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Highway Energy Harvesting System: A Hybrid Energy Mat System for Toll-Based Power Generation

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Abstract: India's heavy highway traffic presents a vast opportunity to convert the daily flow of cars into clean, renewable energy. Called Highways Harvest, this new hybrid energy mat technology was carefully designed to harvest electricity from the mechanical stress and friction that happen at tolls—locations where cars naturally slow down or stop. The system combines high-efficiency piezoelectric sensors, which can transform vertical pressure into electricity, and triboelectric layers that harvest energy from surface contact and movement, forming a thin but efficient dual-layer mat.

The resultant power is channelled through a smart conditioning circuit and into Li-ion battery packs, controlled by an IoT-based power controller. Power can be supplied to toll booth lighting, display boards, or CCTV systems, nearby villages, households, etc.—converting traffic into a source of power. Engineered for India's varied climatic and load conditions, every mat is cost-effective, low-maintenance, and modular. Optimized 6-lane toll plaza with mats can conservatively produce –55-65 kWh/day, and scalability is traffic-dependent. At high-traffic expressway locations such as Coimbatore-Salem or Delhi-Agra, potential energy output and ROI are multiple. The power output also multiply. In addition to sustainability, Highway Harvest has tremendous economic advantages: it reduces operational energy costs, offers quick payback (ROI), and creates opportunities for the reduction of carbon emission. The system effortlessly merges with existing road infrastructure and is set to integrate with future smart highway systems. It also works around the clock, day and night, unbothered by the weather fluctuations, and takes up little space.

Through the conversion of India's toll plazas into micro energy centres, this solution creates a new frontier in renewable energy-based infrastructure.

I. INTRODUCTION

India's rapid economic growth has resulted in tremendous growth in energy consumption, particularly in transportation and rural electrification. Solar power and wind power have come a long way, but we are not tapping so much kinetic and frictional energy from moving vehicles. Large numbers of vehicles go through national highway toll plazas every day, particularly in the congested regions of South India. These are an opportunity to reap wasted energy. The triboelectric effect happens when two different materials touch and then separate, leading to a transfer of electrons. This creates an electric charge due to friction or movement. When this charge links to a circuit, it can generate electricity through electrostatic induction. The piezoelectric effect occurs in specific materials that produces an electric charge when you produce mechanical stress. When these materials are compressed or vibrated, their internal structure changes, creating voltage. Both effects convert mechanical energy into electrical energy.

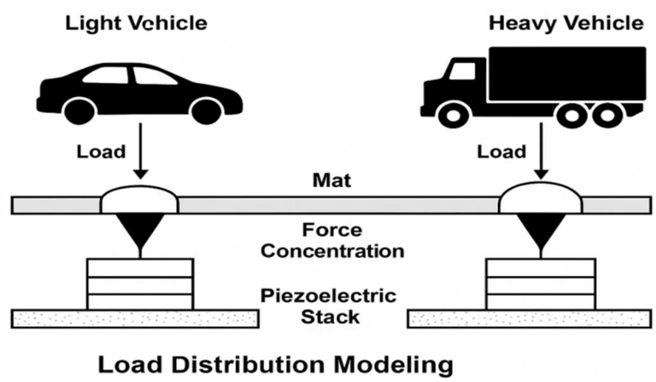

Figure 4: Load Concentration Through Dome Plates to Sensor Array

This paper introduces "Highway Harvest" — a system that harvests power through two technologies: piezoelectric and triboelectric. These are installed on rugged mats placed in toll booths. As vehicles pass over the mats, pressure and friction generate electrical power that can be tapped.

The created power is channelled to batteries and regulated with IoT-based systems for monitoring and efficient utilization. The figure of the model is displayed above. (Fig.4)

This system operates independently of weather and light, and thus it is ideal for India's various climates. Further, is able to supply energy locally. This implies the ability to supply power to nearby rural villages that lack a stable grid of electricity.

