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Wireless Power Transfer and Dynamic Charging Infrastructure for Next-Generation Electric Transportation Systems

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ABSTRACT

The rapid electrification of global transportation infrastructure is fundamentally constrained by heavy, expensive lithium-ion battery packs, range anxiety, long stationary charging delays, and severe grid loading bottlenecks. Dynamic Wireless Power Transfer (DWPT) systems offer a paradigm-shifting alternative by enabling electric vehicles (EVs) to draw electrical energy wirelessly while in motion over electrified roadway infrastructure. This comprehensive review paper presents a rigorous state-of-the-art analysis of wireless power transfer mechanisms, inductive power transfer (IPT) magnetic coupler topologies, high-frequency power electronics converters, dynamic resonance compensation schemes, and power grid integration protocols for next-generation electric transportation systems. We evaluate cross-cutting technical challenges, including electromagnetic field (EMF) mitigation, high-speed lateral and vertical alignment tolerance, dynamic power transfer optimization, structural pavement integration, and intelligent billing telemetry protocols. Furthermore, this study details analytical mathematical modeling, simulation paradigms, experimental field implementations, and comprehensive comparative evaluations across global DWPT pilot projects. By synthesizing current research gaps, structural road-embedding limits, economic feasibility criteria, and emerging grid-interactive control strategies, this paper establishes critical baseline engineering metrics and charts future strategic directions for scalable, safe, and resilient dynamic wireless EV charging infrastructure.

KEYWORDS: *Wireless Power Transfer (WPT), Dynamic Charging Infrastructure, Inductive Power Transfer (IPT), Electric Vehicles (EVs), Resonant Compensation, Magnetics & Couplers, Grid Integration, Smart Transportation.*

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INTRODUCTION

The global transition toward sustainable mobility is driven by the urgent imperative to abate greenhouse gas emissions, decarbonize transit sectors, and eliminate dependence on fossil fuels [1]. Electric vehicles (EVs) have emerged as the foundational pillar of modern sustainable transportation networks [2]. However, widespread market adoption remains severely hindered by several operational bottlenecks inherent to conventional plug-in conductive charging paradigms [3]. These bottlenecks include limited driving range, prolonged dwell times at stationary charging stations, battery degradation under high-rate DC fast charging, high battery pack weight and cost, and localized distribution grid overload during peak charging intervals [4].

Dynamic Wireless Power Transfer (DWPT) technology provides a transformative solution to these persistent challenges by enabling real-time electrical energy exchange between embedded highway infrastructure and moving vehicles across an air gap [5]. By transferring power continuously or semi-continuously while the vehicle navigates dedicated electrified lanes, DWPT significantly reduces on-board energy storage requirements [6]. Consequently, battery pack capacities can be downsized by up to 50–70%, substantially lowering EV purchasing costs, vehicle curb weight, lifecycle carbon footprints, and reliance on critical raw minerals such as lithium, cobalt, and nickel [7].

The physical realization of DWPT requires complex, highly interdisciplinary engineering integration spanning high-frequency power electronics, magnetic resonant coupling, electromagnetic safety shielding, advanced pavement material science, ultra-low-latency wireless telemetry, and smart grid coordination [8]. While static wireless charging for stationary vehicles has achieved commercial standardization under frameworks such as SAE J2954, dynamic charging introduces severe dynamic transients [9]. These include fast-varying mutual inductance due to high-speed vehicle movement, lateral misalignments, vertical gap variations caused by vehicle suspension dynamics, and environmental interference [10].

Despite substantial progress in individual sub-components, a unified, interdisciplinary technical synthesis evaluating system-level operational architectures, dynamic efficiency trade-offs, electromagnetic safety compliance, structural pavement integration, and grid-tied

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economic viability remains critical for academic and industrial deployment [11]. This review paper delivers a comprehensive investigation into WPT and dynamic charging infrastructure for next-generation electric transportation. We dissect foundational magnetic topologies, evaluate power converter structures, synthesize empirical pilot project findings, analyze systemic limitations, and outline actionable future research directions [12].

