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The Sustainable Mobility and Electric Roadway Network

Mrs. Sarita Tiwari[1] Durgesh Kumar Rahthore[2] Noble Bandhade[3] Nikhil Dungdung[4] Priyanshu Sahu[5]
Shivam Kashyap[6] Vanshika[7]
Assistant Professor, Department of Engineering, Bhilai Institute of Technology, Durg, Chhattisgarh – 491001, India
Research Scholars, Bhilai Institute of Technology, Durg, Chhattisgarh – 491001, India

Abstract

This paper proposes a hybrid sustainable transportation framework integrating Electric Road Systems (ERS), inductive Wireless Power Transfer (WPT), and piezoelectric energy harvesting. A combined analytical–simulation model is developed to evaluate system performance under varying traffic conditions. MATLAB-based simulations and parametric analysis indicate that the hybrid system can improve net roadway energy utilization by 22.4% under high traffic density (≥1200 vehicles/hour/lane), with WPT efficiencies reaching 88% under optimal alignment. Economic analysis shows a payback period of 9.6 years for urban highways. The results demonstrate the feasibility of integrating energy-generating and energy-supplying road infrastructure for future smart cities.

Keywords — *Electric Road Systems (ERS), Wireless Power Transfer (WPT), Piezoelectric Energy Harvesting, Sustainable Transportation, Dynamic EV Charging, Smart Road Infrastructure, Energy Efficiency Optimization, Traffic-Based Energy Generation, Inductive Charging Technology, Hybrid Energy Systems.*

1. INTRODUCTION

The global transition toward electric mobility is increasingly constrained by persistent bottlenecks in battery capacity, charging infrastructure density, and energy distribution networks. These challenges create fundamental barriers to the widespread adoption of electric vehicles (EVs), particularly in developing urban corridors with high traffic density. Electric Road Systems (ERS) represent a paradigm shift in transportation energy delivery: rather than requiring vehicles to carry or store all their energy onboard, ERS enables dynamic wireless charging while vehicles remain in motion, substantially reducing dependence on stationary charging infrastructure.

In parallel, piezoelectric energy harvesting has emerged as a viable supplementary technology for smart road infrastructure. Piezoelectric materials embedded within pavement layers convert the mechanical stress generated by vehicular traffic into usable electrical energy. This energy, although supplementary in scale, can power roadside systems, contribute to the grid, or partially offset the energy demands of ERS operations.

Existing literature has predominantly treated these technologies in isolation. ERS research has focused on inductive coil design and coupling efficiency , while piezoelectric road studies have examined material composition and energy yield per vehicle pass . No unified framework has previously been proposed to evaluate the combined performance, economic viability, and environmental benefit of integrating both systems into a single smart roadway architecture.

This paper addresses this gap by proposing and evaluating a hybrid ERS framework that combines inductive wireless power transfer with embedded piezoelectric energy harvesting. A combined analytical–simulation model is developed using MATLAB/Simulink, enabling system performance evaluation under varying traffic densities, vehicle loads, and coil alignment conditions. The study further includes economic feasibility analysis and a comparative assessment against conventional road systems.

2. RESEARCH GAP AND MOTIVATION

A thorough review of existing literature reveals three critical gaps that this study aims to address:

- Absence of Integrated Models: Published studies treat ERS and piezoelectric road systems as independent technologies. No prior work has developed a unified simulation framework combining inductive charging with piezoelectric energy harvesting under real traffic conditions .
- Limited Traffic-Responsive Simulation: Existing simulations use static traffic parameters. The dynamic interaction between traffic density, vehicle load variation, and real-time energy output has not been adequately modelled .
- Insufficient Economic Feasibility Analysis: Most studies focus on technical performance without providing comprehensive cost-benefit analysis or payback period calculations specific to the Indian urban highway context .

These gaps collectively motivate the development of a hybrid simulation framework that is both technically rigorous and economically contextualized for urban deployment.

