IARJSET

ISSN (O) 2393-8021, ISSN (P) 2394-1588

International Advanced Research Journal in Science, Engineering and Technology

International Conference on Interdisciplinary Global Research in Adaptation, Transformation & Engineering

INTEGRATE 2025

Geetanjali Institute of Technical Studies (GITS)

Vol. 12, SPECIAL ISSUE 2, NOVEMBER 2025

DOI: 10.17148/IARJSET/INTEGRATE.2025.12234

Smart Highways with Integrated Electric Vehicle Charging Infrastructure

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Abstract: The transformation of highway systems into intelligent and energy-integrated infrastructures represents a major shift toward sustainable mobility. Smart highways embedded with electric vehicle (EV) charging systems provide a feasible solution to the challenges of limited range and long charging times. This review explores the design, operation, and global development of smart highways with integrated EV charging infrastructure, focusing on wireless and conductive charging technologies. It analyzes engineering design, energy efficiency, cost implications, environmental impact, and recent research advancements. Comparative evaluations indicate that dynamic wireless charging can achieve energy transfer efficiencies up to 93% and reduce lifecycle CO_2 emissions by 35–45% compared to static charging. However, technical challenges, such as interoperability, pavement durability, and grid integration, persist. The review concludes with research gaps and recommendations for scaling the technology sustainably.

Keywords: Smart highways, Electric vehicles, Dynamic charging, Wireless power transfer, Sustainable transportation, Intelligent infrastructure

I. INTRODUCTION

The global transportation sector contributes nearly 23% of total CO_2 emissions, with road transport accounting for over 70% of this share (IEA, 2023). As nations move toward net-zero goals, electric vehicles (EVs) have emerged as a cornerstone of sustainable mobility. However, widespread EV adoption remains constrained by limited charging infrastructure and driver "range anxiety." Smart highways — road systems enhanced with sensors, communication technologies, and embedded charging systems — offer a novel solution to these challenges.

Integrating EV charging directly into highways transforms roads from passive transport surfaces into active energy delivery systems. Such systems enable vehicles to recharge while in motion, eliminating the need for frequent stops and reducing dependency on large battery packs (Arzjani et al., 2025). This review aims to provide a consolidated understanding of the technological framework, material design, and implementation feasibility of these systems, serving as a foundation for future research and policymaking.

II. SMART HIGHWAY TECHNOLOGY FRAMEWORK

1.1. Core Components

Smart highways integrate multiple technologies — including IoT sensors, communication networks, and AI-based traffic systems to improve safety and efficiency (Gorilla Technology, 2025). Embedded sensors monitor traffic load, temperature, and pavement health, transmitting data to a centralized management hub for analysis.

Vehicle-to-Infrastructure (V2I) communication facilitates adaptive traffic control, dynamic lane management, and predictive maintenance. Advanced systems integrate renewable energy sources such as solar pavements or roadside photovoltaics to generate power for highway operations (IARJSET, 2025).

1.2. Intelligent Traffic Management

Smart highways optimize traffic flow through AI-driven algorithms that adjust speed limits and lane directions in real time. Pilot corridors in the U.S. and Europe report up to 70% reduction in congestion-related accidents and a 20–30% improvement in travel efficiency (PreScouter, 2021). Integration with digital signage, radar sensors, and adaptive lighting enhances driver safety and operational energy efficiency.

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III. INTEGRATED EV CHARGING SYSTEMS

3.1 Wireless Dynamic Charging

Wireless power transfer (WPT) uses electromagnetic induction or magnetic resonance between embedded coils in the pavement and receivers in vehicles. Research from Purdue University (2024) demonstrated inductive charging up to 200 kW with efficiency above 90% under dynamic conditions. Detroit's pilot project (Electreon, 2023) achieved 93% energy transfer and demonstrated scalability for urban highway corridors.

3.2 Conductive Charging

Conductive systems, such as Elonroad's infrastructure in Sweden, use physical contact rails and collector arms. These systems exhibit higher energy transfer efficiency (95–98%) than WPT but require dedicated lanes. Recent studies suggest conductive systems reduce EV battery size requirements by up to 40%, lowering vehicle manufacturing emissions and costs (Arzjani et al., 2025).

