sharing among scientific communities. The *SAE (Society of Automotive Engineers)* It contributes with historically relevant vehicle interface documents, and, at the network level, *Open The Charge Alliance* promotes the *OCPP (Open Charge Point Protocol),* which regulates communication between... charging station and its remote server. Although these agents operate at distinct layers, the The scientific phenomenon we are discussing—the recharging session—can only be understood when the whole... It is analyzed in interaction.

The physical basis of the coupling is defined by the *IEC* 62196 family, which specifies dimensions, pins, currents, and voltage ratings for connectors, *inlets ,* and cables. Contrary to popular belief, the *IEC* 62196 is not just about the "socket design": it links geometric characteristics to limits. electrical and thermal factors are addressed, and it establishes the requirements that allow the cable to "announce" its safe capacity through detection circuits. It is in this layer that phenomena such as contact wear, Oxidation, misalignment, and interlocking force are entering the scientific radar, as they modulate resistance to contact and, consequently, local heating and *derating.* In epistemological terms, *IEC* 62196 provides the minimum ontology to distinguish geometric mismatch from thermal incapacity and, Therefore, separate problems that require *hardware* replacement from those that can be resolved in control domain.

Above the physical layer, *IEC* 61851 establishes the conductive charging system and regulates the... Electrical safety signaling that precedes any digital transaction. Two analog lines — *CP (Control Pilot)* and *PP (Proximity Pilot)* implement a simple yet crucial protocol. *PP* encodes the cable capacity and the physical presence of the connector using standardized resistors; In practical terms, it prevents the installation from supplying a current that the cable cannot handle. The *CP* It uses a PWM (pulse width modulation) signal to indicate the current limit that the station...

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is willing to make it available; the vehicle must respect this ceiling. This *CP/ PP* dialectic prevents the If the session begins under unsafe conditions, coordinate state transitions (presence, required ventilation, (enabling contactors) and creates a reliable bridge to the upper layers. During recharging in Direct current *(DC),* specific parts of *IEC* 61851 deal with the interaction between the equipment of supply and the vehicle, including control communication requirements and sequences of Disconnection. The scientific message here is that no "intelligent" conversation is possible when... The analog base is out of compliance.

The high-level communication layer is governed by the *ISO* 15118 family. While the *IEC* ISO 61851 decides "if" it is safe to start and "how much" can flow, while *ISO* 15118 defines what constitutes a vehicle and a station. They negotiate as a service: energy profiles, authentication, control messages and, in particular, the Plug. & Charge *(PnC)* — a mechanism that allows automatic authorization from a chain of Certificates are exchanged between the vehicle and the network ecosystem. From a scientific point of view, the interest The *ISO* 15118 standard is twofold. First, it explicitly defines the *HLC (High Level Communication) handshake,* with time, sequence, and fields that can fail subtly (due to versions, *timeouts, capabilities) .* (asymmetric). Second, it introduces information security variables — certificate validity, Key management and renewal—these issues transform the "car won't charge" problem into a problem for distributed cryptographic infrastructures. It is at this frontier that studies on the robustness of *PnC* and *Latency budget* measurement is gaining ground, especially when the goal is to isolate what is a failure of The policy of something that fails in its implementation.

The fourth link, the *OCPP,* does not participate in the vehicle-station dialogue; it orchestrates the relationship. between the station and the network server. The scientific relevance of *OCPP,* however, is central for two reasons. Reasons. First, the protocol structures the telemetry and events of the station, allowing the construction Session logs with sufficient granularity for searching: initiation, authorization, measurement, Interruption, termination, and fault codes. According to *OCPP* , it is the channel through which remote policies... — tariffs, reservations, power limits, and *smart charging* — all affect the session. Thus, a An interruption that, from the user's perspective, appears to be an "electrical fault" may, from a causal point of view, a *backend* decision and therefore a socio-technical artifact. For academia, this detachment This requires a methodology that treats *OCPP* as an independent variable and not as noise.

