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COMPARATIVE ECONOMIC ANALYSIS OF PIEZOELECTRIC TRANSDUCERS FOR ROADWAY ENERGY HARVESTING

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Abstract

As global energy demands rise and the push for sustainable infrastructure intensifies, piezoelectric energy harvesting has emerged as a promising technology for capturing energy from road traffic. However, despite numerous advancements in piezoelectric transducer design, there remains a significant gap in the literature regarding the economic feasibility of these systems, particularly from a life cycle cost (LCC) perspective. This study aims to bridge that gap by evaluating and comparing the long-term economic performance of three innovative piezoelectric transducers developed by different research groups. A consistent hypothetical traffic scenario—designed to reflect realistic vehicular flow and axle loading—is used as a basis for analysis. For each transducer, the net present worth (NPW) is calculated over a defined project lifetime, accounting for initial investment, maintenance, energy output, and potential revenue. The results provide critical insights into the cost-effectiveness and scalability of piezoelectric harvesting systems for roadway integration. By highlighting the economic trade-offs and performance metrics of these competing technologies, this study offers valuable guidance for researchers, engineers, and policymakers aiming to implement smart, energy-generating infrastructure.

Keywords: Energy Harvesting, Piezoelectric Technology, Life Cycle Cost Analysis

1. Introduction

Despite notable growth in renewable electricity generation over recent decades, fossil fuels remain the dominant source of global power production [1]. The ongoing reliance on these non-renewable resources presents significant challenges, particularly given their contribution to rising levels of atmospheric CO_2 and other greenhouse gases. These emissions are a major driver of climate change and have prompted many governments to adopt more aggressive renewable energy policies aimed at reducing carbon footprints and fostering long-term sustainability.

As renewable energy technologies become more cost-effective and widely adopted, alternative strategies such as ambient energy harvesting have gained attention for their potential to support sustainable development. Energy harvesting involves capturing residual energy from environmental sources and converting it into usable electrical power. This concept has been explored across various domains to enhance urban energy resilience and environmental sustainability.

Several energy harvesting methods exist, including photovoltaic, thermoelectric, geothermal, electromagnetic, electrostatic, and piezoelectric systems. Among these, piezoelectric transduction—where mechanical stress generates electrical charge—has emerged as particularly promising due to its high power density and voltage output characteristics [2,3].

Transportation infrastructure, particularly roadways, presents a practical setting for piezoelectric energy harvesting. Road surfaces are continuously subjected to dynamic mechanical stress from vehicular traffic, making them ideal for the deployment of piezoelectric transducers (PZTs). When embedded beneath the pavement, these devices convert mechanical strain into electrical energy that can be used to power roadside lighting, sensors, and signage, or potentially supplement the local grid. With over 6.4

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million kilometers of road network in the United States alone, the opportunity for large-scale application is considerable [4].

Piezoelectricity, derived from the Greek word "piezein" meaning "to press," refers to the ability of certain materials to generate electrical charge in response to mechanical stress. This phenomenon was first observed by Pierre and Jacques Curie in 1880 [5,6]. Piezoelectric materials can be naturally occurring (e.g., quartz) or engineered, including ceramics, polymers, composites, and semiconductors. These materials operate primarily in two modes—d_{33} and d_{31}—based on the orientation of the applied stress relative to the material's polarization. The d_{33} mode typically provides higher energy conversion efficiency, making it more suitable for pavement applications [7,8,9].

Among the synthetic piezoelectric materials, lead zirconate titanate (PZT) and polyvinylidene fluoride (PVDF) are the most commonly used in energy harvesting. PZT offers high conversion efficiency, rigidity, and cost-effectiveness, which make it well-suited for rigid pavement integration. PVDF, while less efficient, offers advantages in flexibility and resistance to thermal and chemical stress, making it suitable for applications requiring mechanical adaptability [9,10,11].

Piezoelectric transducers typically consist of piezoelectric materials coupled with metallic electrodes. Various transducer designs—such as Cymbal, Moonie, Multilayer, Cantilever Beam, MFC, THUNDER, and RAINBOW—have been explored for energy harvesting applications. However, most of these designs have not been fully optimized for integration into asphalt pavements [12].

