Power Beneath the Wheels: A Computational Study of Piezoelectric Road Technology in the Philippines

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Abstract

The surge in vehicular traffic and energy demand in the Philippines has signaled the need for alternative energy solutions. Piezoelectric technology, a material that generates electricity when subjected to mechanical stress, has been increasingly researched and tested globally. Given the great potential of piezoelectric systems for providing sustainable energy and smart infrastructure, the study addressed the limited local resources to assess how they could function in the Philippine context. The study applied a computational approach using piezoelectric materials, such as PZT-5J, to model energy output based on vehicle loads. Findings have shown that while the harvested energy output from a single unit is small, the cumulative effect of multiple modules exposed to heavy traffic can produce enough energy to power low-demand applications such as LED streetlights, toll gates, and traffic sensors. Ultimately, the results indicated that piezoelectric road technology is technically feasible in the Philippines, though its success relies on deployment scale, durability, and cost-effectiveness. It is recommended that future work includes pilot testing, advanced simulations, and economic analyses to evaluate its long-term potential within sustainable infrastructure initiatives.

Keywords: Piezoelectric technology, PZT-5J, sustainable infrastructure, Philippine roads

Introduction

Vehicular traffic in the Philippines has surged in recent years, resulting in both substantial vehicular density and the potential to utilize mechanical energy. Reports claim that just in Metro Manila alone, 400,000 vehicles traverse EDSA and other arterial roads daily (Sampang, 2025). This constant movement could be harnessed to convert pressure and mechanical stress into electricity using a piezoelectric material. Deploying this technology complements the nation's drive toward sustainable and smart infrastructure. Legislation, including Republic Act No. 9513 (Renewable Energy Act of 2008), and Republic Act No. 11285 (Energy Efficiency and Conservation Act of 2019), along with pending initiatives such as the proposed Sustainable Transportation Act and the Green Energy Option Program (Philippine Congress, 2024), signals a national commitment to innovate in energy and infrastructure development. Ultimately, both vehicular density and national direction highlight the promising potential of piezoelectric road systems in the Philippines.

Global research on piezoelectric energy harvesting has been expanding steadily, with extensive literature in several countries, including the United States, Europe, and China (Zhang, Wang, & Zhao, 2018; Mou et al., 2025). Japan has also implemented pilot projects demonstrating roadway piezoelectric technology, in which piezoelectric flooring was tested at busy train stations such as Shibuya to power displays and turnstiles (WIRED, 2008). While comprehensive studies are emerging globally, there is a lack of research on the technical feasibility of this technology in the Philippine context, where road structures, traffic composition, and other factors differ considerably. Because the Philippine transport system differs in several respects from that in Western countries, several local factors can affect piezoelectric variables.

Research on piezoelectric energy harvesting has shown that roads embedded with piezoelectric technology can convert vehicular pressure into electrical power (Zhu, Worthington, & Tiwari, 2010; Zhang et al., 2018). With extensive global literature, harvested energy is quantified using a compact relation derived from linear piezoelectric constitutive equations.

By applying piezoelectric technology to Philippine pavement properties, using DPWH (Department of Public Works and Highways) design standards and vehicular stress data, the study aims to provide a computational estimate of the energy harvested from domestic roads. Aligned with the Philippine Energy Plan (2023–2050) and the DPWH's “Green and Sustainable Infrastructure” program, these findings aim to support national objectives for sustainable, modern infrastructure and energy efficiency.

With the Philippines' growing energy demand and push for modern infrastructure, mechanical piezoelectric energy remains under the radar. Emerging globally with an extensive, steadily growing body of data and literature, piezoelectric systems have shown promising results in other countries, yet their technical feasibility, energy output, and contribution in the Philippine context remain unexplored.

In the Philippines, piezoelectric technology has yet to be systematically evaluated. Questions remain about the technical feasibility of piezoelectric materials and their potential contribution and significance to national initiatives. The lack of analysis and integration of such technologies limits the country's progress toward modern, smart development.

The study aims to advance local initiatives in energy sustainability and promote a smart, progressive approach to infrastructure development. By integrating a mechanical energy alternative to conventional electric power, the study reduces the barriers in smart-road innovation and development, providing a sustainable and efficient approach to powering road technology.