With the layers outlined, the *AC* and *DC* architectures can be described without resorting to... Mechanical engineering. In *AC,* the typical causal path is as follows: the integrity of the connector and the cable (62196) enables the correct reading of *PP;* the station, through the *CP,* announces its limit of Currently, the vehicle determines its load profile based on this information and internal conditions. (temperature, state of charge, cell balancing), and the session progresses as long as the limits are met. respected. In *DC,* the sequence includes additional phases: the 62196/61851 layers establish the safety channel and enable contactors; *ISO* 15118 negotiates high power parameters and

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authentication; internal sensors validate pre-charge and isolation; *timeouts* and checks of Plausibility closes the cycle. In both cases, the *OCPP* can create exogenous conditions: denying authorization, reduce power via network command, end a session by time window, or update. The *firmware* between cycles.

The value of a unified regulatory framework lies not in piling up acronyms, but in creating... observable predicates that guide causal inference. If a connector heats up and the station reduces the Regarding power, the plausible hypothesis is thermal *derating* triggered by sensors or by a local voltage drop. — a phenomenon consistent with *IEC* 62196 and the EVSE protection heuristics . If the CP It announces a ceiling that is incompatible with the installation, and the vehicle respects this limit, *IEC* 61851 explains. The limitation does not appeal to vehicle defects. If a DC session fails with authentication messages And since *PnC* certificates have expired, *ISO* 15118 provides the error grammar without the need for... Blaming the "operator" is not the answer. If a session ends abruptly at specific times and the *OCPP* logs... They show a remote control; the phenomenon is political, not physical. For academia, this Mapping is what transforms anecdotal reports into cumulative science: the same symptom may have Distinct mechanisms, therefore requiring mutually exclusive hypotheses tested on data.

There are, of course, challenges. The literature up to 2023 indicates a heterogeneity of versions (by For example, stations in OCPP 1.6 and 2.0.1 coexisting, vehicles with partial support for profiles from 15118) and subtle interactions between power quality and analog signaling (harmonics, neutral/ground, (sensitivity of differential devices). Consequently, compliance programs and events Interoperability issues emerge as useful, but still poorly documented, experimental arenas in public databases. We therefore propose that the framework not be taken as a "manual of conformity," but as an operational ontology: a map of layers, events, and measurements that Support reproducible assay protocols and facilitate the publication of anonymized *datasets* with common semantics.

This normative background allows us to propose, in the following chapter, a taxonomy of Interoperability failures. Instead of exhaustive lists, the proposal organizes the problem space. through physical-logical mechanisms and measurable evidence, while preserving the principle of parsimony. causal. The objective is twofold: to guide the design of experiments and to provide a theoretical basis for the metrics that, Later on, they will be used to evaluate the robustness and success of *AC* and *DC sessions.*

Chapter 3 — Taxonomy of interoperability faults (proposal and rationale)

Science progresses when dispersed phenomena receive a taxonomy that makes them... comparable. By organizing recharge failures into layers and mechanisms, this proposal seeks three properties: uniqueness (each instance belongs to a class without ambiguity),

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practical exhaustiveness (coverage of the most relevant cases in *AC* and *DC)* and observability (each (The class produces detectable signals in measurements or *logs).* Instead of exhausting the case studies, priority is given to... Generating mechanisms — which facilitates replication and testing.

In the physical layer *(IEC* 62196), faults emerge from the contact-heat relationship. The resistance of Contact increases with oxidation, contamination, and misalignment, and the result is overheating. localized. Heating, in turn, produces two scientific effects: it alters the resistance in a way that... non-linear *(thermal feedback)* and activates *derating* protections in the EVSE or the vehicle itself, reducing Current or ending the session. Observationally, these failures leave traces: heat marks. in pins, thermal asymmetry between phases, odor of degraded polymeric material and, when there is Instrumentation, temperature *spikes* correlated with power drops. They also belong to This class of incomplete mechanical locks prevents full contact and micro-movements. They cause intermittent arcing in *AC;* although *IEC* 62196 deals with construction and testing, the phenomenon is Physical and measurable through electrical noise and momentary continuity failures.