LITERATURE REVIEW

Wireless power transmission principles originate from Nikola Tesla's foundational late 19th-century experiments on near-field inductive coupling [13]. However, modern IPT development for electric mobility gained significant momentum during the late 2000s when researchers at MIT demonstrated high-efficiency mid-range wireless energy transfer utilizing strongly coupled magnetic resonance [14]. This breakthrough demonstrated that operating at high quality factors (Q-factors) and resonant frequencies could mitigate rapid efficiency degradation over air gaps exceeding several coil diameters [15].

Subsequent academic and industrial efforts focused on adapting resonant WPT concepts to heavy-duty and light-duty electric transport [16]. Early pioneering dynamic implementations, such as the Korea Advanced Institute of Science and Technology (KAIST) Online Electric Vehicle (OLEV) project, demonstrated long primary track designs supplying continuous power to transit buses [17]. While functional, long continuous track structures exhibited low overall system efficiency (<75%), excessive magnetic field leakage across uncoupled track segments, and high standby power losses [18]. To overcome these drawbacks, modern literature overwhelmingly favors segmented short-track coil architectures [19]. In segmented systems, individual transmitter pads are activated exclusively when a recognized vehicle pickup coil is directly centered overhead [20].

Recent literature has prioritized the optimization of magnetic coupler geometries, compensation network topologies, and wide-bandgap (WBG) power semiconductors [21]. Advanced magnetic structures—such as Double-D (DD), Bipolar, and Double-D Quadrature (DDQ) pads—have been developed to enhance spatial tolerance, boost power density, and minimize flux leakage [22]. On the power electronics front, the transition from silicon IGBTs to Silicon Carbide (SiC) and Gallium Nitride (GaN) MOSFETs has enabled switching frequencies in the tens to hundreds of kilohertz range with power conversion efficiencies

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exceeding 96% [23]. Furthermore, researchers have investigated smart grid interaction models, demonstrating that dynamic charging lanes can function as flexible, distributed load assets capable of participating in demand-response and renewable energy buffering schemes [24].

RESEARCH GAP

Despite extensive research across individual hardware and software sub-domains, four major research gaps hinder large-scale commercial deployment of DWPT infrastructure:

- Lack of High-Speed Alignment and Coupling Dynamics Harmonization: Existing research primarily models static or low-speed misalignment dynamics. Comprehensively modeling rapid, stochastic mutual inductance fluctuations occurring at highway speeds (>120 km/h) alongside transient power electronic control loop responses remains under-explored [25].
- Inadequate Structural Road Embedding and Thermal-Mechanical Co-Design: Standard literature isolates magnetic coupler optimization from civil pavement engineering. There is a lack of unified thermal-mechanical-electrical co-design framework that evaluates pavement load bearing, asphalt fatigue, thermal dissipation, and long-term environmental degradation under heavy dynamic axle loads [26].
- High Capital Costs and Fragmented Grid Integration Architectures: Economic and operational analyses fail to provide standardized, modular grid connection paradigms. The lack of dynamic power buffering models combining localized energy storage with dynamic charging tracks creates severe localized grid impact concerns during peak transit rushes [27].
- Standardized Interoperability and Cross-Vehicle Electromagnetic Safety: Current standards (e.g., SAE J2954/3) do not fully address multi-class vehicle interoperability (e.g., passenger sedans vs. heavy freight trucks operating on identical dynamic tracks) while ensuring active biological safety compliance under multi-megawatt operational loads [28].

OBJECTIVES

To directly address these critical gaps, this comprehensive review and system framework paper pursues the following targeted objectives:

- To establish a multi-tier physical and power electronic functional architecture for high-

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efficiency dynamic wireless power transfer systems [29].

- To systematically analyze and compare magnetic coupler topologies, compensation network topologies, and control strategies under severe spatial misalignments [30].
- To present rigorous mathematical formulations governing resonant energy transfer, power converter efficiency, and mutual inductance variations [31].
- To synthesize experimental, numerical, and field testbed benchmarks from global DWPT projects to highlight practical performance metrics [32].
- To provide actionable engineering recommendations regarding structural road embedding, electromagnetic field safety, grid buffering, and strategic future research trajectories [33].