The integration of PZTs into roadway systems began with foundational studies by Kim et al. in 2004 [13], which demonstrated the feasibility of harvesting traffic-induced mechanical energy. This research initiated further investigations into optimizing device performance, durability, and energy output under vehicular loading conditions. Among various designs, cymbal transducers have exhibited promising performance, particularly due to their compatibility with asphalt materials and their high energy conversion efficiency.

Following the initial demonstrations, numerous studies have assessed different piezoelectric prototypes under both laboratory and field conditions. These efforts have primarily focused on understanding mechanical performance, energy yield, and material behavior under traffic-induced stress.

However, despite these technological advancements, economic considerations remain insufficiently addressed. Only a limited number of studies have performed Levelized Cost of Energy (LCOE) analyses for piezoelectric systems embedded in roadways. Most investigations emphasize technical validation without incorporating comprehensive cost-effectiveness or life cycle assessments. Without this economic insight, the scalability and real-world feasibility of piezoelectric energy harvesting systems remain uncertain.

2. Literature review

Following the foundational work by Kim et al. [13], extensive research has been conducted to explore the technical performance of piezoelectric energy harvesting systems through experimental, simulation-based, and field-based investigations.

Several studies have focused on laboratory experiments to evaluate the performance of different piezoelectric configurations under controlled conditions. Kim et al. [14] tested cantilever-based harvesters embedded in speed bumps and pavement, revealing that under-pavement installations were more efficient, with diminishing returns observed when increasing the number of cantilevers above 20 km/h. Daniels et al. [15] achieved 1.2 mW using a cymbal disk sandwich transducer under a 50 N load at 2 Hz, while Cafiso et al. [16] recorded 2.43 mW and 1.6 V from PZT disks under direct compression. Hill et al. [17] assessed Innowattech devices, estimating 0.017 W per unit under 600 vehicles/hour but questioned the claimed performance. Roshani et al. [18] demonstrated enhanced output from multilayer PZT disks embedded between copper plates with increasing load and vehicle speed. Song et al. [19] reported 4.91 Wh/m² using PZT-PZNM cantilevers tested via a Universal Testing Machine under moderate traffic simulations. In related work, Roshani et al. [20] generated 0.45 mW from a PZT pile under 1 kN at 10 Hz.

In subsequent efforts, Kim et al. [21] found that reducing harvester mass increased voltage output, while Guo and Lu [22] introduced an EHPS with layered PZT design optimized to deliver up to 300 mW at 30 Hz. Roshani et al. [23] tested 11 parallel PZT layers using an Asphalt Pavement Analyzer, producing 64.12 mW per tire pass. Jasim et al. [24] employed 64 PZT-5X units in four layers, generating 26.6–30.1 mW under 0.7 MPa at 5 Hz. Wang et al. [25] used MTS testing and observed 11.67 mW under similar pressure at 15 Hz. Rui et al. [26] tested MFC-M8514-P2 cantilevers on a lab shaker and reported enhanced performance across a wide frequency range. More recently, Heller et al. [27] harvested ~50 mWh/month using a cantilever array subjected to 1,500 vehicles/day, sufficient to power roadside LEDs.

Other studies have employed simulation and modeling techniques to optimize transducer design and predict performance. Kim et al. [28] used finite element modeling (FEM) to analyze cymbal transducers and found power output increased with vibration frequency, identifying the metal-ceramic composite as the optimal configuration for engine vibration harvesting. Zhao et al. [29] extended FEM modeling to cymbal devices embedded in asphalt, achieving 1.2 mW at 20 Hz and a potential of 97.33 V (0.06 J). Zhao et al. [30] compared six transducer types (Multilayer, MFC, Moonie, Cymbal, Bridge, Thunder), concluding that multilayer and Thunder offered highest efficiencies, while Cymbal and Bridge transducers were best suited for pavement due to their mechanical compatibility. Zhao and Erturk [31] developed integrated deterministic-stochastic models for multilayer stack harvesters, enhancing predictive capability in infrastructure applications.

Field studies under real-world traffic have also been conducted to assess practical implementation. Wichke et al. [32] monitored vibrations in tunnels and developed a piezoelectric harvester capable of powering an RF-enabled microcontroller despite low energy yields. Xiong [33] evaluated six harvester designs at a weigh station and recorded up to 3.1 mW per truck, with peaks at 116 mW. Building on this, Xiong and Wang [34] installed multiple prototypes in real pavement, demonstrating that axle configuration and load magnitude significantly affected energy output.