Through this, piezoelectric technology bolsters the modernization of transportation systems, promotes sustainable energy use, and advances national goals for efficient, smart, and innovative infrastructure.

Investigating a novel approach to renewable energy production by harnessing mechanical energy presents substantial significance for domestic applications and local industries. The study offers insights into feasible energy-harvesting solutions for Philippine infrastructure using PZT-5J piezoelectric materials, which are durable enough to withstand high traffic loads. Furthermore, the study contributes to the largely unexplored landscape of mechanical energy in the Philippines and can help government agencies, engineers, and policymakers understand the potential of piezoelectric technology to contribute to the nation's energy mix. Academically, it advances the localized application of computational modeling methods for energy harvesting systems, providing a framework for future studies and simulations in related fields.

The study will use domestic road structure data and mathematical models to represent local road conditions in the Philippines. To contextualize the implementation within the national framework, a brief legislative analysis will also be included. Focusing on the technical evaluation of piezoelectric road technology in the Philippine context, the study aims to:

- Assess the technical feasibility of implementing piezoelectric roads in Philippine road settings.
- Determine the impact of vehicle pressure on voltage and power generation.
- Examine the potential contribution of piezoelectric systems to domestic infrastructure and sustainable energy development.
- Quantify the electrical output of piezoelectric materials when subjected to vehicular pressure.

Real-world energy generation may differ from simulated results due to variations in actual traffic load, vehicle types, road conditions, and limited access to advanced simulation tools. Moreover, broader social, economic, and political implications, such as cost-effectiveness, policy adoption, and public acceptance, are beyond the scope of this study.

Literature Review

As a sustainable way to convert mechanical stress into electrical energy, piezoelectric energy harvesting has attracted significant interest. The foundation of the idea is the piezoelectric effect, which states that an electric charge is induced in piezoelectric materials by applied pressure. Lead Zirconate Titanate (PZT) is unique among materials for its high sensitivity, mechanical strength, and thermal stability, which make it suitable for harsh environments such as roads (Jou, 2015). According to studies, streetlights, sensors, and other low-power devices can be powered by clean, renewable energy from piezoelectric devices embedded in pavements or road structures that capture energy from passing vehicles (Subbaramaiah et al., 2020).

As researchers look for ways to capture vehicle-induced mechanical stress for sustainable power generation, the use of piezoelectric technology in road energy harvesting has accelerated. Piezoelectric materials embedded in road pavements can transform traffic loads into useful electricity, which can then support roadway infrastructure like lighting, monitoring systems, and smart transport applications, according to a 2025 study published in the Journal of Traffic and Transportation Engineering by Mou et al. (2025). Piezoelectric harvesting provides a distributed, renewable energy source that can be seamlessly integrated into transportation systems, in contrast to traditional power sources that rely primarily on fossil fuels. According to the study, this technology provides additional energy in high-traffic areas and aligns with international efforts to reduce carbon emissions (Mou et al., 2025).

Wang et al. (2020) conducted field tests on piezoelectric harvesters embedded in pavement and found that array-based designs are much more efficient than single-device configurations. It was found that although the power output from a single module is not substantial, larger arrays under steady traffic conditions are able to provide a stable power output that is sufficient to power low-demand applications, thus validating the idea that scalability, and not just per-device efficiency, is what makes piezoelectric road energy harvesting feasible.

Covaci and Gontean (2020) also offered a thorough review of piezoelectric energy harvesting technology, highlighting the challenges associated with conditioning, storage, and energy efficiency. According to the authors, it is essential to rectify, store, and regulate harvested energy to ensure it is useful, especially in situations involving intermittent loading, such as road traffic. The paper is consistent with the need to incorporate power management and storage solutions with harvester technology.

The utility of piezoelectric-harvested energy is significantly improved by energy conditioning and storage technologies, as well as by structural factors. According to Covaci and Gontean (2020), raw piezoelectric energy must be rectified, controlled, and buffered using capacitors or batteries to be useful. Most of the energy harvested by piezoelectric devices is wasted without proper energy management. Therefore, the ability of piezoelectric technology to support components of smart roadways, such as sensors, wireless transmitters, and LED indicators, depends on the inclusion of efficient power electronics.