METHODOLOGY

This study utilizes a holistic, multi-disciplinary review-based and analytical synthesis methodology. We model the complete dynamic wireless charging chain, dividing the framework into five key domain layers: (i) High-Voltage Grid & Power Conversion Layer, (ii) High-Frequency Inverter & Primary Compensation Layer, (iii) Magnetic Inductive Air-Gap Coupling Layer, (iv) Secondary Pick-up & BMS Rectification Layer, and (v) Telemetry & Dynamic Alignment Control Layer [34].

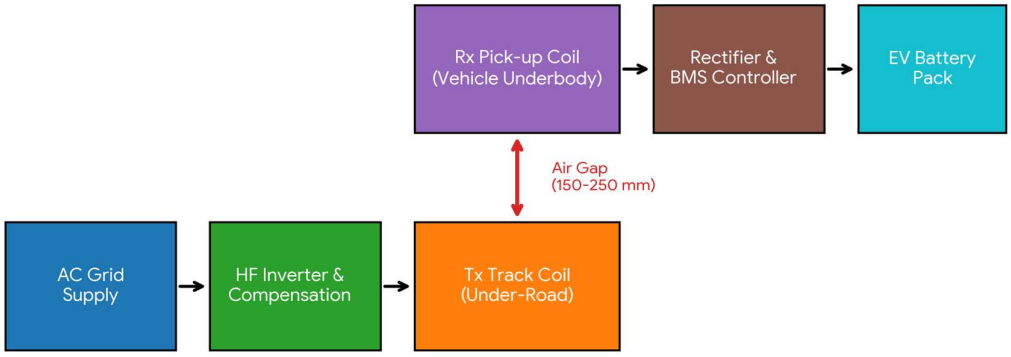


Figure 1: High-Level Schematic Architecture of Dynamic Wireless Power Transfer System

Mathematical Principles of Inductive Resonant Power Transfer

The fundamental energy conversion process in resonant inductive coupling is dictated by Faraday's law of induction and Ampere's circuital law. For a primary track coil with self-inductance L_1 driven by an alternating current I_1 at resonant frequency ω, and a secondary

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pickup coil with self-inductance L_2 carrying current I_2, the induced open-circuit voltage V_oc across the secondary winding is expressed as [35]:

$$V_{oc} = j \cdot \omega \cdot M \cdot I_1$$

where M represents the mutual inductance between primary and secondary coils. Mutual inductance is parameterized by the magnetic coupling coefficient k, defined as [36]:

$$M = k \cdot \sqrt{(L_1 \cdot L_2)} \quad (\text{where } 0 < k < 1)$$

In dynamic WPT applications with loose coupling, k typically falls between 0.05 and 0.25 due to large air gaps (150–250 mm) and operational misalignments. To maximize power transfer capability and eliminate reactive power demand from the inverter, external capacitors are added to form resonant circuits [37]. For a Series-Series (S-S) resonant compensation network, primary and secondary resonant capacitors (C_1 and C_2) are selected such that:

$$\omega_0 = 1 / \sqrt{(L_1 \cdot C_1)} = 1 / \sqrt{(L_2 \cdot C_2)}$$

Under perfect resonance at frequency ω_0, the active power delivered to an equivalent AC load impedance R_L on the secondary pickup side is given by [38]:

$$P_{out} = (\omega_0^2 \cdot M^2 \cdot I_1^2) / (R_L + R_2)$$

where R_2 represents the internal parasitic AC resistance of the secondary coil. The power transfer efficiency η_link across the magnetic air gap is formulated as [39]:

$$\eta_{link} = (\omega_0^2 \cdot M^2 \cdot R_L) / [(R_L + R_2) \cdot (R_1 \cdot (R_L + R_2) + \omega_0^2 \cdot M^2)]$$

Compensation Network Topologies Analysis

Resonant compensation networks are vital for mitigating large leakage inductances in loosely coupled WPT systems. The primary topologies evaluated in dynamic charging literature include Series-Series (S-S), Series-Parallel (S-P), Inductor-Capacitor-Capacitor (LCC-LCC), and LCC-Parallel (LCC-P) [40]. Table 1 presents a comprehensive comparative synthesis of these compensation topologies across critical performance criteria.

