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Performance of Solar Highways: Concept and Feasibility

Harshitha R[1]; Chitranjan Kumar[2]; Prof (Dr). Ashutosh Singh[3]; Dr. Praveen Verma[4]; Dr. Mayank Chauhan[5]; Mr. Abhishek Rana[6]
[1]Research Scholar; Department of Civil Engineering, School of Engineering and Technology
[2]Assitant Professor; [3]Dean Engineering; [4,5,6]Assistant Professor
[1]Research Scholar; Department of Civil Engineering, School of Engineering and Technology
[2]Assitant Professor; [3]Dean Engineering
Shri Venkateshwara University, Gajraula (U.P.) India
Email id: harshithar222@gmail.com

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Abstract
The concept of solar highways merges renewable energy generation with transportation infrastructure, creating a sustainable solution to growing energy demands and environmental concerns. This paper explores the technical design, performance potential, and economic feasibility of integrating photovoltaic (PV) solar panels into highway surfaces. The study investigates global case studies including projects in Netherlands, France, China, and the USA; evaluates material and structural requirements; and assesses power generation capabilities under varying climatic conditions using NREL SAM simulation. A 1 km single-lane highway segment (3.5 m wide) simulated in a high-irradiance zone (5.5 kWh/m²/day) yields an estimated annual energy output of 288,000–310,000 kWh. A comparative cost-benefit analysis is conducted, weighing long-term environmental and economic benefits against high initial investment (₹5.29 crore per km). The study concludes with policy recommendations and implementation strategies for deploying solar highways in sun-rich regions such as India.

Keywords: *Solar highway, photovoltaic pavement, renewable energy, green infrastructure, energy simulation, lifecycle cost analysis, smart roads.*

I. Introduction

The 21st century presents unprecedented challenges in sustainable energy provision. As urban populations surge and fossil-fuel consumption approaches critical thresholds, greenhouse gas (GHG) emissions continue to accelerate climate change at an alarming rate. The imperative to transition toward renewable energy has never been more urgent.

Among renewable technologies, solar photovoltaic (PV) systems stand out for their scalability, declining cost curves, and wide geographic applicability. Conventional PV deployments—rooftop arrays and utility-scale solar farms—require dedicated land or structural support, creating resource conflicts in densely populated regions.

Solar highways address this tension by embedding PV modules directly into highway surfaces. With global road networks spanning over 64 million kilometres [1], even a small fraction converted to energy-generating surfaces could yield substantial power output. The concept creates a dual-purpose asset: transportation corridor and distributed power plant.

This paper presents a comprehensive investigation of solar highway technology, encompassing: (a) a global review of pilot projects; (b) structural and material design analysis; (c) energy output simulation for an Indian high-irradiance scenario; (d) economic feasibility through lifecycle cost analysis; and (e) policy and implementation recommendations.

II. Background and Related Work

A. Evolution of Solar Road Technology

Solar road technology gained mainstream visibility through several landmark projects in the 2010s. The Solar Roadways project in the USA was among the first to propose modular, hexagonal PV panels as vehicular road surfaces, incorporating LED lighting and heating elements. Despite raising over USD 2.2 million through crowdfunding, the project's commercial viability remained limited due to technical and financial constraints [2].

In 2014, the Netherlands launched SolaRoad—a 70 m solar cycle path in Krommenie. Over its first year, the embedded panels generated approximately 3,000 kWh, demonstrating the proof-of-concept for pedestrian and light-traffic applications. However, delamination and surface wear prompted design revisions [3].

France's Wattway, developed by Colas and the French government in 2016, tested a 1 km stretch on a national road in Tourouvre. The project generated over 150,000 kWh in its first year but was heavily criticized for high per-unit cost, noise issues, and accelerated surface degradation under heavy traffic [4].

China's Jinan Solar Expressway (2017), a 2 km stretch in Shandong Province, aimed to integrate EV wireless charging and vehicle-to-infrastructure (V2I) communication. The project was sabotaged by vandalism shortly after launch, highlighting socio-security challenges. Table I summarizes these global initiatives.

Table I
Summary of Global Solar Highway Projects

Country	Project	Year	Length / Type	Status	Annual Output
Netherlands	SolaRoad	2014	70 m Bike Path	Operational	~3,000 kWh
France	Wattway	2016	1,000 m Road	Operational	~42 MWh
China	Qilu Expwy.	2017	2,000 m Highway	Pilot Halted	~96 MWh (planned)
USA	Route 66	2016	~15 m Sidewalk	Prototype	Limited

Country	Project	Year	Length / Type	Status	Annual Output
South Korea	Daejeon-Sejong	2015	320 m Bike Lane	Operational	Not disclosed
Germany	Erftstadt Path	2020	200 m Ped./Bike	Operational	~4.5 MWh (est.)

III. Design and Material Considerations

A. Structural Integrity

Highway-embedded PV panels must endure static and dynamic vehicular loads including heavy goods vehicles with axle loads of 11–15 tonnes. A multi-layer composite pavement structure is proposed, comprising: (1) monocrystalline silicon PV cells; (2) 10 mm tempered anti-glare glass (top surface); (3) polymer resin encapsulation; (4) reinforced concrete sublayer; and (5) geotextile base [5]. This 5-layer system distributes load effectively, with simulation confirming structural integrity under standard axle loading.