The system proposed is a green, low-maintenance, and scalable solution that is in line with India's national smart infrastructure plan, green energy, and rural empowerment.

II. LITERATURE REVIEW

India's growing infrastructure for transportation offers a once-in-a-lifetime chance to find alternative ways of harvesting energy. India has the second largest road network in the world and isn't capturing the energy generated by mobile vehicles. Indian roads carry more than 25 crore vehicles, and with central power grids being stretched more and more, new small-scale energy harvesting technologies like piezoelectric and triboelectric systems are being demanded more and more as alternatives to conventional ones.

So, the piezoelectric effect has been studied a lot throughout the world, but it's not being used much by Indian engineering. You have materials like lead zirconate titanate (PZT) and polyvinylidene fluoride (PVDF) that can transfer energy, which would be extremely helpful in congested places like toll plazas, bus stops, and highways in India. They conducted this small pilot study in 2017 in the Delhi region on a highway with piezoelectric sensors under rumble strips, and they found that it generated about 18–25 Wh/day per mat unit, which could power streetlights or traffic lights.

But the thing is, the technology is not really catching on because there's no support, not good policies, and no proper facilities to manufacture all these materials on a large scale.

Triboelectric nanogenerator (TENG) is a new contact electrification and electrostatic induction-based device. Laboratory TENGs are of high output voltage, i.e., higher than 100 V peak, but in actual applications in India, they are plagued by dust deposition, humidity degradation, and surface wear. They are, however, light, inexpensive, and flexible and hence suitable for use in public areas like stations, walkways, and bus stops. Mat form TENGs in metro stations have been studied by IIT Madras researchers with satisfactory energy harvesting by pedestrian traffic with 1.5–2 mWh per footstep output depending upon materials and force applied.

India still heavily relies on coal-based power-even for remote areas-despite renewable energy goals. Over 55% of electricity in 2024 came from coal, leading to high emissions, health issues, and over 20% transmission losses in rural zones. This system is inefficient and environmentally harmful.

III. METHODOLOGY

A. *Site Selection and Load Profile*

The Vanagaram Toll Plaza on NH-32 (Chennai Bypass) was selected due to its exceptionally high daily traffic load (~95,000 PCUs/day), of which 15–20% are heavy vehicles. Case study data confirms ~200 heavy vehicles per hour, with each vehicle exerting axle loads ranging from 150 kN to 400 kN. This consistent high-pressure traffic environment makes the location ideal for pressure-based hybrid energy harvesting.

B. *System Overview*

The system consists of a dual-layer hybrid energy mat measuring 3 m × 1.5 m, designed to convert both compressive and frictional forces from vehicle movement into electrical energy. The architecture includes:

- Top Layer: PDMS + PTFE triboelectric nanofilm with embedded copper mesh electrodes
- Middle Layer: Stainless-steel dome-structured pressure plate for force concentration
- Bottom Layer: 180 PZT-5H piezoelectric disks, arranged in 90 stacked units (2 disks per point)
- Power Conditioning Circuit: AC-DC rectifier, DC-DC boost converter, capacitor bank
- Storage: 12V, 100Ah Li-ion battery with BMS and overcurrent protection