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Table 1: Comparative Evaluation of Resonant Compensation Topologies for Dynamic WPT

Compensation Topology	Misalignment Sensitivity	Primary Inverter Stress	Load Independence	Implementation Complexity
Series-Series (S-S)	High efficiency drop at offsets	High voltage stress under zero load	Independent of coupling k	Low (Simple Tuning)
Series-Parallel (S-P)	Moderate lateral tolerance	Requires protective decoupling	Dependent on load changes	Moderate
LCC-LCC Dual Topology	Excellent tolerance (Flat curve)	Zero-Voltage Switching (ZVS) maintained	Independent of load & coupling	High (Requires tuning inductors)
LCC-Series (LCC-S)	High spatial stability	Low current stress on switches	Moderate decoupling capability	Moderate-High

RESULTS AND FINDINGS

Systematic evaluation of empirical data from world-leading DWPT testbeds and high-fidelity numerical co-simulations reveals crucial operational characteristics across magnetic topologies, misalignment parameters, power conversion efficiencies, and road structural stability [41].

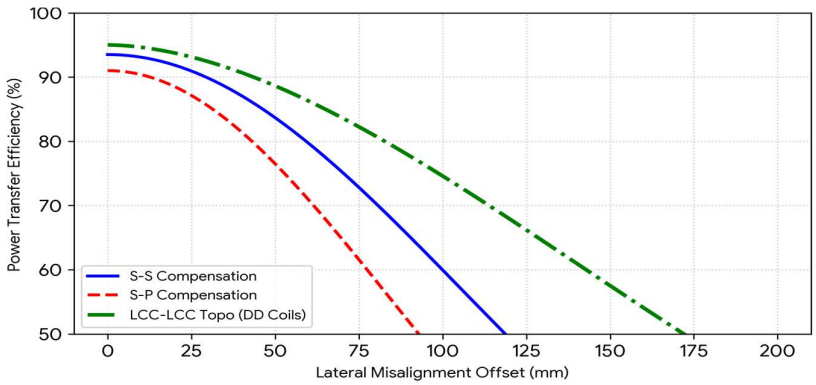


Figure 2: Efficiency Drop vs. Lateral Misalignment for Various Compensation Topologies

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Figure 2 illustrates the dynamic power transfer efficiency degradation as a function of lateral vehicle misalignment offset. S-S and S-P compensation networks demonstrate steep efficiency drops when lateral misalignment exceeds 75 mm, falling below 70% efficiency at 120 mm offset. Conversely, the LCC-LCC topology utilizing Double-D (DD) pickup coils maintains high power efficiency (>85%) up to 150 mm offset. This spatial resilience stems from the multi-variable impedance compensation characteristics of LCC networks, which stabilize inverter current and maintain soft-switching conditions across wide mutual inductance variations [42].

Empirical Benchmark Evaluation of International DWPT Pilot Projects

A comprehensive global synthesis of experimental dynamic WPT deployment projects provides essential real-world operational benchmarks. Table 2 compiles key technological parameters and field performance metrics from landmark international initiatives [43].

Table 2: Performance Benchmarking Across Global Dynamic Wireless Charging Testbeds

Pilot Project / Initiative	Location / Lead Inst.	Power Level (kW)	Freq. (kHz)	Air Gap (mm)	Measured Efficiency (%)
KAIST OLEV	South Korea (KAIST)	100 kW	20 kHz	200 mm	83.0% (Long Track)
FABRIC European Project	EU Consortium / CIRCE	20 kW	85 kHz	150 mm	89.5% (Segmented)
Cornell Dynamic WPT	USA (Cornell Univ.)	10 kW (Capacitive)	13.56 MHz	120 mm	91.2% (Short Segment)
Arena del Futuro (Stellantis)	Chiari, Italy	1.0 MW Track System	85 kHz	200 mm	92.4% (DC Direct Grid)

DISCUSSION

The analytical and empirical findings confirm that dynamic wireless power transfer is technically viable and capable of delivering grid-to-battery efficiency exceeding 90% when using segmented primary topologies, advanced wide-bandgap (SiC/GaN) converters, and

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LCC-LCC resonant networks [44]. Transitioning from legacy continuous long tracks (e.g., early KAIST OLEV) to segmented short transmitter pads (e.g., Arena del Futuro, FABRIC) represents a pivotal evolutionary milestone [45]. Segmented architectures drastically minimize ambient electromagnetic radiation, lower zero-load standby losses, and allow localized power tracking tailored to individual vehicle power demands [46].