In the signaling layer (IEC/ABNT NBR 61851), the failures result from inconsistency of *CP* and *PP .* PP indicates the cable's capacity; if the resistive value is out of specification, the The system will interpret a cable as "smaller" than it actually is and limit the current to frustrating levels. The *CP,* When announcing the current ceiling via PWM, it can be affected by timing tolerances, noise, ground reference or sensitive protection devices — a small displacement in the width of The pulse makes the ceiling communication inconsistent with the installation's capacity. There are also faults. associated with grounding and differential devices (RCDs/GFCIs), which are triggered by leakage. transients or induced *common-mode .* The observable trait here is a session that starts in *AC,* It stabilizes and, as the current increases, it falls without any obvious error in the physical layer; *logs* and oscillography of *Public contracts* frequently reveal discrepancies between what is advertised and what is actually offered.

In the communication layer (ISO 15118), HLC *handshakes* and mechanisms of Authentication is the main source of instability in *data centers.* Negotiating profiles... Power requires strict time synchronization; short *timeouts ,* partially modified versions. Divergent implementations and interpretations of the same field lead to non-deterministic failures. The same *EV–EVSE* combination works in one location and fails in another, with no apparent change in... *hardware.* When Plug & Charge (PnC) comes into play, the certificate chain adds a Second axis: expiration, revocation, and conflicts of authority. These events are observable in *Logs* containing error codes and abnormal timing until the start of the transfer; the regularity of failures. The operator also indicates a dependence on the network configuration.

In the backend layer (OCPP), the mechanism is organizational: remote policies and states. Interact with the session. Authorizations denied, power limitation by tariff window, reservations. competitors, firmware updates sent during sessions, and loss of connectivity with the

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Server errors appear to the user as "loader failure"—but, scientifically, they belong to another causal domain. The evidence is in the remote command logs and state events: The same station, in *standalone mode,* behaves stably; on a network, it terminates sessions under certain conditions.

The proposed taxonomy suggests patterns of hypothesis. If the symptom is "connected to and limited to 6–8 A", The *a priori* hypothesis is *PP* out of specification (signaling) or erroneous *CP* announcement (signaling). before investigating the vehicle. If "it works on one operator and crashes on another" in *DC,* the primary hypothesis Migrate to communication (ISO 15118 versions and profiles) or backend (OCPP *policies),* only then Returning to physics. If there is differential heating of the pins and the power is progressively reduced, The priority is the physical layer. The goal is not to prescribe, but to order scientific research by causal likelihood and cost of testing.

This organization also helps to avoid frequent false positives. For example, assigning the "Car defect" refers to an *AC* session that is interrupted shortly after the current increase, when the *CP* It was communicating a lower ceiling than the installation could support; this is a classification error. The vehicle, in this case, was in compliance. Conversely, attributing a *DC* outage to the "network" when The *logs* reveal expired *PnC* certificates , which masks a key governance problem. an operator problem. Robust taxonomies exist to undermine these cognitive shortcuts and force... an explanation of the mechanism.

For the remainder of the work, this taxonomy will serve as a common language for the design of diagnostic tool (next chapter) and for the analysis of empirical results. The merit The scientific endeavor is not about cataloging all possible cases, but about demonstrating that causal classes Distinct signatures produce different measurable signatures and, therefore, can be distinguished by a replicable protocol. By aligning the classes with the standards and metrics, we create the conditions for... Different laboratories and research groups compare findings with semantic compatibility — an essential step towards consolidating the area.

Chapter 4 — Methodology and diagnostic tool (design-science)

The methodological approach adopted in this work is that of design *science:* instead of just To describe the problem of interoperability, we propose, construct, and evaluate an artifact—a layered diagnostic tool — which can be replicated in academic settings and, Ideally, this would be replicated by other research groups. The choice of design *science* is justified. because recharge interoperability is not an exclusively observational phenomenon; it emerges of normative implementations (IEC/*ISO families),* station and vehicle software, and policies of A network. Thus, an artifact that organizes hypotheses, measurements, and decisions provides not only a method, but also... also an operational language for comparing results between laboratories.

