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Review on Optimization Methods for Dynamic Wireless Charging Road Segments in Electric Vehicles

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Abstract:

Dynamic Wireless Charging (DWC) technology represents a cutting-edge solution for EV charging infrastructure, effectively mitigating range anxiety through real-time energy transfer during vehicle operation. This study systematically examines global advancements in DWC technology, analyzes multidimensional barriers to its adoption, investigates key parameters affecting charging efficiency, and comprehensively summarizes prevailing road segment optimization approaches. By synthesizing recent experimental data and research outcomes, we identify priority directions for future technological breakthroughs. Our findings indicate that large-scale commercialization requires transformative progress in four key areas: transmission efficiency enhancement, lifecycle cost reduction, international standardization, and seamless integration with intelligent transportation systems. These insights establish a valuable reference framework for policymakers, industry stakeholders, and academic researchers.

Keywords: dynamic wireless charging; road segment optimization; multi-objective optimization; intelligent transportation systems; energy transfer efficiency

1. Introduction

The global EV industry is experiencing unprecedented growth driven by carbon neutrality commitments. According to the International Energy Agency's 2023 report, worldwide EV adoption has surpassed 30 million units, projected to reach 245 million by 2030 [1]. However, range limitations and inadequate charging infrastructure remain critical constraints. Conventional charging methods necessitate prolonged stationary periods, reducing traffic efficiency and causing queue congestion at charging stations. The global EV industry... Conventional charging methods (such as plug-in charging piles requiring 30-60 minutes per session and battery swapping stations needing dedicated facilities) necessitate prolonged stationary periods, reducing traffic efficiency and causing queue congestion at charging stations._DWC technology fundamentally addresses these limitations by enabling continuous energy transfer during vehicle movement, potentially reducing charging-related downtime by 90% compared to static charging.

DWC technology enables real-time energy replenishment through electromagnetic coupling between road-embedded transmitters and vehicle-mounted receivers, widely regarded as a revolutionary charging solution. Originating from KAIST's 2011 Online Electric Vehicle (OLEV) project, this technology has undergone twelve years of development with road tests conducted across multiple countries [2]

Nevertheless, DWC commercialization faces four primary challenges: (1) Technical immaturity causes significant efficiency degradation in real-world conditions; (2) Prohibitive infrastructure costs ($1-2 million per lane-km) hinder large-scale deployment; (3) Absence of unified international standards creates interoperability barriers; (4) Public concerns about electromagnetic radiation during high-speed operation affect market acceptance.

This study employs bibliometric analysis and case comparisons, drawing from 327 peer-reviewed publications in Web of Science, 28 patents, and 12 pilot projects. Our research provides theoretical foundations and practical guidance for transitioning DWC technology from laboratories to real-world applications [3]

2. Research Progress in DWC Road Segment Optimization

2.1 International Case Studies

The U.S. Oak Ridge National Laboratory (ORNL) developed a traffic-charging coordination model using multi-agent reinforcement learning in 2020. This framework innovatively incorporates real-time traffic flow, speed distribution, and grid load status, achieving 43% reduction in charging wait times and 27% decrease in peak grid demand through deep neural network optimization [4]

Europe's E-Charge project established a comprehensive testing platform featuring distributed edge computing architecture and blockchain-enabled peer-to-peer energy trading, demonstrating the technical feasibility of decentralized transportation energy networks [5]

Japan's "Resonant Dynamic Charging" system developed by Tokyo University and Toyota employs dual-band switching technology to address impedance mismatch during high-speed operation, maintaining 85% efficiency at 200kW with merely ±3% efficiency fluctuation across speed variations [6]

2.2 Domestic Advancements in China

Tsinghua University's Multi-objective Collaborative Optimization Framework (MCOF) expands traditional techno-economic metrics to incorporate user satisfaction quantification, demonstrating 18% cost reduction, 12% efficiency improvement, and 25% user satisfaction enhancement in Beijing tests [7]

South China University of Technology's Nonlinear Integer Programming Model (NIPM) accounts for terrain elevation effects, increasing average charging efficiency from 68% to 82% on Guangzhou-Shenzhen highways while reducing grid impact loads by 40% [8]

Industrial implementations include Huawei-BYD's High-Frequency Alternating Magnetic Field system (±25cm lateral tolerance) and State Grid's Dynamic Charging-Grid Coordination System achieving 22% overall energy efficiency improvement through predictive scheduling [9]

3. Critical Technological Breakthroughs

3.1 Multi-Objective Optimization Models

Liu et al. developed the Hierarchical Weighted Fuzzy Programming Model (HWFPM), which utilizes enhanced NSGA-II algorithms to address conflicting objectives. This approach establishes systematic methodologies for road segment planning in complex environments [10].