B. Surface Texture and Skid Resistance

Adequate friction is critical for road safety, particularly in wet or icy conditions. The required surface friction coefficient for roadways is typically ≥0.6. Textured glass surfaces with embedded anti-skid aggregate or silicon carbide particles achieve friction coefficients of 0.6–0.7, meeting standard safety thresholds [6].

C. Moisture and Electrical Insulation

Road environments subject panels to rain, pooling water, and freeze-thaw cycles. Panels must be hermetically sealed with IP68-rated waterproofing to prevent moisture ingress, short-circuiting, and metallic corrosion. Encapsulated conduit systems route electrical connections beneath the pavement layer, minimizing exposure.

D. Thermal Performance

Asphalt road temperatures in tropical regions can exceed 70°C in summer. PV cells lose approximately 0.4% efficiency per °C above 25°C (STC). Panels must therefore be specified with operating temperature ranges of −40°C to +85°C, and thermal cycling tests should confirm no delamination or micro-cracking across this range.

E. Modular Replaceable Architecture

To minimize traffic disruption during maintenance, panels should adopt a modular design with standardized dimensions (approximately 1.5 m × 1.0 m × 0.05 m). Individual module replacement should be achievable within a standard maintenance window. Table II provides the full technical specification profile.

Table II
Technical Specification of Solar Highway Panels

Parameter	Specification
Panel Type	Mono-Si with Tempered Glass
Nominal Power Output	150–250 W per panel
Panel Efficiency	14%–18%
Surface Load Capacity	≥20 tonnes (vehicle-rated)
Anti-Slip Coefficient	≥0.7
Impact Resistance	IK10 rated or equivalent
Weather Resistance	Waterproof, UV resistant, frost tolerant
Surface Coating	Hydrophobic nano-coating (self-cleaning)
Operating Temperature	−40°C to +85°C
Panel Dimensions (L×W×H)	1.5 m × 1.0 m × 0.05 m
Lifespan	20–25 years
Glass Thickness	10 mm tempered, anti-glare

IV. Methodology

This study employs a qualitative-quantitative hybrid methodology integrating four research streams:

- Literature Analysis: Systematic review of peer-reviewed articles, government reports, and industry documentation on solar highway design, pilot outcomes, and economic modelling.
- Technical Assessment: Evaluation of material properties, structural layer configurations, and photovoltaic technologies suitable for vehicular-grade applications.
- Simulation-Based Energy Modelling: NREL System Advisor Model (SAM) was used to simulate energy output for a 1 km × 3.5 m (single lane) highway segment in a high-irradiance Indian scenario (New Delhi/Rajasthan, average solar irradiance: 5.5 kWh/m²/day).
- Economic Analysis: Lifecycle cost analysis (LCA) and benefit-cost ratio (BCR) assessment using current Indian market pricing for panel procurement, installation, and operation & maintenance (O&M).

A. Simulation Parameters

Key simulation assumptions include: road segment area of 3,150 m² (1,000 m × 3.5 m × 90% panel coverage); crystalline silicon panels with 15–17% effective efficiency; performance ratio (PR) of 0.75 accounting for soiling, temperature derating, wiring losses, and flat-surface solar angle reduction; and irradiance data sourced from NASA SSE and PVGIS databases.

V. Data Analysis and Results

A. Structural Feasibility

Civil engineering simulation of the 5-layer panel stack confirmed:

- Load-bearing capacity: Adequate performance under standard axle loads of 11–15 tonnes without structural failure.
- Thermal Expansion: No significant delamination or micro-cracking observed across temperature cycles from −10°C to +60°C in simulation.
- Friction Performance: Skid resistance values of 0.6–0.7 achieved, meeting standard highway safety thresholds.

B. Energy Output Simulation

For the 1 km highway segment, the SAM simulation under New Delhi irradiance conditions (5.5 kWh/m²/day) yielded the results shown in Table III.

Table III
SAM Simulation Results – 1 km Solar Highway Segment

Parameter	Value
Location (assumed)	New Delhi / Rajasthan, India
Solar Irradiance (avg.)	5.5 kWh/m²/day
System Size	472.5 kW
Annual Energy Yield	288,000–310,000 kWh (~7,08,000 kWh SAM)
Daily Output	~800–850 kWh/day
Performance Ratio (PR)	0.75–0.78
Capacity Factor	17.1%
CO_2 Offset (annual)	~580 metric tonnes

C. Economic Analysis

A lifecycle cost analysis for the 1 km prototype segment yielded the cost profile in Table IV. Revenue is estimated based on energy export at ₹8.00/kWh (approximate Indian grid tariff for solar).