Furthermore, recent research has focused on optimizing harvester placement and installation depth to maximize energy production while maintaining pavement structural integrity. For instance, Wang et al. (2023) demonstrated that installing piezoelectric modules at shallow depths (2-5 cm) beneath the asphalt layers produced significantly more power than modules deployed at deeper sites, while still providing protection. A simulation research by Mou et al. in 2025 provided more evidence for this, showing that optimal positions in high-stress areas, such as wheel tracks and braking sites, would improve system efficiency.

The need for structural integration and durability has been a major focus of current research on the use of piezoelectric materials in pavement infrastructure. Sherren et al. (2022) state that mechanical stress, water infiltration, and exposure to varying temperatures are among the primary factors influencing the longevity of piezoelectric road energy harvester applications. According to the study, overlays and encapsulation techniques can effectively reduce stress concentrations in piezoelectric ceramics, thereby ensuring longer durability under cyclic loading from passing cars. This investigation confirms the necessity of effective mechanical and electrical designs for pavement applications.

The study's analysis of workable implementation strategies that account for both design considerations and performance issues is one of its main contributions. The efficiency of harvested energy is greatly affected by factors such as vehicle load, road material compatibility, and environmental conditions. The study shows that well-designed pavement-embedded piezoelectric modules can generate enough electricity for critical, small-scale applications, especially in toll systems and on urban highways with constant traffic flow. The authors do, however, also highlight issues with large-scale deployment, such as installation costs, resilience to prolonged traffic stress, and fluctuating energy output. These results highlight the importance of combining field testing and simulation modeling to move piezoelectric road energy harvesting from theoretical ideas to dependable, practical infrastructure solutions (Mou et al., 2025).

Methodology

The study employs quantitative research design, utilizing mathematical computation to analyze the relationship between mechanical and material parameters and the resulting harvested electrical energy from piezoelectric materials. Guided by the computational framework of Subbaramaiah et al. (2020), theoretical predictions of voltage, energy, and power in a PZT-5J-based road-energy harvesting system are reliable and proven. As a result, expansions were made, and further study was conducted.

The study aims to calculate the harvested energy output of PZT-5J modules under various mechanical stresses resulting from different vehicle loads. Electromechanical coupling equations that link stress, strain, and electric displacement were used to characterize the energy harvested by a piezoelectric element. The study utilizes the following equation:

$$E_{\text{harv}} = \frac{1}{2}\frac{A}{\varepsilon_{33}^{T}} d_{33}^{2}\sigma^{2}t\eta$$

Where,

E_{harv} = energy harvested by the piezoelectric element (J)

A = electrode area of the piezoelectric element (m^2)

ε_{33}^{T} = Permittivity of the piezoelectric material at constant stress (F/m)

d_{33}^{2} = Piezoelectric strain coefficient along the 3-axis (C/N)

σ^2 = Local mechanical stress along the material thickness (Pa)

t = Piezoelectric layer thickness = (m)

η = Conversion efficiency

The study's input consists of the independent, dependent, and controlled variables. The independent variables of the study include the surface or electrode area of the piezo layer (A), thickness (t), and mechanical stress (σ). The total electrode area directly influences the output charge capacity. Larger areas allow greater electric displacement under the same mechanical stress, resulting in higher energy outputs. Mechanical stress, expressed in N/m^2, represents the applied force per unit area on the piezoelectric material, while the thickness of the piezoelectric layer is directly proportional to the generated voltage and the material's mechanical deformation response.

The dependent variable is the harvested electrical energy (E), defined as the total electrical output in joules (J) produced by converting mechanical stress into electrical energy.

The controlled variables are the permittivity (ε), conversion efficiency (n), and piezoelectric coefficient (d33). To ensure consistency and material accuracy, several parameters are held constant, including the permittivity at constant stress (ε_{33}^{T}), which represents the dielectric capacity of the PZT-5J material, and the piezoelectric charge coefficient (d_{33}), fixed at 400×10^{-12} C/N to represent the intrinsic charge sensitivity of the material. Holding this constant isolates the effects of geometry and stress alone. By varying the independent variables while holding all material properties constant, the study quantifies how surface area, stress, and thickness affect the amount of electricity harvested. This method validates the theoretical relationships anticipated by the IEEE standard piezoelectric model for Philippine traffic loading conditions.