While the technical performance of piezoelectric energy harvesters has been well-documented, fewer studies have addressed economic viability. The Levelized Cost of Energy (LCOE) remains the most widely used metric for evaluating cost-effectiveness, especially in high-traffic scenarios where energy generation is optimized. Guo and Lu [22] estimated LCOE values between $19.5 and $57.46 per kWh for their EHPS prototype, assuming a 10–15 year lifespan but excluding installation costs. Moure et al. [35] conducted a more comprehensive analysis, reporting an LCOE of 1.98 €/kWh for cymbal-based systems over 15 years under real traffic.

Additional evaluations by Roshani et al. [20] and Papagiannakis et al. [36] reported LCOE values ranging from $10.78 to $34.7 per kWh, depending on prototype design and assumptions. Papagiannakis et al. specifically found Prototype III to yield $8.7–$34.7 per kWh and Prototype IV to achieve $4.8–$19.4 per kWh over 20 years. These results show that while some prototypes demonstrate improved cost feasibility, they remain more expensive than conventional grid electricity. To close this gap, future research should focus on improving energy output, reducing material and fabrication costs, and conducting full Life Cycle Cost Analysis (LCCA) that includes installation, maintenance, and operational expenses to better inform large-scale deployment decisions.

3. Research objectives

As such, the present study develops a dynamic life cycle cost (LCC) model to estimate the electrical energy output and evaluate the economic performance of piezoelectric roadway systems. The model integrates key parameters such as capital cost, operational lifespan, traffic data, and energy production rates, providing a comprehensive assessment framework. Three representative prototypes selected from the literature are used to validate the model.

The study proceeds in two main steps. First, relevant input parameters including cost data, timeframes, traffic characteristics, and energy rates are identified and used to construct the system's cash flow profile. Second, the model is applied to a hypothetical high-traffic scenario, allowing comparative evaluation of the selected prototypes in terms of LCC and overall economic feasibility. This approach provides a practical foundation for guiding future implementation strategies and policymaking related to piezoelectric energy harvesting in roadway infrastructure

4. Methodology

This study adopts a structured Life Cycle Cost Analysis (LCCA) approach based on standards from the National Institute of Standards and Technology (NIST) [37] and Stanford University [38] to evaluate the economic feasibility of integrating piezoelectric energy harvesting systems into roadway infrastructure. The analysis compares a no-action baseline with an alternative scenario that includes piezoelectric technology implementation. Input parameters include construction and installation costs, traffic data, energy pricing, and operational factors, all derived from reliable literature and data sources.

A dynamic spreadsheet-based model was developed to simulate energy generation under predefined traffic conditions. Using this output, the model computes the net present value (NPV) and life cycle costs for three selected prototypes—Roshani et al. [20], Guo and Lu [22], and Papagiannakis et al. [36]. The methodological workflow is illustrated in Figure 1. This analytical framework offers a replicable foundation for evaluating future deployment of piezoelectric harvesting technologies in transportation systems.

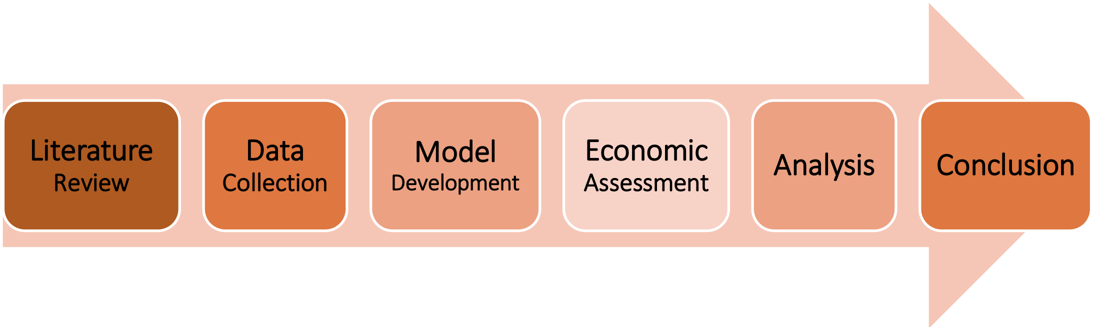

Fig. 1. research methodology

5. Model development

This study employs a dynamic spreadsheet-based model developed in Microsoft Excel to evaluate the financial viability of roadway-embedded piezoelectric energy harvesting systems. Using traffic data, device specifications, and implementation parameters, the model estimates total energy output and applies life cycle cost analysis to calculate key economic indicators. The results support decision-making by assessing feasibility across different traffic scenarios.