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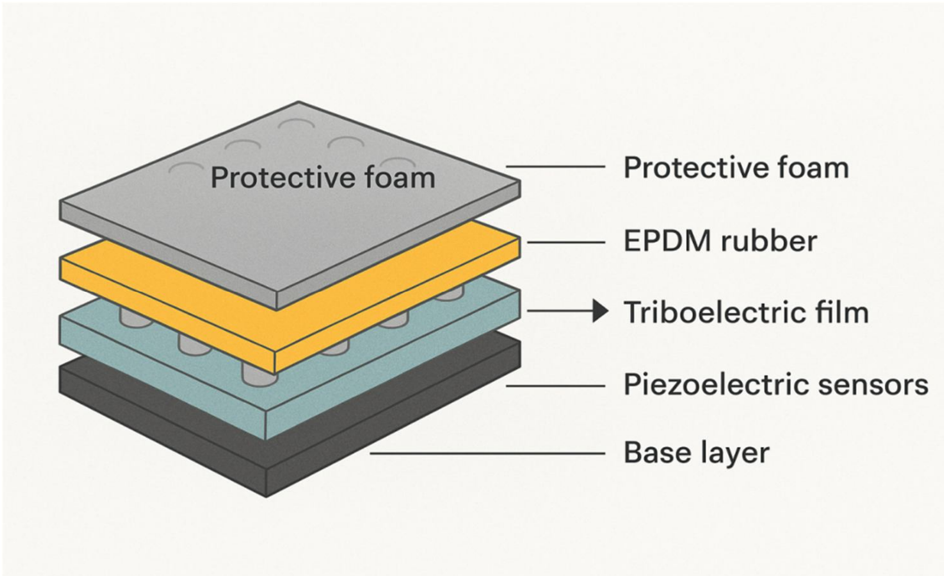

C. *Materials Used*

Component	Material Specification
Piezo Disks	PZT-5H ceramic, high d33 (~600 pC/N), Ø20 mm × 2 mm
Triboelectric Film	PDMS base with corona-treated PTFE top layer
Electrodes	Woven copper mesh (0.5 mm), chemically etched
Dome Structure	304-grade stainless steel domes, rubber base bonded
Surface Layer	UV-resistant polyurethane-coated rubber sheet (5 mm)
Frame and Protection	Polycarbonate subframe with EPDM sealing (IP67 rated)
Storage	Li-ion LFP battery, 12V/100Ah, 2000+ cycle life

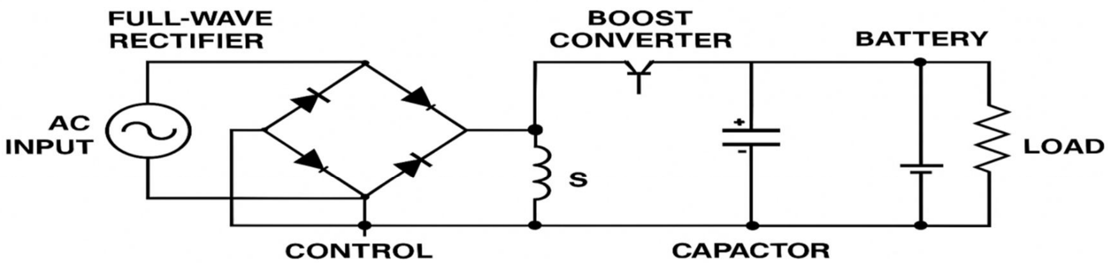

Figure 6: Power Conditioning and Energy Storage Flow

D. Load and Force Distribution Modelling

The mechanical force exerted by passing vehicles is modelled based on axle weight and tyre contact width:

- Heavy vehicles (trucks/buses): 15,000–40,000 kg → ~400,000 N
- Light vehicles (cars, autos): 1,000–2,000 kg → ~15,000–20,000 N

Dome plates redirect and concentrate **30–60% of vertical force** directly into the piezoelectric disk clusters, enhancing voltage output by up to 50%.

E. Electrical Energy Conversion

Piezoelectric Output

- Voltage: 30–80 V per stacked disk under ~400 N
- Current: 0.5–1.5 A burst
- Energy per heavy vehicle pass: ~2.3 Wh(loaded trucks)
- Energy per light vehicle pass: ~0.35 Wh

Triboelectric Output

- Surface-generated AC charges collected via copper mesh
- Adds ~10–15% extra energy per pass (0.2–0.3 Wh per heavy vehicle)