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The artifact is defined by four principles. The first is the principle of layers, which It imposes a causal order: it begins at the physical layer of coupling and only after excluding Based on plausible hypotheses, the focus shifts to analog signaling, high-level communication, and... Finally, *backend.* This ordering is not purely aesthetic; it avoids the confusion of domains that so often arises. It contaminates field reports ("the car is to blame", "the power grid brought everything down") and induces false positives. The second is the principle of instrumental parsimony: the minimum set of instruments should be realistic for an academic laboratory — without resorting to opaque proprietary equipment — but sufficient to generate measurable evidence: documented physical inspection, *CP/ PP* measurements *(Control/ Proximity Pilot),* pin temperature and structured log collection in *AC* and *DC.* The third It is the principle of traceability, which requires that each decision in the protocol leaves a verifiable trail: Firmware identification , protocol version, time, environmental conditions, codes and messages. relevant. The fourth is the principle of reproducibility, which implies publishing the data schema, Glossary and classification criteria so that another group can replicate the same steps with high accuracy. faithfulness, without depending on the original author.

The instrument design is based on a *pipeline* with defined stages, even if executed... as a continuous narrative. It begins with the observation of the symptom and its anchoring in variables. operational: "does not start", "starts and crashes", "limits power below expected level", "works in a "operator and not another," "interrupts during specific time windows." These labels, by themselves, are not... conclusions; they only reinforce the initial hypothesis about the likely layer. Next comes the Physical screening: connector integrity (geometry, locks, wear), presence of debris or oxidation, gaps that favor micro-movements and signs of previous heating (discoloration, (odor). The record is made with standardized photography and, when available, with surface thermometry after a short session at low power. It is deliberate that this stage precedes any other tests. Electrical measurement: if there is physical evidence of contact degradation, there is a risk of overinterpretation. The resistance of upper layers decreases. In many cases, the phenomenology of contact resistance and Thermal *derating* alone explains the "mysterious limitations" of current.

If physical screening does not yield a diagnosis, the device moves on to analog signaling. for safety. Here, the readings from *PP,* which encodes the cable capacity, and *CP,* which, are important. It announces the current limit of the charging point in pulse width modulation. This was avoided. to prescribe a single piece of equipment; any arrangement that allows measuring the *PP* resistor and characterizing it. The PWM of the *CP* (levels, *duty cycle* , and temporal stability) is sufficient. In *AC,* it is common for the The combination of "PP suggesting a shorter cable" with "PWM announcing a conservative ceiling" produces Sessions that stabilize at 6–8 A, even though the installation supports more. This stage also includes checking the grounding and sensitivity of differential devices (when known), because random protection triggers tend to manifest as interruptions under

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Current rise, a pattern erroneously attributed to digital communication when the basis is analog. She is responsible. All readings are logged with *timestamp,* station *ID ,* and firmware version. so that the condition can be reproduced in the future.

If the problem persists, the protocol reaches high-level communication. The interest is twofold: Reconstruct the *handshake* and, if present, examine the authentication and Plug & Charge states. The instrument does not require proprietary decoding of the traffic; it is sufficient that the station or *middleware...* Provide structured logs (albeit with generic fields) with status markers: attempt at initiation, negotiation, authorization, transfer, interruption and termination, accompanied by fault codes and transition times. The methodological point is that, even without "Seeing" the content of the messages, anomalous times to complete the negotiation cycle, or patterns. Repetitive behaviors (e.g., three consecutive attempts before giving up) are rich signatures for causal inference. In environments with certification and chain of trust, the artifact includes verification. Regarding the validity of certificates (when the station displays this status) and the renewal date: the literature and Practices converge on pointing to expired certificates as a source of intermittent failures that... They express interest more by operator than by vehicle.

Only when the previous layers fail to provide an explanation does the dimension of *backend.* At this stage, the artifact collects *OCPP (Open Charge Point)* events from the charging point. Relevant *protocols :* authorization, *smart charging* policies , remote start/stop commands, Network-imposed *derating , firmware* updates , and loss of connectivity with the server. Methodologically, the counter-proof is important: whether the same equipment, operating in isolation mode (or with minimized policies), produces stable sessions while, in connected mode, it suffers Interruptions at specific times or under specific conditions cause the hypothesis of causality to shift, cautiously, to network policy and cease to be attributed to "electrical failure." It is common, at this point, for series... Temporal events reveal "windows" of instability, suggesting that the phenomenon is not physical, but systemic.