Implementing piezoelectric energy harvesting systems impacts cost structures significantly, requiring a detailed Life-Cycle Cost Analysis (LCCA). As outlined by Fuller [39], LCCA involves organizing data into categories like Time, Cost, Rates, and Assumptions. Key inputs include traffic parameters (e.g., AADT, vehicle speed, truck percentage, lanes, classifications) and detailed harvester data (e.g., purchase, installation, lifespan, energy output). These inputs are drawn from government sources, global traffic data, and research, assuming consistent harvester performance over time.

The analysis requires key time-related parameters—such as study duration, service life, and base dates—aligned with Federal Energy Management Program (FEMP) guidelines, which cap the analysis period at 30 years. Future costs are discounted to present values using FEMP-sourced nominal rates. For estimating energy output from piezoelectric (PZT) roadway systems, inputs include traffic volumes, cost data, energy production rates, and electricity tariffs. Energy generation per tire pass is calculated separately for personal vehicles and trucks, based on AADT, vehicle types, and axle counts. Using a series of equations, the model estimates hourly and annual energy production, the number of harvesters over a given road length, and total energy revenue. This forms the basis for the Life Cycle Cost (LCC) analysis and performance evaluation.

5.1 Cash flow

A cash flow diagram was developed to compare the alternative implementation scenario against a baseline of no action. Although the sequence of cost events such as payments and replacements remains consistent, the magnitude and timing of these values vary by scenario. The general cash flow structure, shown in Fig. 2, includes all relevant expenditures, starting with initial construction and spanning a 10-year service life. The financial analysis, however, was conducted over a 30-year period in accordance with NIST recommendations to capture long-term costs and benefits. Consistent with the literature, the model assumes no residual value at the end of life due to fatigue-induced degradation of piezoelectric devices.

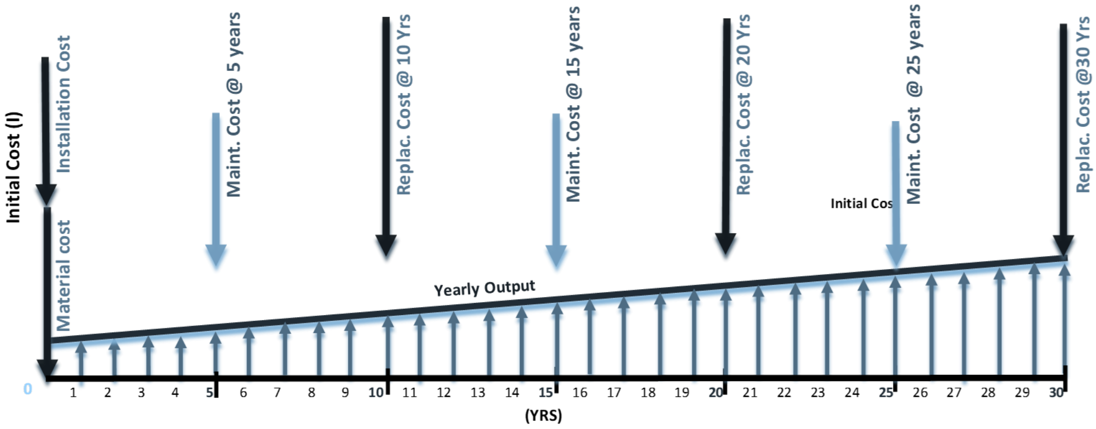

Fig. 2. cash flow diagram

5.2 Cost-effectiveness of a PZT-based energy harvesting system

An Excel-based model was developed to estimate the total electrical energy production from piezoelectric harvesters as a precursor to Life Cycle Cost (LCC) analysis. Input parameters included cost, time, traffic volumes, electricity tariffs, and energy production rates. The model computed the number of tire passes—separately for personal vehicles and trucks—using AADT, vehicle proportions, and axle counts (Equations 1 and 2). Hourly and annual energy outputs were calculated (Equations 3, 4, and 5), and the number of harvesters over the specified road length was determined (Equation 6). Total energy revenue was then estimated by multiplying the annual energy output by the electricity tariff.