Power Conditioning and Storage

- Bridge Rectifier (MB6S) converts sensor AC to DC
- Boost Converter (XL6009) stabilizes voltage to ~12–14 V
- Capacitor Bank (2200 µF) smooths power fluctuations
- 12V, 100Ah Li-ion Battery stores the final output with:
  - Overcurrent trip protection
  - Thermal cutoff (70°C)
  - Deep discharge protection
- Estimated capacity usage per day: ~10.85 kWh
- Monthly usable energy: ~325–330 kWh

F. Power Output Estimation (Based on Vanagaram Case Study)

Vehicle Type	Daily Count	Energy per Pass	Daily Output
Heavy	3,500	2.3 Wh	8,050 Wh
Light	8,000	0.35 Wh	2,800 Wh
Total	11,500		~10.85 kWh/day

This value is validated against traffic case data and modelled using the force-response characteristics of PZT-5H and triboelectric film combinations.

G. Energy Redistribution: Village Use-Case

To demonstrate practical real-world application, the system is designed with a downstream power redistribution strategy:

- Surplus energy (beyond toll infrastructure needs) is routed from the battery to nearby village micro-loads
- Use-cases include powering:
  - LED lighting for streets or public areas
  - Mobile charging stations
  - Water pumps or DC fans
- On average, 1 rural household requires ~2 kWh/day
  → A single mat (10.85 kWh/day) can support 4–5 homes daily

This validates the mat's potential not just for toll booth support, but for rural electrification using traffic energy — particularly along highway-adjacent village

IV. SYSTEM ARCHITECTURE

A. Input Source: Vehicular Load

- Vehicle Types: Heavy (trucks, buses), Light (cars, vans, two-wheelers)
- Impact: Vehicles pass over the mat → mechanical pressure is applied

B. Per Lane Physical Configuration

Feature	Specification
No. of Mats per Lane	2
Size of Each Mat	1.5 m × 1.5 m
Height of Mat	~4 cm (including dome + casing)
Gap Between Mats	30–40 cm
Active Area (Per Lane)	2 mats × 2.25 m² = 4.5 m²
Placement	Placed at exit of Toll gate (This reduces the risk of over compression and increases lifespan). It is semi-embedded on the ground.
Surface Protection	PU rubber layer & waterproof

C. Signal Conditioning and Storage

Component	Purpose
Bridge Rectifier	Converts AC pulse into DC. This process is again repeated in power distribution.
Boost Converter (XL6009)	Regulates voltage to 13.8V
Capacitor Bank	Smooths ripple current
Battery Storage	12V, 100Ah $LiFePO_4$ with BMS(3000+ cycles)
Output Use	Powers booth loads and rural areas
Charge Controller + MPPT Logic	Prevents overcharge, short circuit
IoT monitoring unit (ESP32)	Real time energy data, vehicle count alerts
Power output Distribution	DC output from battery to AC supply to Transformers

Layers Inside the Mat:(Single Mat)

- Top Surface: Textured EPDM rubber (non-slip, weather-resistant)
- Pressure Layer: EVA foam for load distribution
- Piezoelectric Sensors: 90 parallel-connected sensors (e.g., PZT or PVDF film) stacked in parallel. It is placed on the edge zones(More force Distributed by the vehicle
- Triboelectric Layer: PTFE + Aluminium
- Encapsulation: PU coating, waterproof & dustproof
- Buffer Layer: Thermal-insulated sheet
- Support Base: FRP or mild steel sheet