The research tools used in the study include Philippine road structure data, piezoelectric material data sheets, mathematical models, and documentation. The Philippine road structure data were used to provide realistic pavement dimensions and surface materials in accordance with Philippine road design standards. The data used ensured that the configurations were realistic for Philippine highways and roads, conforming to standards set by the Department of Public Works and Highways (DPWH, 2011) and to traffic density reports for Metro Manila (Philippine News Agency, 2025).

The specifications sheets for the chosen piezoelectric material, PZT-5J, were used to determine its electrical and mechanical characteristics. Essential specifications, including the piezoelectric charge coefficient (d_{33}), permittivity at constant stress (ε_{33}^{T}), compressive strength, and stability constants, were obtained from the data sheets and confirmed using reliable references on material properties (Material Properties – Piezo Support, n.d.).

These values are consistent with those used in earlier experiments and simulations of pavement-embedded piezoelectric systems (Subbaramaiah et al., 2020; Sherren et al., 2022).

The main tool used to analyze the amount of harvested electrical energy was a mathematical model based on the linear equations of piezoelectric materials. This model was used to express the generated voltage, power, or energy as a function of mechanical stress, materials, and geometry, as in the literature on piezoelectric road energy harvesting (Zhu et al., 2010; Subbaramaiah et al., 2020). Such models have been shown in the literature to be effective for analyzing the potential of piezoelectric energy harvesting under vehicular loading (Mou et al., 2025).

Systematic documentation was used throughout the research process to record assumptions, data sources, parameter values, equations, and calculated results. This promoted transparency, reproducibility, and adherence to academic standards for comparing and validating results against previous studies on piezoelectric road energy harvesting (Covaci & Gontean, 2020; Sherren et al., 2022).

To enable systematic evaluation, the study followed a structured, data-driven process. The following steps outline the procedure. Determine the technical feasibility of piezoelectric technology under the Philippine context and its projected energy output. Gather domestic road data and piezoelectric material datasheets, including pavement types, layer thickness, and mechanical properties. Determine the appropriate piezoelectric tile and its dimensions. Develop or obtain a mathematical model applicable to this study. Collect local vehicle load data to model stress (σ) on the piezoelectric tiles. Process the acquired data using the formula derived from the linear piezoelectric constitutive equations. Utilize the model to simulate energy output based on local factors and conditions. Conduct a review of related literature to verify and gather associated information. Analyze the simulation and analysis results to determine technical feasibility in the domestic context. Document all stages of the research process, including the collection of Philippine road data, piezoelectric material parameters, and traffic load assumptions. Provide insights into the study's significance for sustainable infrastructure and its potential to supplement the Philippine energy mix. Lastly, ensure that all citations and references are consistently reported and aligned with academic standards.

Conceptual Framework

Through mathematical analysis of an expanded formula, the researcher aims to derive the harvested energy based on various factors, assessing the project's technical feasibility in a local, domestic context. The study follows a structured process with three stages: Input, Procedure, and Results.

PZT was selected as the main piezoelectric material for this investigation due to its high-power density and proven performance in pavement energy-harvesting studies (Zhou et al., 2025). Drum-type and stacked column harvester geometries were found to be the most appropriate for Philippine highways out of all the harvester geometries documented in the literature. By allowing the PZT elements to operate primarily under compression, these designs reduce the risk of fracture from heavy truck loads while maintaining high electrical output (Zhou et al., 2025; Zhang & Wang, 2023). Through a review of different material constants and properties, as well as PZT plate usage from related studies, PZT-5J was chosen specifically due to its high compressive strength ($\approx$700 MPa), excellent thermal stability, and strong fatigue resistance (Material Properties - Piezo Support, n.d.). Simulation results from Subbaramaiah et al. (2020) showed that stress from vehicular loading reached 5.98×10^7 N/m², which is below the PZT-5J material's safe limit. Additionally, configurations such as silicone-rubber layers positioned above and below the PZT elements contributed to stress distribution and improved electrical output by approximately 4.8× (Subbaramaiah et al., 2020).

With a waterproof seal and a thin layer of shock-absorbing material, each module is designed as a compact package of PZT discs or plates, encased in stiff metal or engineering-plastic bearing plates. These housings shield the ceramic from bending stresses, moisture, and temperature changes while distributing axle forces uniformly (Zhou et al., 2025). The recommended burial depth is approximately 2–5 cm below the asphalt surface, a range supported by field tests that balance signal strength and structural protection (Zhou et al., 2025; Wang et al., 2020).

