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ASSESSMENT OF PIEZOELECTRIC PAVEMENT ENERGY HARVESTING FOR DISTRIBUTED POWER SUPPLY IN URBAN TRANSPORT SYSTEMS

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Abstract

This study investigates the feasibility of applying piezoelectric pavement technology in Vietnamese urban roads to harvest energy from traffic loads, using survey data from Route 353, Hai Phong. Based on PCU conversion factors from TCVN 13592:2022, a daily traffic volume of 30,873 vehicles corresponds to 62,710 axle passes. At a baseline configuration of 40 modules per 100 m, the harvested energy is only 20-80 Wh/day/km, far below the demand for street lighting (~12,000 Wh/day/km). However, increasing density to 150-200 modules per 100 m with a hit probability phit ≥20% yields 0.3-0.4 kWh/day/km (110-146 kWh/year), sufficient to power distributed infrastructure such as electronic signage, surveillance cameras, or ITS sensors. Estimated investment costs of 0.85-1.50 billion VND per 100 m highlight economic challenges, yet the technology provides added value by enabling distributed power supply, reducing cabling costs, and improving energy autonomy. The findings confirm the technical feasibility of piezoelectric pavements for smart transport infrastructure in Vietnam, while recommending pilot projects, development of national standards, and hybrid integration with photovoltaics to enhance system efficiency.

Keywords: *Piezoelectric pavement; Energy harvesting; Passenger Car Unit; Smart transportation infrastructure; CAPEX.*

1. Introduction

In the current context, the demand for energy in urban transportation infrastructure has been continuously increasing, as lighting systems, traffic control signals, electronic signboards, and intelligent sensors have been widely deployed. These systems are commonly powered by the national electricity grid, leading to higher operational costs and CO_2 emissions associated with energy production. Heavy reliance on conventional electricity sources has been identified as a barrier to the goals of developing smart and sustainable cities in developing countries, including Vietnam.

To address this challenge, the exploitation of renewable energy sources has been investigated, among which the integration of energy-harvesting devices into infrastructure structures has gained attention in recent years. One of the most promising technologies is piezoelectric pavement, in which piezoelectric elements are embedded within or beneath the pavement surface to convert mechanical energy from traffic loads into electrical energy. This technology has been tested in several countries such as Israel, Japan, and the United States, with results showing that the generated electricity was sufficient to power public lighting systems or traffic signboards.

The piezoelectric technology operates on the principle that when piezoelectric materials undergo mechanical deformation, electrical charges are generated on their surfaces. The relationship between applied force and induced charge is determined by the piezoelectric coefficient, commonly denoted as $d33$ or $d31$ depending on the force direction. When piezoelectric elements are integrated into pavement structures, the energy from passing vehicle wheels can be harvested as voltage and current. This energy can subsequently be stored in supercapacitors or lithium-ion batteries and used for roadside infrastructure devices. The working principle of piezoelectric pavement is illustrated in **Fig. 1**, where mechanical stress from vehicle loads is converted into electrical energy.

Numerous international studies have demonstrated the feasibility of this technology. In Israel, Innowattech conducted a pilot installation on Highway 4, where piezoelectric modules were embedded under asphalt layers. Results indicated that the average monthly power output reached

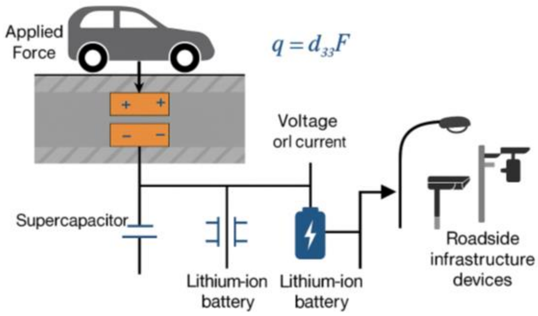

Figure 1. Principle of Piezoelectric Pavement Energy Harvesting

Figure 2. Innowattech project: Piezoelectric Systems for Green Environment

approximately 2,000kWh for a 100-meter road section [1]. The large-scale implementation of piezoelectric harvesting technology under real traffic conditions is shown in **Fig. 2**. In Japan, piezoelectric plates were installed beneath the floor of Tokyo Station, where extremely high pedestrian traffic occurs. Although the output of each plate was only a few watts, the total daily generation amounted to several hundred kWh [2]. In the United States, studies were carried out on university campuses to harvest energy from pedestrians, which was then used to power intelligent LED lighting systems [3].