The artifact needs metrics that allow for comparison and evaluation of its effect. corrections. To this end, we have defined a basic set of performance indicators. The time until *The handshake* quantifies, from the first contact to the start of the transfer, how long the system takes to "settle in." "understand"; *firmware* improvements or timing adjustments should reduce this value. The rate of The number of completed sessions (success/total) captures overall robustness and should be stratified by model. vehicle, station version and operator, when applicable. Interruptions for 100 sessions help to To determine the residual instability after corrections. In *AC,* the pin temperature over time... A standardized session (same intensity and duration) is susceptible to physical degradation and may be used as a risk marker; in *DC,* the incidence of *timeout* failures during trading indicates implementation problems or *link degradation.* Finally, the distribution of causes (by layer) along an observation window provides a snapshot of the "problem profile" of

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The studied ecosystem is useful for both prioritization and longitudinal comparison.

The operationalization of the instrument requires a data collection protocol. Each diagnostic cycle It begins with recording the versions: charging point *firmware ,* protocol version, date and time, ambient temperature and, when possible, the initial state of charge of the vehicle. Then, the following is carried out a standard *AC* session at controlled intensity, with *CP/ PP* and temperature monitoring. of the pins, followed by a standard *DC* session (when available) to capture trading times. and possible *timeouts.* Between one and the other, photographic inspection and recording of evidence is carried out. physical. Finally, the station log and the *backend event are collected,* along with the identifiers that allow for the alignment of the layers in the analysis. The protocol recommends three repetitions per condition, for to reduce the risk of accidental accidents, and to provide a counter-proof with another cable or another charging point for Testing hardware hypotheses .

The classification of the result, in turn, follows a decision-making scheme derived from... taxonomy proposed in the previous chapter. If the thermal signature is clear and the current limitation It evolves with temperature, the classification prioritizes the physical layer (with replacement recommendations). (of the cable/connector). If *PP* indicates a capacity incompatible with the nominal cable, the rating migrates. for signaling (resistor correction or cable replacement). If the negotiation times are anomalous and Authorization messages fail in *DC,* with evidence of invalid certificates, the class is communication (and the *remedy* is key governance and coordinated updating). If the OCPP registers Remote shutdown command in specific windows, the class is *backend* (and the fix is policy). The general rule is to avoid compound labels; when two layers appear to be in use, priority should be given to the one that... that initiates the chain of events, not the one that "only reacts".

A methodology that aspires to be scientific needs to declare threats to its validity and how... It mitigates. There are construct threats (imperfect *CP/ PP* measures in low-cost instruments). which are reduced through cross-calibration between devices and uncertainty documentation. There are threats. internal (firmware effects that change silently during the collection cycle), mitigated by Freezing versions during the campaign or through strict logging of updates between rounds. There are external threats (generalization to other vehicle models or other networks) that require diversified sampling and, above all, the publication of the data scheme so that meta-analyses incorporate results from multiple groups. And there are threats to the conclusions (experimenter bias). (interpreting *logs),* which can be addressed with double-blind reading of events by evaluators. independent and with the publication of classification rules prior to analysis.

Finally, the ethical and openness dimension is not secondary. When *logs* include User identifiers or data that could track individuals must be strictly anonymized, and If necessary, submission to research ethics committees. The same applies to certificates and keys. The research should not expose cryptographic materials that compromise operational security.

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Conversely, as much of the artifact as possible should be public: data schema, glossary, *scripts.* analysis, classification criteria, and samples of synthetic *logs* that preserve semantics. This Openness is a necessary condition for the area to cease being a mosaic of isolated accounts and become... to create a cumulative body of evidence on recharge interoperability.

In short, the proposed instrument is not a "black box" for finding culprits, but A transparent method for testing causal hypotheses in a sociotechnical system. By imposing order. By applying layers and discipline to measurements, it renders ad hoc explanations refutable and establishes standards — so often treated as bureaucracy — at the heart of a reproducible scientific practice. In the chapter Next, we present empirical results and analyses that illustrate how the artifact distinguishes, with operational precision, similar symptoms arising from distinct mechanisms, and how small interventions — a suitable cable, a PWM correction, a certificate renewal, the Changes to a backend policy translate into measurable gains in robustness.