3. RESEARCH OBJECTIVES

primary objectives:

1. Develop a hybrid ERS energy model integrating piezoelectric harvesting and inductive wireless power transfer within a single unified framework.
2. Simulate traffic-dependent energy generation across a range of traffic densities (200–1500 vehicles/hour) and quantify energy output per kilometre of roadway.
3. Evaluate the wireless power transfer efficiency as a function of coil alignment and derive the efficiency–alignment relationship.
4. Assess overall system efficiency and compare the hybrid system against standalone ERS and conventional road infrastructure.
5. Conduct economic feasibility analysis, including installation costs, annual energy revenue, and payback period for urban highway deployment.
6. Evaluate the environmental impact in terms of CO_2 emission reductions and fossil fuel displacement.

4. METHODOLOGY

4.1 System Architecture

The proposed hybrid system architecture consists of four integrated subsystems: (i) embedded piezoelectric layers within the road pavement structure for mechanical-to-electrical energy conversion; (ii) inductive coil arrays for wireless power transfer to EVs in motion; (iii) a power conditioning and rectification unit for stabilizing and storing harvested energy; and (iv) a grid interface and energy storage system (ESS) for surplus energy distribution.

The system operates in a closed-loop energy cycle: vehicular traffic generates mechanical stress that activates the piezoelectric layers, producing electrical pulses that are rectified and stored. This stored energy supplements the inductive coil arrays to dynamically charge passing EVs, creating a semi-autonomous roadway energy network.

4.2 Mathematical Modeling

The analytical model is based on three interconnected governing equations that describe energy generation, traffic flow, and power transfer:

Piezoelectric Energy Model: The energy generated by a single piezoelectric sensor element under vehicular loading is expressed as:

$$\mathbf{E = \eta \cdot F \cdot d} \qquad \textit{(Equation 1)}$$

where: E *= Energy generated per sensor element (Joules)*
η *= Piezoelectric conversion efficiency (dimensionless, 0.20 – 0.35)*
F *= Compressive force applied by vehicle (Newtons, 3,000 – 8,000 N)*
d *= Mechanical displacement of sensor under load (metres)*

Traffic Flow Model: The vehicular traffic flow rate, expressed as the number of vehicles traversing the roadway segment per unit time, is given by:

$$\mathbf{Q = N / t} \qquad \textit{(Equation 2)}$$

where: Q *= Traffic flow rate (vehicles per hour)*
N *= Total number of vehicles in the measurement interval*
t *= Time interval (hours)*

Total Energy Generation: The aggregate energy generated per kilometre of roadway over one hour is:

$$\mathbf{E\_total = E \times Q} \qquad \textit{(Equation 3)}$$

Wireless Power Transfer Model: The instantaneous power transferred via inductive coupling between the road coil (primary) and vehicle receiver coil (secondary) is modelled as:

$$\mathbf{P = k \cdot \omega \cdot M \cdot I_1 \cdot I_2} \qquad \textit{(Equation 4)}$$

where: P *= Power transferred (Watts)*
k *= Magnetic coupling coefficient (0.0 – 1.0)*
ω *= Angular frequency of the coil excitation (rad/s, at 85 kHz per SAE J2954)*
M *= Mutual inductance between primary and secondary coils (Henries)*
I_1, I_2 *= Currents in primary and secondary coils respectively (Amperes)*

4.3 Simulation Setup

The complete hybrid system is simulated using MATLAB/Simulink R2023a, supplemented by ANSYS for structural stress analysis of piezoelectric layers and Microsoft Excel for numerical parameter sweeps. Table 1 summarises the simulation parameters.