In the field of road infrastructure, many in-depth studies have been conducted to model and predict electricity generation from piezoelectric systems. Multiscale finite element simulations have been applied to evaluate the mechanical and electrical behavior of piezoelectric modules under vehicular axle loads [4]. Findings revealed that the harvested power could reach 100-200 kWh/day/km depending on traffic density and average axle load [5]. Laboratory tests have also been carried out to determine energy conversion efficiency and material durability, with the d33 coefficient of PZT ceramics reported in the range of 350-600 pC/N [6].

To date, no official scientific publication has reported the deployment of piezoelectric pavements under real-world conditions in Vietnam. Domestic studies have remained at the level of conceptual exploration or small-scale laboratory trials, which are insufficient to provide quantitative data on energy efficiency or structural durability [7, 8]. As a result, a significant research gap exists, particularly in terms of field-based experimental evidence. This gap highlights the urgent need for pilot projects of 1-2 km in key urban corridors to validate technical feasibility, assess economic performance, and establish a foundation for developing technical standards for future applications in Vietnam.

Against this background, Highway 353, which connects Hai Phong City with the Do Son tourist area, was selected as the case study. This road experiences high and diverse traffic flow, including buses, trucks (4-axle, 3-axle, and 2-axle), coaches, passenger cars, and motorcycles, with an average daily traffic volume estimated around 25,000 PCU/day. In addition, the road plays a crucial role in tourism connectivity, which means the demand for lighting, monitoring, and electronic signage is consistently high. These characteristics make Highway 353 a suitable environment for piloting a distributed power supply model based on piezoelectric pavement systems.

The objective of this paper is to evaluate the potential application of piezoelectric pavement on Highway 353 by simulating the energy harvested from real traffic flow. The findings are expected to provide a scientific basis for pilot implementation in Vietnam and contribute reference data for the development of sustainable urban transportation infrastructure based on renewable energy.

2. Theoretical Background

The theoretical foundation of piezoelectric pavement research is not limited to the physics of the piezoelectric effect but is also reinforced by the intrinsic properties of the materials, the modeling approaches for harvested energy, and validated experimental findings. By integrating these elements, a comprehensive framework emerges in which the mechanisms of energy conversion, the governing equations, and the range of practical applications can be logically assessed within the context of modern transportation infrastructure.

2.1. The piezoelectric effect and fundamental formulas

The piezoelectric effect was first identified in the late 19th century, when certain crystalline materials were observed to generate surface charges under applied mechanical stress [9]. In principle, when a force F is exerted on a piezoelectric element, the induced charge Q is expressed as:

$$Q = d \times F \quad (1)$$

where d is the piezoelectric coefficient (C/N), representing the efficiency of electromechanical conversion. The resulting voltage V is related to the stored charge by:

$$V = \frac{Q}{C} \quad (2)$$

with C being the capacitance of the element. The harvested energy E for each impulse is calculated as:

$$E = \frac{1}{2}CV^2 \quad (3)$$

These formulas have been extensively adopted for predicting the output of piezoelectric modules embedded in pavement systems [10].

2.2. Materials used for piezoelectric energy harvesting

Piezoelectric materials are generally classified into two main groups: piezoelectric ceramics (primarily PZT - lead zirconate titanate) and polymer-based materials (such as PVDF - polyvinylidene fluoride). In recent years, numerous studies have employed ceramic-polymer or ceramic-carbon fiber composites in order to optimize both mechanical durability and electrical performance [6].

2.3. Modeling of harvested energy

Predictive modeling of harvested energy is often conducted using finite element methods (FEM) that couple mechanical and electrical responses of the module [4].