Chapter 5 — Results and Analysis

The following results are from controlled campaigns in *AC* and *DC recharging,* with Minimum repetition of three sessions per condition, station log recording, firmware identification. and environmental conditions. The empirical design prioritized reproducibility: each session has *timestamp,* and the inferred causal chain is always linked to measurable evidence in the layers. defined in previous chapters.

I'll start with a scenario that, at first glance, seemed banal: "connect and limit" in *AC.* In At a 22 kW power station, several vehicles persistently stabilized between six and ten amperes, still that the installation could handle higher currents. Physical inspection revealed no damage to the connector — Firm latches, absence of polymer odor, and visually intact pins. Thermal phenomenology This confirmed the finding: temperature peaks remained low throughout the session, which This allowed us to rule out *derating* due to heating. The picture changed when we moved to the layer Signaling standard (IEC/ABNT NBR 61851): the *PP* "declared" a capacity lower than the nominal capacity of cable, and the *CP* advertised, with a consistent *duty cycle ,* a current ceiling compatible with that "cable". "small". Replacing the cable with another one with compatible *PP* and checking the *PWM* stabilized it. The behavior changed immediately. The time until the *handshake,* which was around four The time frame decreased slightly, and the success rate jumped from about eight out of ten sessions. for virtually all attempts. Here, what seemed like a "car defect" turned out to be a Nonconformity in the analog layer: when CP/PP tell the right story, the session ceases to be... to drift in low currents.

The second pattern emerged in *DC:* sessions that started, transferred energy until something in Around twenty percent of the SoC would crash with generic messages to the user. The physical examination

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No abnormal heating of the pins or loss of contact was identified; attention therefore shifted, for high-level communication *(ISO* 15118). The *logs* revealed longer negotiation times. more than expected and repetitive behavior — three attempts to complete the cycle before the Interruption. By checking the status of the *Plug & Charge certificates,* we found a clue. unequivocal: validity expired in the station's local repository. Chain renewal and update. The *firmware* update corrected the sequence. The time to *handshake,* previously close to eight seconds, has decreased. to just over five; the rate of completed sessions approached 100%, and interruptions They have become residual. The lesson here is methodological: without looking at HLC and governance of Keys, this type of failure disguises itself as an "electrical problem" when, in fact, it is in the domain of cryptographic and temporal protocol.

The third set of findings dealt with the most socially controversial phenomenon: "it works in "Operator X, Operator Y fails." Maintaining the same vehicle, cable, and station combinations, the Sessions were completed at X and interrupted at Y. The physical and signaling layers remained. stable in both environments, and *ISO* 15118 completed the *handshake* in Y before the session was over. aborted. What the OCPP logs showed, however, left no doubt: remote commands of Limitation and closure during specific tariff windows in Y; absent in X. After the policy reconfiguration on the Y — power profile adjustments and *smart charging* review —, the The behavior converged toward that of X. The experimental gain was clear: more sessions completed, Fewer interruptions, without any hardware changes. The implication is central to the research: the *Backend* is not noise — it's an independent variable that needs to be controlled or, at the very least, recorded. and interpreted as such.

Finally, we examined intermittent RCD/GFCI firing in *AC* when increasing the current. This is one of those cases where taxonomy prevents shortcuts. The hasty replacement of the connector It would have been a waste. The physical inspection was clean; the *CP* reading showed stability. The marginal *PWM signal* under load, and the ground reference showed atypical noise, in an arrangement with High-sensitivity differential device. The confirmatory test — repeat the sessions with grounding. Dedicated and properly specified RCD — eliminated the tripping. The causal mechanism, therefore, The problem lay in an interaction between power quality and *IEC* 61851 signaling , and not in the vehicle itself. From a methodological point of view, the gain lies in tying symptoms, measurements, and decisions together in one line. continuous, without explanatory leaps.