Table 1: Simulation Parameters and Ranges

Parameter	Value / Range
Simulation Tool	MATLAB/Simulink R2023a
Traffic Range	200 – 1500 vehicles/hour/lane
Vehicle Load	3,000 – 8,000 N per vehicle
Piezo Efficiency (η)	20% – 35%

WPT Coupling Coefficient (k)	0.2 – 1.0
Coil Frequency (ω)	85 kHz (standard SAE J2954)
Alignment Factor Range	0.0 – 1.0 (full misalignment to full alignment)
Road Segment Length	1 km reference segment
Simulation Duration	1 hour per traffic density scenario

The simulation proceeds in sequential steps: (1) traffic input data is generated for the specified density range; (2) vehicle load is applied to the piezoelectric layer model; (3) energy generation is calculated using Equation 1 through 3; (4) wireless power transfer efficiency is simulated across alignment factors using Equation 4; and (5) hybrid system outputs are aggregated.

4.4 Evaluation Metrics

System performance is evaluated using four primary metrics that align with technical, economic, and environmental analysis goals:

- Energy output per unit roadway length (kWh/km) — primary measure of harvesting productivity.
- Wireless charging efficiency (%) — ratio of power received at vehicle to power transmitted from road coil.
- Installation and lifecycle cost (₹/km) — capital expenditure for full hybrid system deployment.
- Payback period (years) — time required for cumulative energy revenue to recover initial capital investment.

5. RESULTS AND ANALYSIS

5.1 Energy Generation vs. Traffic Density

Simulation results demonstrate a strongly linear relationship between traffic density and piezoelectric energy output in the range of 200 to 1000 vehicles/hour/lane, consistent with the proportional dependence described in Equation 3. At 200 vehicles/hour, the system generates approximately 2.8 kWh/km, rising to approximately 15 kWh/km at 1000 vehicles/hour. Beyond this threshold, efficiency saturation occurs due to inter-sensor interference and thermal dissipation effects in the piezoelectric material. The maximum recorded energy output of approximately 22.5 kWh/km is achieved at 1500 vehicles/hour under ideal conditions.

This non-linear saturation behaviour beyond 1000 vehicles/hour is a critical design consideration for deployment on urban arterial roads, where peak-hour traffic regularly exceeds this threshold. The result suggests that sensor grid spacing and material selection are important optimisation variables for high-density deployments.

Fig. 1 — Energy Output (kWh/km) vs. Traffic Density (vehicles/hour). Linear increase observed up to ~1000 vehicles/hour, followed by efficiency saturation at higher densities.

5.2 WPT Efficiency vs. Coil Alignment

The wireless power transfer efficiency shows a near-linear positive relationship with coil alignment factor across the full range (0.0 to 1.0). At perfect alignment (factor = 1.0), the system achieves a peak transfer efficiency of approximately 88%, consistent with values reported in recent high-performance inductive charging studies [14], [38]. Efficiency drops sharply at alignment factors below 0.4, falling below 40% — this is significant for real-world deployment as vehicle lane positioning varies dynamically.

This result underscores the importance of active coil alignment compensation or lane-marking guidance systems to maintain acceptable WPT efficiency in operational conditions. Integration with vehicle positioning systems or dedicated EV charging lanes would significantly improve the practical average efficiency beyond the theoretical peak.

Fig. 2 — WPT Transfer Efficiency (%) vs. Coil Alignment Factor. Peak efficiency of 88% achieved at full alignment (factor = 1.0). Significant performance degradation below alignment factor 0.4.

5.3 Hybrid System Performance Comparison

Table 2 presents a comprehensive comparative analysis of the three system configurations evaluated: conventional road infrastructure, standalone ERS, and the proposed hybrid ERS + piezoelectric system. The hybrid system demonstrates superior performance across all key metrics, achieving the highest energy output, lowest effective charging time, and best overall efficiency. Importantly, the hybrid system's payback period of 9.6 years compares favourably against standalone ERS deployment (12–15 years), due to the additional revenue stream from piezoelectric energy generation.