The average output power can be generalized as:

$$P = \frac{n \times f \times E_S}{A} \quad (4)$$

where n is the number of vehicle passes, f is the impact frequency, E_s is the mean energy per load event, and A is the effective pavement area.

Dynamic tire-pavement interaction models have also been employed to simulate output under varying speed and axle loads [11].

2.4. International experimental evidence

Several pilot projects worldwide have provided solid evidence of the potential of piezoelectric energy harvesting in transportation infrastructure. In Israel, Innowattech implemented a trial section of 100 m on a highway, where the harvested electricity was reported to reach approximately 2,000kWh per month under high traffic volumes. In Japan, rather than being deployed on roadways, the technology was applied in high-density railway stations, where pedestrian footsteps generated several hundred kWh daily, sufficient to operate electronic LED information boards. In the United States, experimental studies were mainly conducted in university campuses, where piezoelectric plates were embedded beneath pedestrian pathways to power local LED lighting systems.

In addition to field results, international simulation studies have provided relatively consistent estimations: the average harvested output ranged from 100-200 kWh per day per kilometer of pavement, under traffic flows of 10,000-15,000 PCU/day. These findings suggest that piezoelectric pavement technology is not only technically feasible but also

Table 1. Comparison of Typical Piezoelectric Materials

Property	**PZT** (Ceramic)	**PVDF** (Polymer)
Material type	Ceramic	Polymer
d33 (pC/N)	300 - 600	20 - 30
kp (Electromechanical coupling)	0.6 - 0.7	0.1 - 0.2
Mechanical strength	Low	High
Curie temperature (°C)	~ 300 - 370	~ -40 to 80
Environmental stability	Poor (moisture, thermal sensitivity)	Good (moisture-resistant)
Environmental friendliness	No (Pb-contained)	Good
Cost	Moderate	Low
Main applications	Energy harvesting, sensors, piezoelectric pavements	Pressure sensors, piezoelectric pavements

practically adaptable to Vietnamese urban roads, where both traffic densities and pavement structures exhibit comparable characteristics.

2.5. Technical limitations and challenges

Despite proven feasibility, several limitations remain:

- The energy conversion efficiency is relatively low, typically 10-20% [11];

- Durability issues arise under millions of cyclic loadings, with long-term performance still uncertain [12];

- Encapsulation to protect against moisture, dust, and overloads requires further optimization [13];

- Standardized life-cycle cost assessment (LCCA) frameworks have not yet been established for piezoelectric pavements [14];

These challenges highlight the necessity of localized studies to validate theoretical expectations under specific traffic and climatic conditions.

3. Research methodology

3.1. Research framework and scope

This study evaluates the feasibility of integrating piezoelectric modules into urban pavement structures to harvest energy from vehicular loads. The selected case is Route 353 (Hai Phong - Do Son), which carries a representative mixed traffic flow with high shares of passenger cars, motorcycles, and trucks. The methodological framework comprises the following steps:

1. Converting traffic volume into Passenger Car Units (PCU) based on the official coefficients defined in Vietnamese Standard TCVN 13592:2022 - Urban roads - Design requirements.

2. Estimating daily axle counts as the total mechanical load input to the pavement.

3. Determining the hit probability phit to estimate the number of impulses acting on modules.

4. Defining the piezoelectric module configuration using the “full-pressure” principle.

5. Establishing embedding rules and optimal placement of modules in pavement layers.

6. Formulating energy harvesting equations and benchmark scenarios (Case A and Case B).

7. Defining module density scenarios (40-200 modules/100m).

8. Comparing harvested energy with urban infrastructure demands (lighting, traffic signs, surveillance systems).

3.2. Traffic conversion into PCU

In Vietnam, traffic is highly heterogeneous. To standardize the analysis, this study applies the conversion coefficients from TCVN 13592:2022 - Urban roads - Design requirements [15].

Table 2. PCU conversion coefficients

Vehicle class	PCU factor
Motorcycle	0.3
Passenger car	1.0
2-axle truck, small bus	2.0
≥3-axle truck, large bus	2.5
Tractor–semitrailer	3.0

The daily PCU is computed as:

$$PCU_{day} = \sum_i N_i \times f_i \quad (5)$$

where: N_i is daily volume of vehicle class *I; f_i* is PCU factor from TCVN 13592:2022.