In aggregate terms, the layered intervention produced three robust effects. First, the time until the *handshake* was reduced : what, on average, took about six seconds under baseline conditions, it began to occur below five after the corrections. especially in scenarios where *ISO* 15118 and authorization policies were the bottlenecks. According to the rate of completed sessions rose from around 80% to close to 96%, and

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Interruptions per 100 sessions dropped from nearly thirty to single digits. Third, in *AC* sessions standardized, the temperature of the pins at the peak decreased from something like sixty-something degrees to the A range below fifty is an indirect sign that worn cables and connectors need replacing. This reduced contact resistance and therefore the risk of thermal *derating .* It was also observed that... Shift in the distribution of causes: failures originally concentrated in signaling and Communication issues became residual after simple fixes — correct *PP ,* consistent PWM, Valid certificates—and the *backend* contribution decreased sharply when the policies They were made explicit and compatible with the usage profiles.

Some cross-sectional patterns deserve highlighting. The temporal signature of events — anomalous trading times, repeated attempts, drops in regular SoC windows — It proved to be a reliable discriminator between communication and signaling problems: even Without decoding the full content of the messages, the rhythms of the process reveal the mechanism. In *AC, CP/ PP* form the foundation; when they are consistent and the temperature is cold, it rarely makes sense. Blame the vehicle. In *DC,* PnC governance is often the weak link: expired certificates and Misaligned versions generate errors that only become visible when correlating local logs and states of authorization. And, in all scenarios, treat *OCPP* as a potential cause, not as a black box. He avoided jumping to conclusions: the behavior of a station "alone" and "on a network" can be fundamentally different.

These gains do not negate the limitations of the study. Low-cost instruments for reading. Measuring *CP/ PP* and surface temperature introduces uncertainty; we mitigate this with calibration. Cross-referencing and repetition. Generalization to other brands and versions requires larger samples and, Ideally, interlaboratory cooperation. There is also the risk of silent *firmware* updates. Because the behavior changes between rounds, we version each session and log the changes. *Software* changes are included as part of the data. Finally, the interpretation of *logs* is susceptible to bias. We minimize this with classification rules published before analysis and independent readings when Disagreements arose.

Taken together, the results validate the causal taxonomy and the layered instrument: Similar symptoms had different origins, and minor interventions — a cable with the correct PP, a Stable PWM, certificate renewal, remote policy review—these yielded gains. proportional in robustness and predictability. More than just resolving isolated cases, the process He transformed a collection of anecdotes into a measurable narrative, in which each layer has a defined role, each measure has clear semantics, and each decision leaves a verifiable trace. That is the grammar. common ground that underpins, in the following chapter, the discussion of the scientific and normative implications: how convert the findings into better compliance tests, more realistic academic benches and Databases that allow, finally, a comparison of interoperability with the precision that the subject demands.

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Chapter 6 — Discussion: scientific and normative implications

The results described in the previous chapter support a simple yet powerful thesis: a Interoperability is a layered problem and, as such, should be addressed by tools of investigations that respect the causal relationship between them. When research ignores this architecture, Similar symptoms are interpreted as generic "electrical" phenomena, and specific solutions. — swapping cables, blaming the vehicle, restarting the station — these things end up masking the underlying mechanisms. fundamentals. Layered reading, on the other hand, explains the variability that intrigues users and operators and, in doing so, creates opportunities for standardization, certification, and comparison between studies.

There are three levels of direct involvement:

The first implication is normative: IEC 62196 (connectors and thermal limits), IEC/ABNT NBR 61851 (signaling and control), ISO 15118 (HLC and *Plug & Charge)* and OCPP (telemetry and Network policies can — and should — be articulated in test cases that capture the dynamics. observed in the field. What the cases show is that "paper" compliance is not enough: it is necessary rehearse transitions (current increase, trading *timeouts ,* certificate renewals, commands) remote tests in time windows). Tests that only measure the steady state miss the points of most frequent fractures. Thus, it is proposed that interoperability events and laboratories of certifications incorporate timed scenarios and thermal signatures as primary elements. class, documenting handshake times , PWM stability, CP/PP coherence and responses to OCPP policies.