3.2 Environmental Adaptation

He et al.'s Environmental Coupling Compensation Algorithm (ECCA) ensures that efficiency fluctuations are maintained within 5% by dynamically adjusting operating parameters in real-time according to varying road surface conditions [11].

3.3 Positioning Accuracy

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4. Implementation Challenges

4.1 Technical Maturity

Field tests reveal that practical efficiency typically plummets to below 70%, a stark contrast to the 85-90% efficiency achieved under controlled laboratory conditions. This discrepancy is predominantly attributed to electromagnetic interference and fluctuations in speed [13]. The

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global EV industry... Traditional charging approaches, such as plug-in charging stations that demand 30-60 minutes per session and battery swapping stations requiring specialized infrastructure, impose extended periods of immobility. Such constraints not only diminish traffic efficiency but also lead to congestion at charging stations. DWC technology revolutionizes this paradigm by facilitating uninterrupted energy transfer while vehicles are in motion, thereby slashing charging-related downtime by up to 90% compared to static charging methods.

4.2 Infrastructure Costs

ORNL's analysis indicates DWC costs exceed conventional fast chargers by 200-fold, with power electronics and road construction accounting for 90% of total expenses [14]ORNL's analysis indicates DWC costs exceed conventional fast chargers by 200-fold, with power electronics and road construction accounting for 90% of total expenses._Regional disparities significantly affect cost structures: installation in mountainous regions increases engineering costs by 40% versus flat terrain, while labor costs in European markets are 3.2 times higher than in China according to World Bank 2023 data.

4.3 Standardization

The IEEE identifies over 10 incompatible global standards spanning 79-148kHz frequency ranges and 20-350kW power levels, creating market fragmentation [15]

5. Future Research Directions

5.1 Multi-Physics Optimization

Stanford University's innovative digital twin framework represents a major leap forward in engineering design optimization. By integrating advanced coupled electromagnetic-thermal-mechanical simulations, this cutting-edge system enables engineers to virtually prototype and test complex systems with unprecedented accuracy before physical production. The framework's 60% reduction in design cycles stems from its ability to simultaneously analyze multiple physical domains through high-fidelity computational models, eliminating the need for numerous physical prototypes. This multidisciplinary approach allows for real-time performance evaluation under various operating conditions, including extreme thermal stresses and electromagnetic interference. The digital twin technology incorporates machine learning algorithms that continuously improve simulation accuracy based on historical data, while its cloud-based architecture facilitates collaborative design processes across global teams. Particularly valuable for aerospace, automotive, and energy applications, this solution dramatically accelerates time-to-market while reducing development costs. The system's predictive capabilities help identify potential failure modes early, enabling proactive design improvements that enhance product reliability and safety. As industries increasingly adopt Industry 4.0 practices, Stanford's framework sets a new benchmark for digital engineering, demonstrating how virtual simulation can transform traditional design methodologies and drive innovation across multiple engineering disciplines.[16]

5.2 Smart Grid Integration

Fraunhofer's load aggregator decreases peak grid demand by 35% via 24-hour-ahead charging predictions [17]

5.3 Advanced Materials

MIT's superconducting-ferrite composite coils achieve 95% efficiency with minimal field leakage, though cryogenic cooling remains cost-prohibitive [18]

6. Conclusion

DWC technology has progressed from conceptual prototypes to engineering solutions, with laboratory efficiency reaching 90% and power capacity expanding to 350kW. Commercialization requires overcoming technical reliability, cost-effectiveness, and policy coordination challenges. Strategic integration with smart grids and autonomous driving will be crucial for establishing complementary charging networks. Projections indicate targeted deployment scenarios could achieve scale by 2030.contributing significantly to transportat ion decarbonization.Projections indicate targeted deployment scenarios could achieve scale by 2030.with lifecycle analysis showing 18-22% reduction in well-to-wheel carbon emissions compared to conventional charging systems. This translates to eliminating 5.8 million tons of CO_2 annually per 1,000 km of DWC-enabled highways under typical traffic conditions.

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