Application to Route 353:

- Motorcycle lanes: operating speed <50 km/h → PCU = 0.3.

- Car/truck lanes: operating speed 60-70 km/h → PCU = 2.0-2.5.

3.3. Axle counts and hit probability

a) Axle counts

Average axle numbers were assigned as follows:

- Passenger cars, small buses, large coaches: 2;
- LGV and 2-axle trucks: 2;
- 3-axle trucks: 3;
- ≥4-axle trucks: 4;
- Tractor-semitrailers: 5-6 (average 5.5)
- Motorcycles: 2 contact points (front & rear);

Formula:

$$N_{axle} = \sum_i N_i \times a_i \quad (6)$$

where a_i is the average axle number of class *i*.

b) Hit probability

The selected hit probability values of 5%, 10%, and 20% were not arbitrary but were based on experimental and simulation results reported in international studies. When modules are embedded without alignment to dominant wheel paths, the effective hit probability can be as low as 5-10% [13]. Conversely, when modules are strategically aligned with wheel paths, the hit ratio may reach up to 20%. Therefore, the present study adopts 5% as a conservative scenario, 10% as a typical scenario, and 20% as an optimized scenario to reflect practical ranges of pavement integration.

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Not all axles pass directly over modules. Thus:

$$N_{hit} = N_{axle} \times p_{hit} \quad (7)$$

Scenarios:

- p_{hit}=5%: non-optimized alignment;
- p_{hit}=10%: moderate alignment;
- p_{hit}=20%: optimized along wheel paths;

3.4. Piezoelectric module configuration and full-pressure principle

A "full-pressure" piezoelectric module was selected, as described in ***Fig. 3***, where the entire wheel load is directly transferred through the load plate into the piezoelectric ceramic block, while the base acts solely as support. This arrangement enhances conversion efficiency by avoiding load sharing. PZT-5H ceramics, with compressive strength up to 0.9 GPa, were used to ensure structural safety under vehicular loads. The module consists of a load plate, piezoelectric element, base, sealing rings, and anti-shift blocks [12].

Table 3. Full-pressure piezoelectric module configuratio

Component	Function	Notes/Source
Load plate	Transfers wheel load directly to PZT	No load transmitted to base edges
PZT-5H ceramic	Converts mechanical stress into electricity	$\sigma_{compression}$ ≈ 0.9 Gpa
Base & sealing	Provides environmental protection, not load-bearing	Encapsulation with anti-shift blocks

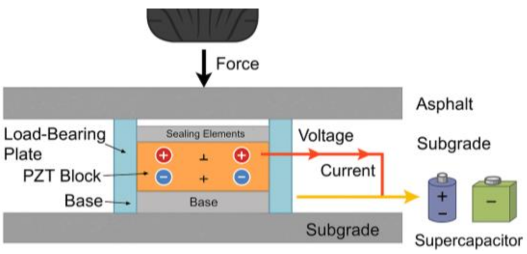

Figure 3. Full-pressure piezolectric module and

3.5. Embedding rules and optimal placement

a) Embedding rules

- Modules should be embedded 2-4 cm below the surface of asphalt or concrete layers.
- This depth ensures effective load transfer while preventing environmental damage (e.g., moisture).
- A protective epoxy mortar or fine asphalt overlay is recommended.

b) Optimal placement

Modules must be positioned along dominant wheel paths. Wheel paths are identified using traffic video recordings or sensor surveys. If modules are misplaced laterally by 10-15 cm, harvested energy may decrease by 40-60% [13].

Fig. 4 illustrates the recommended embedding depth and optimal placement of the modules along dominant wheel paths.

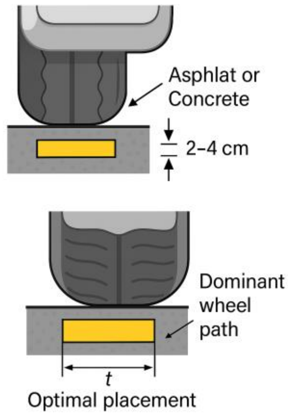

Figure 4. Embedding rules and optimal placement

3.6. Energy equations and benchmark scenarios

Harvested energy per impulse is given by Formula 3.