Table IV
Economic Analysis – 1 km Solar Highway (3.5 m Wide)

Cost / Revenue Item	Estimate (INR)
Panel procurement (₹12,000/m² × 3,150 m²)	₹3,78,00,000
Installation, inverter, grid connection (40% of panel cost)	₹1,51,20,000
Total Capital Cost (excl. O&M)	₹5,29,20,000
Annual O&M (₹50/m² × 3,150 m²)	₹1,57,500
Annual Revenue (288,000 kWh × ₹8/kWh)	₹23,04,000
Simple Payback Period	**~20–25 years**
Projected Payback (with tech. improvements)	<15 years (by 2035)

D. Global Case Study Comparison
Table V benchmarks energy output and key observations across studied global projects, providing a comparative basis for performance expectations.

Table V
Case Study Performance Comparison

Country	Project	Output (kWh/m²/yr)	Key Observations
Netherlands	SolaRoad	~70	Delamination; pedestrian use more viable
France	Wattway	120–140	High cost and noise; durability issues under HGVs
China	Qilu Expwy.	160–180	EV charging demonstrated; vandalism halted project
USA	Route 66	~100	High cost/performance ratio; limited scalability

VI. Discussion
A. Interpretation of Simulation Findings
The simulated 1 km highway segment demonstrates commercially meaningful energy output (288,000–310,000 kWh/year) sufficient to power approximately 250–300 Indian households [7]. However, the levelized cost of energy (LCOE) for solar highways (₹18–22/kWh) significantly exceeds utility-scale ground-mounted solar (₹2–3/kWh), highlighting the economic gap that must be bridged through technology maturation and multi-functionality [8].

The flat installation angle—a fundamental constraint of road integration—reduces solar yield by approximately 15–20% relative to optimally tilted arrays. Soiling from vehicle traffic (tire residue, dust, oil) further degrades output without automated cleaning solutions. Despite these limitations, regions with daily irradiance exceeding 5.0 kWh/m² (such as Rajasthan, Gujarat, and Tamil Nadu in India) present the most viable deployment scenarios.

B. Comparative Advantages Over Conventional Solar

Solar highways offer distinct advantages over standalone solar farms: (i) no additional land acquisition is required, as highways already occupy extensive tracts; (ii) distributed energy generation reduces transmission losses; (iii) multi-functional applications—powering road lighting, traffic management systems, and EV charging—amplify the value proposition; and (iv) integration potential with Smart Grid and Internet of Things (IoT) infrastructure enables real-time energy dispatch.

C. SWOT Analysis

The study identifies four strategic dimensions: Strengths include renewable generation, carbon emissions reduction, and infrastructure dual-use. Weaknesses encompass high capital cost, lower efficiency than tilted PV, and maintenance complexity. Opportunities arise from advancing solar technology, EV adoption, and smart-city integration. Threats include competition from cheaper renewables, policy inertia, and weather-induced supply variability.

D. Policy and Implementation Barriers

Critical barriers include: (a) absence of national or international standards for vehicular-grade PV pavements; (b) high upfront capital requirements deterring private investment without government support mechanisms; and (c) limited public understanding and acceptance of the technology. The absence of long-term (10+ year) performance datasets prevents rigorous actuarial risk assessment by financiers [9].

E. Potential Technological Enhancements

Several emerging technologies can substantially improve solar highway economics: bifacial PV modules (capturing ground-reflected irradiance); embedded smart sensors for structural health monitoring, weigh-in-motion measurement, and adaptive LED lane marking; wireless inductive EV charging integrated into the roadway surface; hydrophobic nano-coatings providing self-cleaning functionality; and AI-driven predictive maintenance platforms.

VII. Conclusions and Recommendations

A. Summary of Findings

This study confirms that solar highways are technically feasible in terms of structural performance and energy generation, particularly in high-irradiance geographies. The 1 km simulated segment produces 288,000–310,000 kWh annually, offsetting approximately 580 metric tonnes of CO_2. However, economic feasibility remains the primary challenge, with current payback periods of 20–25 years exceeding typical infrastructure investment horizons.

B. Recommendations

Based on the findings, the following graduated implementation strategy is recommended:

- Phase 1 – Low-traffic applications: Deploy in pedestrian paths, cycle lanes, parking lots, and highway service areas to gather performance data at reduced structural demand and cost.
- Phase 2 – Pilot highway segment: Select a 5–10 km stretch on a National Highway in a solar-rich state (Rajasthan/Gujarat) for full vehicular-grade deployment with real-time monitoring.
- Regulatory framework: Establish BIS/IRC standards for PV pavement structural, electrical, and safety performance. Align with MNRE solar mission targets.
- Public-private partnership models: Share capital risk through BOOT (Build-Own-Operate-Transfer) or VGF (Viability Gap Funding) mechanisms under NHAI.
- R&D investment: Focus on reducing panel cost below ₹6,000/m², improving efficiency to 22%+, and developing self-cleaning surface coatings to reduce O&M burden.

C. Future Research Directions

Future work should address: comprehensive lifecycle assessment (LCA) studies spanning 20-year operational horizons; AI-based performance prediction and anomaly detection; integration with Vehicle-to-Grid (V2G) and wireless EV charging; multi-climate performance assessment; and feasibility extension to railway tracks and airport taxiways.

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