Table 2: Comparative Performance — Traditional Road vs. ERS vs. Hybrid System

Parameter	Traditional Road	ERS Only	Hybrid System
Energy Output	None (0 kWh/km)	Medium	High (>22 kWh/km at peak)
Charging Mode	Stationary only	Dynamic (while moving)	Dynamic + Supplementary
Charging Time	High (hours)	Low	Very Low
System Efficiency	Low	High (~75%)	Very High (~88%)
CO_2 Emissions	High	Reduced	Minimized (−35 to 45%)
Infrastructure Cost	Low (₹0.5–1 Cr/km)	Medium (₹4–6 Cr/km)	High (₹6–10 Cr/km)
Payback Period	N/A	~12–15 years	~9.6 years
Scalability	High	Medium	High (with AI optimization)

5.4 Key Results Summary

Table 3 consolidates the principal quantitative outcomes from the simulation study for reference.

Table 3: Summary of Key Simulation Results

Performance Metric	Value	Condition / Remark
Net Energy Utilization Improvement	22.4%	At ≥1200 vehicles/hour/lane
Peak WPT Efficiency	88%	Under optimal coil alignment
Piezoelectric Energy at 1000 veh/hr	~15 kWh/km	25% piezo efficiency assumed
Saturation Traffic Density	1000 vehicles/hour	Beyond this, efficiency drops
Economic Payback Period	9.6 years	Urban highway deployment
CO_2 Emission Reduction	35 – 45%	vs. conventional fossil-fuel road
Installation Cost	₹6 – 10 Crore/km	Full hybrid system

Break-even Point	~9 – 10 years	Revenue from energy supply

5.5 Economic Analysis

Economic analysis of the hybrid system is based on a 1 km urban highway reference segment. The initial capital expenditure for full hybrid installation ranges from ₹6 to ₹10 crore per kilometre, encompassing embedded piezoelectric sensors, inductive coil arrays, power conditioning equipment, and grid integration infrastructure. Revenue is modelled from two streams: energy sold to the grid from surplus piezoelectric generation, and per-vehicle charging fees for dynamic WPT services.

The payback curve analysis indicates cost recovery is achieved at approximately 9 to 10 years under conservative revenue assumptions, improving to approximately 7.5 years under optimal traffic density and electricity tariff scenarios. Sensitivity analysis confirms that the payback period is most sensitive to traffic density — consistent with the traffic-energy relationship established in Section 5.1 — and to grid electricity pricing. For traffic densities consistently exceeding 1000 vehicles/hour, the system achieves profitability within a single decade, making it economically viable for high-density urban corridors.

Fig. 3 — Payback Curve: Cumulative Cost Recovery (₹ Crore/km) vs. Time (Years). Break-even achieved at approximately 9.6 years under standard deployment conditions.

6. DISCUSSION

The simulation results confirm the technical feasibility of the proposed hybrid ERS framework and provide quantitative support for its advantages over both conventional road infrastructure and standalone ERS deployment. The 22.4% improvement in net energy utilization arises from the complementary nature of the two integrated technologies: piezoelectric harvesting generates energy from traffic mechanical stress regardless of vehicle electrification status, while inductive WPT provides energy supply to EVs proportional to traffic density and coil alignment quality.

However, several practical challenges must be acknowledged. First, the durability of piezoelectric sensors under sustained heavy vehicle loading and extreme temperature cycling remains a limiting factor for large-scale deployment. Studies on long-term structural fatigue of embedded sensors [39], [40] indicate that sensor replacement cycles of 5 to 7 years should be factored into lifecycle cost models. Second, WPT coil misalignment in real traffic conditions will reduce average efficiency below the theoretical 88% peak. The incorporation of dynamic coil positioning, active frequency tuning, or designated EV charging lanes would be necessary to approach peak operational efficiency [35], [36].

Third, the initial capital cost of ₹6–10 crore/km represents a significant barrier to adoption without policy-level support. A comparative perspective is instructive: EV charging infrastructure investment in urban India is already receiving government support under FAME-II and state-level EV policies. Extension of such policy frameworks to smart road infrastructure, including incentive structures for highway concession operators, would substantially improve the economic case.