Case A represents the impulse energy measured in laboratory reference tests under controlled loading of 0.7 MPa, where peak stresses are applied directly to the module surface [5]. This condition produces relatively high impulse energy per hit (≈0.058 J). In contrast, Case B reflects the steady-state energy delivered through an electrical load under optimal matching resistance, where significant coupling losses occur [10], yielding a much lower per-hit output (≈4.7×10^{-4} J). In real road applications, actual output is expected to fall between these two cases, depending on module robustness, load magnitude, and circuit efficiency. Thus, Case A serves as an upper-bound estimate, while Case B represents a lower-bound scenario.

Daily energy harvested per module:

$$E_{day,100m} = N_{hit} \times E_{impulse} \quad (8)$$

3.7. Module density and scenario configurations

Module density was considered as a key parameter:

- 40 modules/100m (baseline);

- 100 modules/100m (intermediate);
- 150 modules/100m;
- 200 modules/100m (maximum in this study).

Formula for 100-m segment:

$$E_{day,100m} = E_{day,mod} \times N_{mod} \qquad (9)$$

where N_{mod} is the number of modules per 100 m;

3.8. Infrastructure energy demand for comparison

To evaluate application potential, harvested energy is compared with actual urban infrastructure demand:

Street lighting:

$$E_{demand} = P_{LED} \times N_{NED} \times t_{op} \qquad (10)$$

with: E_{demand} (Wh/day or kWh/day) → The total daily energy demand of the infrastructure system (e.g., street lighting, traffic signs, surveillance cameras). This is the final value used to compare with the harvested energy from piezoelectric modules;

P_{LED} (W) → The rated power of each LED lamp or device. For example, street lighting LEDs typically consume 30-60 W per unit, while surveillance cameras consume 15-30 W;

N_{LED} (quantity) → The number of LED lamps or devices along the study segment (e.g., 1 km);
In the case study: 40 lamps/km;

t_{op} (h/day) → The average daily operating time; For street lighting: typically, 10-12 h/day (nighttime). For surveillance cameras: up to 24 h/day;

Example:

Assume: $P_{LED} = 30W$; $N_{LED} = 40\ lamps/km$; $t_{op} = 10h/day$ then:

$E_{demand} = 30 \times 40 \times 10 = 12{,}000$ *Wh/day/km* = *12 kWh/day/km* → This represents the basic daily energy demand for lighting a 1-km road segment.

Thus:
- P_{LED} indicates device power capacity;
- N_{LED} indicates system scale;
- t_{op} indicates usage cycle;
- E_{demand} is the final outcome used for comparison with harvested energy from piezoelectric pavements;

4. Energy Yield Calculation for Route 353

4.1. PCU conversion

Traffic survey data on Route 353 (Hai Phong - Do Son) reported 30,873 vehicles/day [16], consisting of 13,961 passenger cars, 13,722 motorcycles, 1,049 light trucks (LGV), 443 2-axle trucks, 306 3-axle trucks, 329 4-axle trucks, 467 minibuses, and 596 large coaches.

Following Vietnamese Standard TCVN 13592:2022, conversion coefficients were applied (motorcycle = 0.3; car = 1.0; 2-axle truck & minibus = 2.0; ≥3-axle truck & large bus = 2.5; tractor-semitrailer = 3.0).