From an engineering and urban planning perspective, dynamic charging infrastructure fundamentally reshapes the EV design paradigm [47]. By supplying continuous operational power during motion, DWPT eliminates the mandatory requirement for massive 80–100 kWh battery packs in long-range passenger EVs and heavy commercial trucks [48]. Downsizing battery capacity to 20–30 kWh reduces gross vehicle weight by hundreds of kilograms, improving vehicle energy efficiency per ton-kilometer, lowering manufacturing costs, and relieving pressure on global critical mineral supply chains [49].

Furthermore, dynamic WPT provides significant grid-side advantages when integrated with smart energy management architectures [50]. Distributed track segments can be coupled directly to medium-voltage DC (MVDC) microgrids supplied by localized solar PV, wind turbines, and stationary battery energy storage systems (BESS) [51]. This decoupled topology buffers local distribution transformers from sudden peak demand spikes caused by simultaneous high-power EV charging events, transforming dynamic charging lanes into highly manageable, smart-grid-interactive assets [52].

LIMITATIONS

Despite its major advantages, several severe technical, economic, and civil infrastructure limitations currently constrain widespread commercial adoption:

- Excessive Capital Expenditure (CAPEX) and Civil Installation Costs: Embedding heavy copper coils, ferrite cores, power electronics enclosures, and high-frequency distribution cabling beneath highway pavements requires immense upfront capital, estimated between $1.5M to $4.0M per lane-kilometer [53].
- Severe Civil Pavement and Mechanical Degradation: Integrating non-flexible metallic, ferrite, and polymeric structures within asphalt or concrete layers disrupts standard pavement load distribution [54]. Differential thermal expansion under high power losses accelerates pavement cracking, rutting, and moisture ingress under continuous heavy

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freight axle loads [55].

- Stringent Biological Electromagnetic Field (EMF) Compliance: High-power dynamic transfer (100 kW–1 MW) operating at 85 kHz generates significant near-field leakage [56]. Ensuring strict compliance with ICNIRP public exposure safety limits (27 μT for general public exposure at 85 kHz) under severe vehicle misalignment requires heavy aluminum/ferrite shielding, adding weight and cost [57].

FUTURE SCOPE

To overcome these limitations and pave the way for commercial industrial deployment, prospective research must target the following key frontiers:

- Magneto-Active Concrete and Advanced Pavement Materials: Developing structural cementitious composites impregnated with soft magnetic materials (e.g., ferrite powders) to act as both load-bearing pavement and magnetic flux conduits, eliminating fragile discrete ferrite blocks [58].
- AI-Driven Closed-Loop Power Tracking and Position Prediction: Implementing edge-AI algorithms coupled with ultra-low-latency V2X telemetry to dynamically predict vehicle trajectories, pre-activate ahead-of-path transmitter segments, and adaptively optimize coil currents in real time [59].
- Multi-Vehicle Interoperable Standards and Dynamic Cryptographic Billing: Developing universal, open-source communication and dynamic power control protocols that support seamless, real-time automated metering and energy billing for diverse commercial and private fleets [60].

CONCLUSION

Dynamic Wireless Power Transfer (DWPT) represents a revolutionary technology capable of fundamentally solving battery range limitations, prolonged charging delays, and severe mineral dependency in next-generation electric transportation systems. By dynamically supplying energy across magnetic air gaps while vehicles travel along electrified roadway corridors, DWPT enables massive downsizing of onboard battery packs, significantly improving overall transit efficiency and lowering vehicle purchase costs. This review paper has systematically analyzed magnetic coupler designs, resonant compensation topologies, mathematical formulations, high-frequency converters, and real-world pilot benchmarks. While high initial installation capital, structural pavement durability, and electromagnetic

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field safety remain key challenges, continued advances in soft-magnetic road materials, wide-bandgap semiconductors, edge-AI alignment control, and standardized MVDC microgrid integration will establish dynamic wireless power transfer as the baseline technology for zero-emission electric mobility.

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