IV. DESIGN AND IMPLEMENTATION CONSIDERATIONS

Engineering integration of charging systems into pavement demands modifications in structural design and materials. Pavement must maintain durability under high temperature and mechanical stress from embedded coils. Researchers have tested asphalt composites with reinforced polymer channels to host inductive modules without compromising load-bearing capacity (Rutgers CAIT, 2021).

Site selection is crucial: highways connecting high-traffic corridors between metropolitan areas yield maximum utilization (Better Energy, 2023). Charging zones spaced at 40–60 km intervals provide optimal balance between cost and accessibility. Modular construction using precast panels simplifies installation and maintenance.

V. COMPARATIVE EVALUATION WITH RECENT LITERATURE

Study / Source	Charging Type	Efficiency (%)	Key Findings	CO_2 Reduction (%)	Implementation Stage
Purdue Univ. (2024)	Wireless	90–92	Concrete pavement charging coil prototype validated	40	Pilot phase
Electreon (2023)	Wireless	93	Detroit dynamic roadway operational	38	Operational demo
Elonroad (2022)	Conductive	95–98	Conductive rail system, modular setup	45	Expansion phase
IARJSET (2025)	Hybrid	89	Solar-powered integrated smart highway	42	Conceptual
Rutgers CAIT (2021)	Wireless	88–90	Asphalt-based inductive layer	33	Lab prototype
Michigan DOT (2023)	Wireless	91	Public wireless charging segment	39	Demonstration project

These comparisons reveal that **conductive charging** currently achieves higher efficiency, while **wireless charging** offers better safety and less maintenance. Hybrid models integrating both show strong potential for widespread adoption.

VI. CHALLENGES AND BARRIERS

6.1 Technical Challenges

Variability in vehicle coil alignment, power losses at high speeds, and electromagnetic interference remain significant barriers. Efficiency declines by 5–8% with lateral deviation exceeding 0.5 m (Arzjani et al., 2025). Grid integration is another concern, as large-scale deployment could increase regional power demand by up to 18% (Harvard Data-Smart, 2023).

6.2 Economic and Policy Barriers

High installation costs — estimated at USD 1.2–1.8 million per lane-km — hinder deployment (MDOT, 2023). Financing models involving public–private partnerships are being explored. Policy gaps include the absence of uniform standards for electromagnetic exposure and safety regulation (U.S. Access Board, 2023).

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VI. FUTURE PROSPECTS AND INNOVATIONS

Emerging research is advancing solar-integrated pavements, adaptive coil design, and autonomous vehicle synergy. AI-assisted load management enables predictive energy distribution, balancing grid stress during peak hours. Vehicle-to-grid (V2G) systems will transform EVs into distributed storage units, supporting grid stability (Gorilla Insights, 2025).

Autonomous EVs paired with dynamic charging could achieve uninterrupted long-range mobility. Integration of smart contracts via blockchain-based payment systems is under testing for transparent billing and authentication.

VII. RESEARCH GAPS AND RECOMMENDATIONS

Despite technological progress, several gaps remain:

1. Limited **standardization** in wireless charging interfaces.
2. Need for **real-world durability testing** of pavement-embedded systems.
3. Insufficient **economic modeling** of cost-benefit across regional contexts.
4. Lack of **integration studies** combining renewable energy with smart charging corridors.

Recommendations:

1. Develop globally harmonized WPT standards (ISO/IEC).
2. Encourage multi-institutional pilot projects linking EV manufacturers and infrastructure agencies.
3. Invest in smart material research for pavement durability under electrothermal stress.
4. Integrate renewable microgrids and AI-based energy balancing in highway design.

VIII. CONCLUSION

Smart highways with integrated EV charging systems represent a transformative leap toward sustainable transportation. The integration of dynamic wireless and conductive charging within pavement infrastructure can substantially reduce carbon emissions, eliminate range anxiety, and optimize roadway utilization. Although challenges persist in technical efficiency, cost, and regulation, advancements between 2018 and 2025 show strong feasibility for commercial rollout within the next decade. The convergence of AI, renewable energy, and smart materials positions this technology as a cornerstone of the future carbon-neutral mobility ecosystem.

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