Table 4. PCU conversion for traffic on Route 353

Vehicle type	Vehicles/day	PCU factor	PCU/day
Passenger car	13,961	1.0	13,961.0
LGV (light truck)	1,049	2.0	2,098.0
2-axle truck	443	2.0	886.0
3-axle truck	306	2.5	765.0
4-axle truck	329	2.5	822.5
Minibus	467	2.0	934.0
Large coach	596	2.5	1,490.0
Motorcycle	13,722	0.3	4,116.6
Total	**30,873**	—	**25,073.1**

4.2. Axle counts and impulse estimation

Each vehicle class was assigned an average axle number: Cars, minibuses, and coaches=2; LGV/2-axle trucks=2; 3-axle trucks=3; 4-axle trucks=4; motorcycles =2. So, according to Formule 6, the daily axle shall be defined ad ***Table 5***. Although motorcycles account for 43.8% of daily axle passes, the energy calculation model currently applies an average impulse energy per hit across all classes. This assumption risks overestimating motorcycle contributions, since actual piezoelectric output scales with axle load. The results should therefore be considered as an upper-bound estimate for motorcycles. The relationship between daily axle counts and harvested energy levels is depicted in **Fig. 5**.

Table 5. Daily axle counts on Route 353

Vehicle type	Vehicles/day	Avg. axles	Axles/day
Passenger car	13,961	2	27,922
LGV	1,049	2	2,098
2-axle truck	443	2	886
3-axle truck	306	3	918
4-axle truck	329	4	1,316
Minibus	467	2	934
Large coach	596	2	1,192
Motorcycle	13,722	2	27,444
Total	**30,873**	—	**62,710**

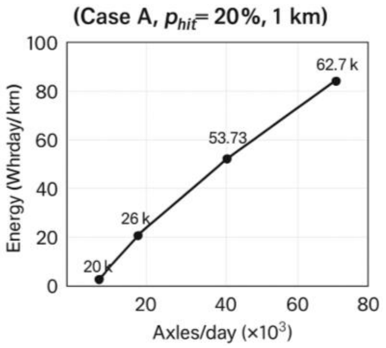

Figure 5. Axle count vs Enery harvest

Not all axles strike the modules and assuming 40 modules/100m placed along wheel paths, the daily impulses are:

$$N_{hit,mod} = N_{axle} \times p_{hit}\ ; \quad (11)$$

$$N_{hit,mod} = N_{axle} \times p_{hit} \times 40$$

Table 6. Impulse counts under different hit probabilities

p_{hit}	Impulses/day/ module	Impulses/day/100 m (40 modules)
5%	3,136	125,420
10%	6,271	250,840
20%	12,542	501,680

4.3. Energy output for 100 m (40 modules)

Table 7. Harvested energy per 100 m/day

p_{hit}	Case A (Wh/day)	Case B (Wh/day)
5%	2.02	0.016
10%	4.04	0.033
20%	8.08	0.065

Scaling to 1km (400 modules) yields:

Table 8. Harvested energy per 1 km/day

p_{hit}	Case A (Wh/day)	Case B (Wh/day)
5%	20.2	0.16
10%	40.4	0.33
20%	80.8	0.65

Comparison with demand:

- Street lighting (40 × 30 W LED, 10 h): ≈ 12,000 Wh/day/km → harvested energy covers only 0.2-0.7%.

- Traffic signs/cameras (500-1,000 Wh/day): Still above current harvest, but partial support is possible when combined with solar PV.

4.4. Sensitivity to module density

Energy scales linearly with module density. For 100-200 modules/100m (1,000-2,000 modules/km), Case A results:

At 200 modules/100m and p_{hit} 20%, output reaches 404 Wh/day/km (corresponds to approximately 404 Wh/day/km, or ≈147kWh/year), sufficient for powering distributed ITS devices. The influence of module density on total harvested energy is demonstrated in **Fig. 6**.

Table 9. Energy output by density (Wh/day/km, Case A)

Density (modules/100m)	p_{hit} 5%	p_{hit} 10%	p_{hit} 20%
100	50.5	101.0	202.1
150	75.8	151.5	303.1
200	101.0	202.1	404.1

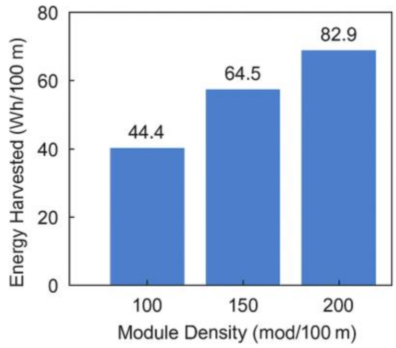

Figure 6. Sensitivity to module density

4.5. Investment cost framework (CAPEX)

The unit module cost of approximately 200 USD was referenced from [3], whose products are primarily designed for pedestrian applications. Such figures likely underestimate the cost of vehicular-grade modules, which require reinforced encapsulation and enhanced durability. For this reason, the present CAPEX calculations should be viewed as a conceptual framework rather than actual procurement prices. Studies by Innowattech [1] and California Energy Commission [17] reported significantly higher costs for vehicular road-energy harvesting projects, suggesting that future commercial deployment will likely involve more expensive modules.