From an environmental perspective, the modelled 35–45% reduction in CO_2 emissions relative to conventional fossil-fuel road operation aligns with findings from broader electrification impact studies [32]. This reduction is driven primarily by EV adoption enabled by reduced range anxiety, rather than by direct energy system emissions. The long-term environmental payoff significantly strengthens the case for hybrid ERS investment in high-density urban corridors.

7. ENVIRONMENTAL IMPACT ASSESSMENT

The environmental impact of the proposed hybrid ERS system is assessed across four key categories, in comparison with conventional road infrastructure:

- CO_2 Emissions: The hybrid system facilitates a 35–45% reduction in road transport CO_2 emissions by enabling dynamic EV charging, eliminating the need for stationary fossil-fuel-dependent charging and reducing the proportion of conventionally-fuelled vehicles on instrumented corridors.
- Fossil Fuel Dependency: By enabling EVs to operate with smaller battery packs and no requirement for stationary charging stops on instrumented routes, the system materially reduces fossil fuel consumption in urban freight and transit operations.
- Resource Utilisation: The hybrid system does require significant material inputs, including copper windings, piezoelectric ceramics, and power electronics, during construction. However, the lifecycle environmental analysis over a 25-year operation period shows a net positive carbon balance compared to conventional infrastructure.
- Urban Air Quality: Zero tailpipe emissions from EV traffic on hybrid-equipped corridors improve local air quality, particularly relevant in high-density Indian urban environments where vehicular air pollution is a primary public health concern.

8. CONCLUSION

This study has proposed and evaluated a hybrid sustainable transportation framework that integrates Electric Road Systems (ERS) with inductive Wireless Power Transfer and embedded piezoelectric energy harvesting. The combined analytical–simulation model, implemented in MATLAB/Simulink, demonstrates that the hybrid system achieves a 22.4% improvement in net roadway energy utilization under high-traffic conditions (≥1200 vehicles/hour/lane) and WPT efficiencies of up to 88% under optimal coil alignment.

Economically, the hybrid system offers a payback period of approximately 9.6 years for urban highway deployment, supported by dual revenue streams from piezoelectric grid contribution and dynamic EV charging fees. The system further delivers a 35–45% reduction in transport-related CO_2 emissions, providing strong environmental justification alongside the technical and economic case.

While infrastructure cost, sensor durability, and coil alignment variability remain challenges requiring further engineering development and policy support, the results confirm that integrated smart road infrastructure represents a technically viable and economically tractable pathway toward next-generation sustainable urban transportation.

9. FUTURE SCOPE

The findings of this study open several directions for future research and development:

7. AI-Based Traffic–Energy Optimization: Integration of machine learning algorithms for real-time traffic prediction and adaptive coil activation would enable energy-aware road management, dynamically optimising both piezoelectric harvesting and WPT output based on predicted traffic patterns.
8. Advanced Piezoelectric Materials: Investigation of next-generation materials such as lead-free PVDF-TrFE composites and nano-structured piezoelectric polymers may substantially improve conversion efficiency beyond the current 20–35% range while improving long-term structural durability.
9. Large-Scale Pilot Implementation: A controlled pilot deployment on a 1–5 km urban arterial segment would provide real-world operational data to validate and calibrate the simulation model under heterogeneous Indian traffic conditions.
10. Grid Integration and V2G Compatibility: Extension of the framework to include Vehicle-to-Grid (V2G) compatibility would allow EVs equipped with bidirectional chargers to feed surplus energy back to the road network, creating a fully bidirectional smart energy corridor.
11. Standardisation and Regulatory Framework: Development of national standards for ERS coil frequencies, safety zones, and electromagnetic interference (EMI) limits, aligned with SAE J2954 and ISO 15118, is essential for enabling commercial deployment.

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