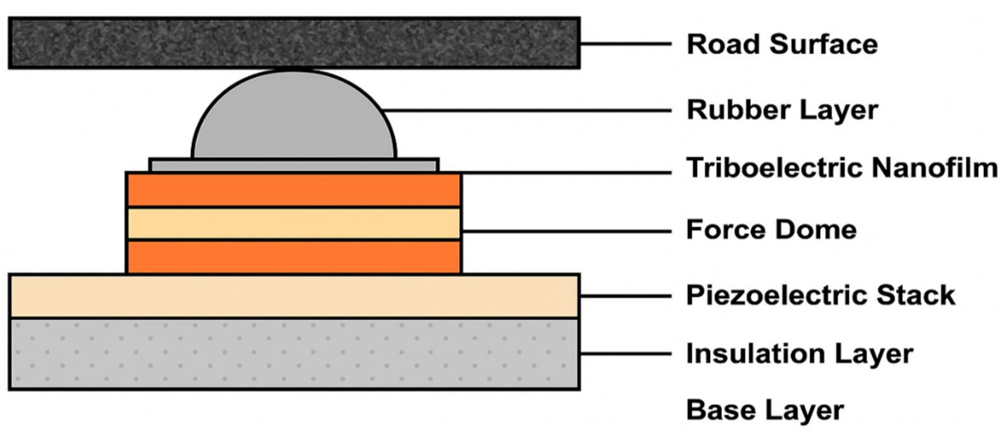

Figure 2: Cross-sectional Structure of Hybrid Mat System

D. Energy Output – Per Lane

Vehicle Type	Avg. Energy / Pass	Avg. Vehicles / Day	Energy Contribution
Heavy Vehicles	~2.3 Wh	3,500	8.05 kWh
Light Vehicles	~0.35 Wh	8,000	2.80 kWh
Total Output			~10.85 kWh/day

Enough to power 3–5 rural homes/day, or all toll booth electronics.

E. Cost Estimate – 1 Lane (2 Mats)

F.

Component	Qty / Spec	Cost (INR)
Piezo Disks (PZT-5H)	180 total	₹12,600
Triboelectric Film (PDMS + PTFE)	4.5 m²	₹1,500
Copper Mesh Electrodes	Embedded per mat	₹800
Force Domes (SS + rubber)	90 domes	₹2,500
PU Surface Layer	Anti-slip top layer	₹1,200
Base Frame (Aluminium / FRP)	2 panels	₹900
Bridge Rectifier + Boost Converter	Shared signal circuit	₹400
Capacitor Bank	2200 µF, 25V	₹200
Battery ($LiFePO_4$, 12V, 100Ah)	Full storage	₹4,500
Wiring + Conduit	10 m, 16 AWG + sealing	₹800
IP65 Boxes + Fixing Hardware	2 boxes + adhesives + mounts	₹600

Total Cost: ₹25,500(varies) per lane

A. Example: Vanagaram Toll Output (All Lanes):

Parameter	Value
No. of Active Lanes	6 lanes
Mats per Lane	2 (split layout)
Total Mats	12
Total Output (Daily)	~65.1 kWh/day
Monthly Output	~1,953 kWh/month

Equivalent to replacing a 2.5 kW solar system per lane, but works 24×7 — even at night and in rain.

V. DISCUSSION

This project comes with the affordable, flexible, and renewable energy solution in the form of a hybrid dual-layer energy mat system. It harvests energy from vehicle movement with stacked piezoelectric sensors and triboelectric nanofilms. With the split-mat installation at Vanagaram Toll Plaza, each lane generates around 10.85 kWh per day without requiring sunlight, fuel, or wide land spaces.