The second implication is methodological: structured logs are not props; they are data. primary factors. Without them, the science of interoperability remains anecdotal. The discipline gains when Researchers publish (anonymized) event trails with timestamps, versions of *firmware* and status codes. These records allow for independent replication, as well as analysis. secondary studies that test the robustness of hypotheses under other criteria (by vehicle, by station, by (operator). A practical consequence is the need for a common minimum data schema: field names, glosses and conventions for marking the beginning, authorization, negotiation, transfer, Interruption and closure. The gain is twofold: it paves the way for meta-analyses and accelerates the transition. from case study to cumulative evidence

Interoperability is not just "socket engineering"; it crosses the physics of contact. Signaling electronics, communication protocols, and key governance. Curricula and workbenches. Academics who keep these areas in silos reproduce the problem that the research seeks to solve. The findings indicate that integrated test benches — with *CP/ PP* reading , HLC log capture, agent OCPP testing and thermometry equipment — can be assembled with sufficient non-proprietary instruments. to reproduce a large part of the field phenomena. The marginal investment (time and organization) It yields disproportionate gains in clarity: the "heads or tails" of blaming the vehicle or the charger.

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gives way to testable hypotheses.

There are also cross-cutting implications:

Information security is no longer a peripheral issue. *Plug & Charge* and its... Certificates introduce a layer of risk that manifests as "recharge failure"—therefore, Key lifecycle practices and validity auditing need to migrate from IT teams to the... experimental design.

Power quality is back at the center of the debate in *AC:* ground noise, sensitivity of RCD/GFCI and *PWM* stability explain interruptions that, in common perception, are "whims". of the vehicle". Including controlled variations in grounding and differential protection in tests brings Realism and accurate diagnosis.

Politics as an experimental variable: without considering *OCPP* and its remote actions, We confuse network decisions with hardware defects. The counter-proof (isolated vs. connected mode) It should be part of the protocol.

In summary, the results not only validate the causal taxonomy and the instrument by layers; they reposition the problem. Instead of looking for a single culprit, the scientific agenda It begins to build evidence-based compatibility between laboratories: same definitions, same metrics, same regulatory frameworks. This allows the field to move from isolated reports to baseline data. quantitative data, capable of informing both the evolution of norms and public policies for charging infrastructure.

Conclusion

This work stemmed from a pragmatic observation — "sometimes it connects but doesn't load; sometimes Sometimes it charges and then drops" — and treated it as a scientific object, not as a user complaint. For Therefore, interoperability was organized into four layers — physical *(IEC* 62196), signaling (IEC/ABNT NBR 61851), communication *(ISO* 15118) and *backend (OCPP)* —, a was proposed A taxonomy of failures aligned with these milestones was developed, and a methodological artifact was constructed to guide the... Diagnosis based on measurable hypotheses. Case studies have shown that symptoms indistinguishable from At first glance, they conceal distinct mechanisms and minor interventions — a cable with *PP.* Correct, a stable *PWM ,* certificate renewal, and remote policy review—produce Significant gains in robustness: reduced time to *handshake,* increased number of completed sessions, Reduced interruptions and less thermal stress on contacts.

From a regulatory standpoint, the contribution lies in making families operational. IEC/ISO/ABNT/SAE and *OCPP* in test criteria that reflect reality: measuring transitions, timing and responding to commands, instead of just checking static states. From the point of view of From a methodological point of view, the defense is unequivocal: structured logs and common data schemas are...

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indispensable for reproducibility and comparison. From a disciplinary point of view, the proposal is pedagogical: to train researchers who navigate between the physical, the analog, the digital and the organizational with a common language.

As for the research agenda, three tracks seem promising. First, public *benchmarks.* of anonymized *datasets* , with annotations by layer and temporal events, for comparison interlaboratory. According to open collection and analysis tools *(HLC-compliant sniffers* , agents Laboratory *OCPP* , *PWM CP/ PP validators),* which prevent capture by proprietary solutions. Third, stress tests that bring the workbench closer to the street: variations in ambient temperature, Simultaneous load, degraded power quality, and dynamic grid policies.

Interoperability of recharge is not a destination; it is a cumulative practice. By offering a a unified normative model, a low-cost diagnostic pipeline, and a fluid narrative that connects From symptoms to mechanisms, this article aims to contribute to the advancement of the field with conceptual clarity, empirical precision, and a shared language. It is in this convergence—between rigor and utility—that Academic research can accelerate the maturity of the charging ecosystem, making "plug and play" easier. "To carry" is as reliable as it appears to be.

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