The cost model is structured as:

$$CAPEX_{100} = N_{mod} \times (C_{mod} + C_{inst}) + C_{elec,100} + C_{civil,100} \quad (12)$$

where:

- N_{mod}: Number of modules per 100m;

- C_{mod}: Unit module cost;

- C_{inst}: Installation cost per module (~60 USD, ~30% of device cost);

- $C_{elec,100}$: electronics (rectifiers, BMS, storage), ~4,800 USD/100m;

- $C_{civil,100}$: civil works (cutting, resurfacing), ~3,200 USD/100m [17].

Example results (100m, one lane):

- 100 modules: ~0.85 billion VND;
- 150 modules: ~1.18 billion VND;
- 200 modules: ~1.50 billion VND.

These values align with Innowattech's reported costs (~650,000 USD/km for 100kW system) [1].

Although the annual energy output is modest (~147 kWh/year per km), the investment cost remains relatively high (0.85-1.50 billion VND per 100 m), resulting in a levelized cost of energy significantly above the grid electricity tariff. From a pure energy perspective, the system is not yet economically competitive. However, its value lies in enabling distributed off-grid power supply for ITS sensors, surveillance, and electronic signage, where the alternative-laying dedicated power cables-can be more expensive in practice.

4.6. Discussion

PCU according to TCVN highlights passenger cars and heavy trucks/buses as dominant in traffic impact, while motorcycles, despite high numbers, contribute less due to PCU = 0.3.

Energy yield depends primarily on axle counts and hit probability; thus, optimizing module placement along wheel paths and increasing density are key.

At 40 modules/100m, harvested energy is too small for real use; increasing to 150-200 modules/100m with $p_{hit} \geq 20\%$ yields 0.3-0.4 kWh/day/km, practical for powering low-demand distributed devices.

Investment costs remain high compared to yield; thus, applications should target distributed off-grid systems (signs, sensors, IoT nodes).

5. Conclusion

The findings of this study confirm the potential of piezoelectric pavement technology for harvesting energy from vehicular loads, particularly when analyzed using the PCU conversion factors defined by TCVN 13592:2022, which accurately reflect Vietnamese traffic characteristics. Passenger cars and heavy trucks/buses dominate traffic impact, whereas motorcycles, though numerous, have limited influence, resulting in more realistic energy assessments. At the baseline density of 40 modules per 100m, harvested output is only a few Wh/day/km, insufficient for powering street lighting or electronic signage. However, increasing density to 150-200 modules per 100 m with a hit probability $p_{hit} \geq 20\%$ can achieve 0.3-0.4 kWh/day/km (corresponds to approximately 110-146 Wh/day/km, or 110-146 kWh/year), sufficient to power distributed devices such as surveillance cameras, ITS sensors, or electronic signs. Current investment costs remain high, ranging from 0.85 to 1.50 billion VND per 100 m, yet the added value lies in providing distributed energy supply, reducing cabling costs, and enhancing energy autonomy for smart infrastructure. Therefore, short pilot sections of 100-300 m should be implemented to calibrate real-world data, while developing national standards for module design and embedding practices, and testing deployments on motorcycle lanes or sidewalks to minimize risks and initial expenses. Future research should focus on long-term durability assessment under tropical climate conditions, optimization of power electronics for local traffic spectra, and hybrid integration of piezoelectric systems with solar photovoltaics to improve efficiency. These directions not only strengthen the scientific foundation of the technology but also open pathways for practical implementation in sustainable urban transport infrastructure development in Vietnam.

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