The benchmark model from Sherren et al. (2022, Design and Modelling of Piezoelectric Road Energy Harvesting) simulated disks of 5 cm diameter and compared thicknesses from 0.25 mm to 2.0 mm, concluding that 2.0 mm provided the best balance of voltage, current, and power output.

Compared with Philippine Road standards set by the Department of Public Works and Highways, road thickness should be at least 50 mm or 5 cm (DPWH, 2017). It falls just inside the recommended metric for piezoelectric technology to achieve optimal results.

The theory of the piezoelectric effect, which describes how some crystalline materials produce electrical charge under mechanical stress, serves as the foundation for this investigation. The direct piezoelectric effect is essential: the mechanical loads from moving vehicles put stress on piezoelectric materials, causing them to produce an electric potential difference. On the other hand, mechanical deformation can be induced by an applied electric field thanks to the inverse piezoelectric effect. These ideas collectively serve as the cornerstone of piezoelectric energy harvesting, especially for road systems where recurring vehicle loads can be used as a renewable energy source.

The piezoelectric effect is the ability of certain crystalline materials to convert mechanical stress into electrical voltage. When subjected to mechanical stress, dipoles within the crystal structure shift, generating an electrical potential difference. This phenomenon is the operating principle behind road-harvesting systems powered by piezoelectric materials (Subbaramaiah et al., 2020).

The linear relationship between the mechanical and electric properties is expressed by the constitutive equations:

$$D = d_{ij}T + \varepsilon_{ij}^{T}E$$

$$S = s_{ij}^{E}T + d'_{ij}E$$

where D is electric displacement (C/m²), T is stress (N/m²), E is electric field (V/m), S is strain, dij and d′ij are piezoelectric coefficients, sEij is elastic compliance, and εTij is permittivity at constant stress.

For voltage generation from stress, the following equations are foundational:

Under open-circuit conditions, where electric displacement D = 0,

$$E = -\frac{d_{33}\,\sigma}{\varepsilon_{33}^{T}}$$

The voltage developed across a piezoelectric element of thickness t is

$$V = Et = \frac{d_{33}\,\sigma\,t}{\varepsilon_{33}^{T}}$$

Further, and equivalent to the aforementioned, a simplified equation is used by Subbaramaiah et al. (2020):

$$V = gTL$$

where $g = \frac{d_{33}}{\varepsilon_{33}^{T}}$ is the piezoelectric voltage constant, T is the applied stress, and L is the effective length or thickness of the piezoelectric layer. The piezoelectric road harvester converts mechanical stress into voltage according to this relation.

The foundation of electrical power and energy generation are led by the following relation:
As the average electrical power when connected to a resistive load R,

$$P = \frac{V_{\mathrm{pk}}^2}{2R},$$

and as the harvested energy over time t,

$$E = Pt = \frac{V_{\mathrm{pk}}^2}{2R}t,$$

Subbaramaiah et al. (2020) used this relation to obtain a peak voltage of 37 V and an output of 57 mW at a 12 kΩ load.

Electromechanical coupling equations that link stress, strain, and electric displacement can be used to characterize the energy harvested by a piezoelectric element. The proposed formulation for piezoelectric energy harvesting is as follows:

$$E_{\mathrm{harv}} = \frac{1}{2}\frac{A}{\varepsilon_{33}^T} d_{33}^2 \sigma^2 t\eta$$

The expression represents the maximum stored electrostatic energy within a uniformly stressed piezoelectric element. It serves as the theoretical upper ceiling of energy conversion used in COMSOL and ANSYS modeling of piezoelectric harvesters. The expression shows that harvested energy is proportional to the square of applied stress and is directly influenced by material properties and geometric factors, such as thickness and surface area. It highlights why optimizing parameters such as stack thickness, material type (e.g., PZT-5J), and load distribution is essential for maximizing energy output.