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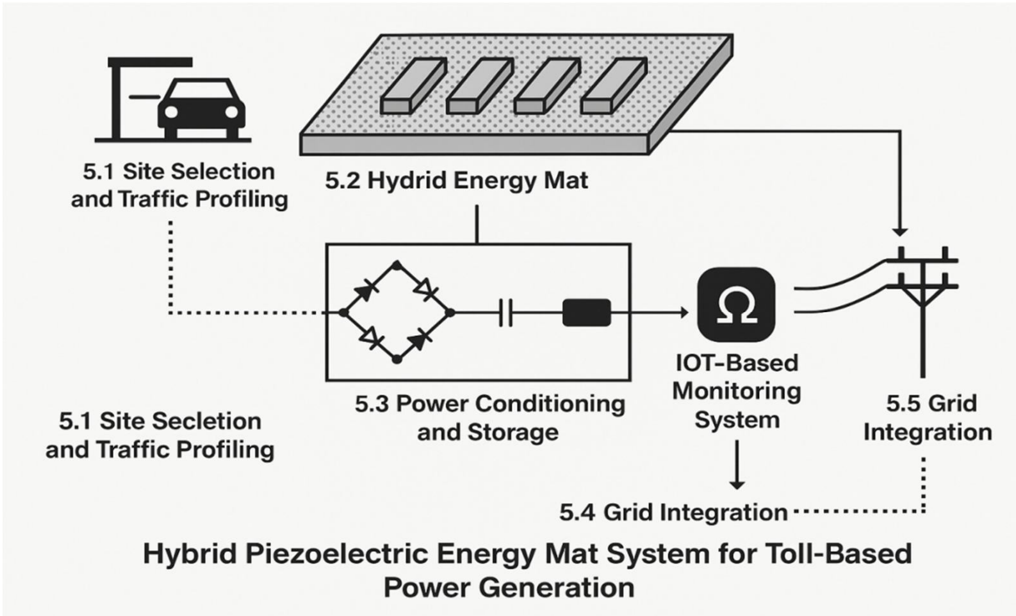

The system runs around the clock, charges a 100Ah $LiFePO_4$ battery, and drives toll infrastructure and rural electrification, powering 3–5 homes per lane per day. It produces nearly four times the output of a solar system costing the same amount of ₹25,500 per lane. Placing the mats in the exit area maximizes performance and reduces sensor fatigue, ensuring long-term reliability.

A. Why our Hybrid Energy Mats Aren't Suitable in other Countries?

1) Lower Traffic Volume = Low Energy Yield:

Countries with small populations naturally have:

- Fewer vehicles per hour
- Lower axle hits per day
- Even highways in places like Norway, Canada, or New Zealand see <2,000–3,000 vehicles/day

2) No Real Need for Decentralized Power:

- Small countries often have full electrification, even in rural zones
- So generating 8–10 kWh/day is too low
  No social impact = no government or public motivation to deploy

3) ROI is Too Low:

- Let's say a toll in Finland gets 1,000 vehicles/day:
  - Even with zoning, energy = ~2–3 kWh/day
  - Mat cost = ₹25k+
  - Payback = 10+ years

4) Fewer Toll Booths Exist

- Countries with low population density rely on:
  - Open tolling
  - No physical plaza = no mat placement opportunity

5) Extreme Weather Shortens Mat Life

- These often face:
  - Heavy Snowfalls
  - Road salting
  - Icing

B. Mat layers degrade faster, especially triboelectric films like PTFE or PDMS.

This is unlike conventional sources of energy since it is decentralized, simple to install, and carbon-free. Below is a summary for comparison:

Feature / Source	Hybrid Mat (Toll)	Solar	Coal	Windmill	Hydro	Nuclear
Output (per unit/day)	~10.85 kWh	2.5–3.5 kWh	Grid-fed	Site-dependent	Seasonal/river-based	24×7, very high
Land Required	None (uses road)	120–150 sq.ft	Huge (mines/plants)	Large open areas	Dams + basins	Massive zone
Deployment Time	Days	Weeks	Years	Months–Years	Years	10+ years
Working Time	24×7 (traffic-based)	Daytime only	24×7	Wind-dependent	Seasonal flow	24×7
Cost (Per 10 kWh unit)	₹25–₹30	₹60–₹80	₹2–₹4 (but polluting)	₹40–₹70	₹20–₹40	₹10–₹20 (after setup)
Carbon Emissions	Zero	Zero	~1 kg CO_2 per kWh	Zero	Minimal	Low
Best Use Case	Roads, Smart Cities	Rooftops	National grid	Rural grid support	River-based generation	Industrial cities
Storage Included?	Yes ($LiFePO_4$)	Extra battery	Grid-integrated	Not direct	Needs buffer storage	Needs heavy systems

Finally, hybrid energy mat system offers a cost-efficient, clean, and scalable alternative to convectional power sources.

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