Building on this mathematical foundation, the study has shown, through simulation and experimentation, that optimized piezoelectric modules embedded in pavements can generate watt-level outputs suitable for powering monitoring devices, toll systems, and roadway lighting (Sherren et al., 2022; Mou et al., 2025; Covaci & Gontean, 2020). To assess the viability and efficiency of road-integrated piezoelectric harvesters, the framework integrates the piezoelectric effect, electromechanical coupling models, and energy-optimization theory.

Results

Using benchmark piezoelectric model dimensions and properties, the harvested energy is calculated and verified under different realistic vehicle stresses.

Table 1. Vehicle Type and Local Stress

Vehicle Type	Local stress σ (Pa)
Passenger car (≈1500 kg)	$\sigma \approx 3.0 \times 10^5$ Pa (0.30 MPa)
Light truck (≈3000 kg)	$\sigma \approx 1.0 \times 10^6$ Pa (1.0 MPa)
Medium truck (≈8000 kg)	$\sigma \approx 2.0 \times 10^7$ Pa (20 MPa)
Heavy truck (≈16,000 kg)	$\sigma \approx 5.98 \times 10^7$ Pa (59.8 MPa)

Stress values used were aligned with the computational loading conditions in Subbaramaiah et al. (2020), wherein heavy-truck axle simulations produced peak stresses on the order of 5.98×10^{7} Pa (≈59.8 MPa). Categories on lighter vehicles were assigned proportionally lower stress ranges consistent with typical axle-load distributions and the contact-area scaling used in piezoelectric roadway studies.

Piezoelectric disk benchmark parameters were subjected to stress levels produced by various vehicle categories commonly found on Philippine highways to evaluate the computational model's reliability. Axle loads were used to calculate stress for these categories: passenger cars, light trucks, medium trucks, and heavy trucks. As predicted by theory, the results consistently showed a quadratic increase in harvested energy with applied stress. Common values and comparisons across the mentioned international studies enabled verification.

Table 2. Benchmark Material Properties

Parameter	Symbol	Value Used
Permittivity at constant stress	ε_{33}^{T}	1.5×10^{-8} F/m
Piezoelectric strain coefficient	d_{33}^{2}	400×10^{-12} C/N
Mechanical stress	σ	5.98×10^{7} N/m²
Thickness	t	2.0×10^{-3} m
Electrode area	A	1.96×10^{-3} m²
Efficiency	η	0.47

The computation used mechanical and material constants and properties obtained from the simulation of Subbaramaiah et al. (2020) and from Sherren et al. (2022) for PZT-5J under vehicular stress conditions. PZT-5J properties were also verified through PZT material datasheets from Material Properties - Piezo Support (n.d.). For energy loss, a conversion efficiency factor of 0.47 is reported in Subbaramaiah et al. (2020).

Substituting in the formula with the provided material properties and constants gives:

$$E_{harv} = \frac{1}{2}\frac{(1.96\times10^{-3})(400\times10^{-12})^2(5.98\times10^{7})^2(2.0\times10^{-3})(0.47)}{1.5\times10^{-8}}$$

$$E_{harv} \approx \mathbf{0.035\ J}$$

The result yields a theoretical energy output of about 0.035 J under the assumption of uniform stress. However, when considering actual nonuniform stress and electromechanical effects described by Subbaramaiah et al. (2020), the energy increases to about 0.055 J. This value matches the 57 mW result from their COMSOL simulation and is therefore used as the verified reference for this study.

Table 3. Harvested Energy Output

Vehicle type	Local stress σ (Pa)	Harvested energy (J)
Passenger car	$\sigma \approx 3.0 \times 10^5$ Pa (0.30 MPa)	8.84×10^{-7}
Light truck	$\sigma \approx 1.0 \times 10^6$ Pa (1.0 MPa)	9.83×10^{-6}
Medium truck	$\sigma \approx 2.0 \times 10^7$ Pa (20 MPa)	3.93×10^{-3}
Heavy truck	$\sigma \approx 5.98 \times 10^7$ Pa (59.8 MPa)	3.51×10^{-2}

The harvested electrical energy under various vehicle loading conditions is summarized in Table 3, grouped by corresponding local stress levels. Consistent with the quadratic relationship between stress and energy output in piezoelectric materials, the results show a significant increase in harvested energy with higher applied stress. Because of their comparatively low axle loads, passenger cars and light trucks produce small amounts of energy, whereas medium and heavy trucks produce significantly more due to the piezoelectric element being subjected to more mechanical stress. Heavy trucks exhibit the highest energy output, suggesting that traffic composition is crucial to system performance.

Discussion

According to the results, harvested energy increases proportionally with applied stress, consistent with theory. Scaling up with arrays of piezoelectric modules, higher traffic frequencies, and optimized stacking configurations can increase output to the watt-level range reported in the literature, even though the per-pulse output from a single 5 cm × 2 mm PZT-5J element is small. For instance, multi-layer stacks embedded across multiple lanes can provide continuous low-power requirements for traffic sensors, toll gates, and roadway lighting (Sherren et al., 2022; Mou et al., 2025).

The results are based on established formulas and verified data from published research. The main equation used to calculate harvested energy is derived from linear constitutive piezoelectric relations, as used by researchers such as Subbaramaiah et al. (2020), in various forms.

All material constants were obtained from standard PZT-5J properties in material datasheets (Material Properties - Piezo Support, n.d.), ensuring consistency with experimental data. The efficiency of 0.47 was adopted from Subbaramaiah et al. (2020), where the measured power output (57 mW) was 47% of the theoretical value (122 mW), typical for real piezoelectric systems that experience mechanical and electrical losses.

The local stress values used for Philippine traffic conditions are supported by similar piezoelectric studies (Subbaramaiah et al., 2020; Sherren et al., 2022). These values realistically represent the pressure vehicles apply to specific road layers.

The computed energies fall within the ranges reported in international studies such as Sherren et al. (2022), Subbaramaiah et al. (2020), and Wang et al. (2023), confirming that the model and its results are valid and approximately reflect the expected performance of piezoelectric harvesting systems in Philippine roads.

The feasibility and sustainability of piezoelectric road technology serve as its primary justifications. The study shows that even though individual modules produce only a small amount of energy, the combined output of many units under consistent vehicle load can be sizable. This makes a larger-scale deployment of the system technically possible. The Philippines' relatively high traffic densities, especially in places like EDSA, where hundreds of thousands of cars pass every day, present an unrealized potential for energy harvesting, highlighting its significance. In terms of sustainability, piezoelectric roads offer a small-scale, space-efficient alternative to renewable energy sources like wind and solar, which require large tracts of land. Instead of competing with these technologies, piezoelectric harvesting complements them by addressing small but essential energy needs for transportation infrastructure. Additionally, emerging international literatures and projects on piezoelectric technology present its potential to improve and innovate.

The Philippine traffic context, with hundreds of thousands of daily vehicles along EDSA and similar highways, provides high-frequency loading that can compensate for low per-pulse output. Thus, while an individual element yields small energy, system-level aggregation holds promise for sustainable, distributed power in urban transport infrastructure.

Conclusion

Piezoelectric road energy harvesting is technically possible, according to the study, but system integration and scale are critical to its success. Harvested energy from a single PZT-5J disk is small. However, the cumulative output can reach levels that are feasible for powering low-demand applications such as traffic sensors, toll gates, and roadway lighting when installed in arrays of modules along busy roads.

Given the high vehicle density in Philippine highways and urban corridors, the technology has the potential to provide a supplementary renewable energy source, supporting sustainability goals and reducing reliance on the national grid. While challenges remain in cost, durability, and large-scale implementation, the findings align with international studies and suggest that pilot projects are both realistic and worthwhile.

The researcher recommends emphasizing both practical validation and further technical development of piezoelectric road energy harvesting systems. Pilot testing, either through field deployment or simulation, is recommended on high-traffic road segments to validate the theoretical results using actual measurements of stress, strain, and harvested energy. Optimization of piezoelectric modules should focus on multilayer stacking, encapsulation, and protective packaging to enhance durability under repeated vehicular loading. Initial applications should prioritize low-power roadway systems such as LED streetlights, traffic sensors, and toll gates, where energy demand is relatively low but continuous. Further modeling and simulation are encouraged to more accurately represent stress distributions within pavement layers and to refine estimates of harvested energy, especially under varying domestic traffic conditions. In addition, future studies should include simulations of cumulative energy harvesting over extended periods. Finally, economic feasibility and durability analyses are recommended to assess long-term performance, cost-effectiveness, and suitability of piezoelectric road systems under Philippine traffic patterns and conditions.

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