$$T_c = \frac{\left(\frac{Q}{L}\right) \times P_c \times X_c}{24} \quad (1)$$

$$T_t = \frac{\left(\frac{Q}{L}\right) \times P_t \times X_t}{24} \quad (2)$$

Where, T_c and T_t represent the hourly number of passenger car and truck tire passes per harvester, respectively; Q is the Average Annual Daily Traffic (AADT); "L" is the number of lanes; P_c and P_t are the proportions of passenger cars and trucks; and X_c and X_t denote the number of axles per passenger car and truck, respectively.

$$E_c = e_c \times T_c \quad (3)$$

$$E_t = e_t \times T_t \quad (4)$$

$$E_A = \frac{E_d \times N \times 365}{1000} \quad (5)$$

Where e_c and e_t represent the energy generated per harvester by a single tire pass of a passenger car and truck, respectively; E_c and E_t indicate the total hourly energy generated per harvester from passenger cars and trucks, respectively; E_A is the total annual energy production (kWh); and E_d is the daily energy output per harvester from both passenger cars and trucks (Wh). 'N' is caluclated using Equation 6.

$$N = \frac{L+s}{0.15+s} \quad (6)$$

‘N’ denotes the total number of harvesters within the coverage area, while ‘s’ represents the gap between adjacent harvesters. A constant harvester width of 0.15 meters per unit is assumed.

$$R = E_A \times C \tag{7}$$

“R” is the annual return from energy generation, and “C” is the electricity tariff in ($/KWh) . Equation 8 shows the present-worth formula used to discount both the replacement costs and maintenance costs, where ‘R’ is the annual revenue of energy production, while Equation 9 is the geometric gradient formula used for discounting energy output energy return from applying the system.

$$PV = F(1 + i)^{-y} \tag{8}$$

$$Rpv = R[1 - (1 + g/1 + i)^{y}]/(i - g) \tag{9}$$

where “PV” is the present value of each cost parameter, “F” is the future cost (such as replacement or maintenance), “i" is the nominal discount rate, “g” is the gradient or the annual rate of increase in energy costs, and “y” is the duration of the study period.

5.3 Life cycle cost

The cost-effectiveness of the piezoelectric (PZT) energy harvesting system was evaluated through a Life Cycle Cost (LCC) analysis. The analysis compared the proposed system to a baseline scenario of no action, which has an LCC of zero. A negative LCC indicates the project is cost-effective, signifying overall economic savings across its lifespan. The LCC, expressed as the present worth, was calculated using Equation 10.

$$LCC = I + Repl - O - Res + OMR \tag{10}$$

where ‘I’ is the initial investment, ‘Repl’ is the present value of replacements, ‘O’ is the present value of annual revenue, ‘Res’ is the residual value, and ‘OMR’ includes operational and maintenance costs. Initial costs were sourced from existing literature and included the purchase of PZT materials, installation, and auxiliary components such as batteries and wiring. Maintenance costs were not included due to insufficient data availability. However, replacement costs and residual values were accounted for, with all cost components discounted to present values using standard financial equations (Equations 8 and 9) over the 30-year analysis period.

6. Implementation

To evaluate the developed model, a hypothetical traffic scenario was implemented, simulating a 100-meter segment of a high-speed, four-lane highway with an Average Annual Daily Traffic (AADT) of 300,000 vehicles, including 35% trucks. Harvesters were embedded 5 cm below the pavement surface, with two harvesting strips (each 0.2 meters wide) per lane, aligned with typical tire paths. The analysis assumed all trucks were Class 9 vehicles with five axles and a semi-trailer, with one harvester unit per strip width – see Fig. 3. This scenario followed the 30-year analysis period recommended by the FEMP and LCCA guidelines.

Three piezoelectric prototypes were selected from prior research [20,22,36] based on documented technical specifications, cost information, and verified performance outcomes. Costs for installation and auxiliary components were incorporated from previous studies, while maintenance costs were omitted under the assumption of negligible upkeep requirements for embedded harvesters. Key specifications of the selected prototypes are summarized in Table 1. The LCC model was then executed using these input data, assumptions, and cash flow details.

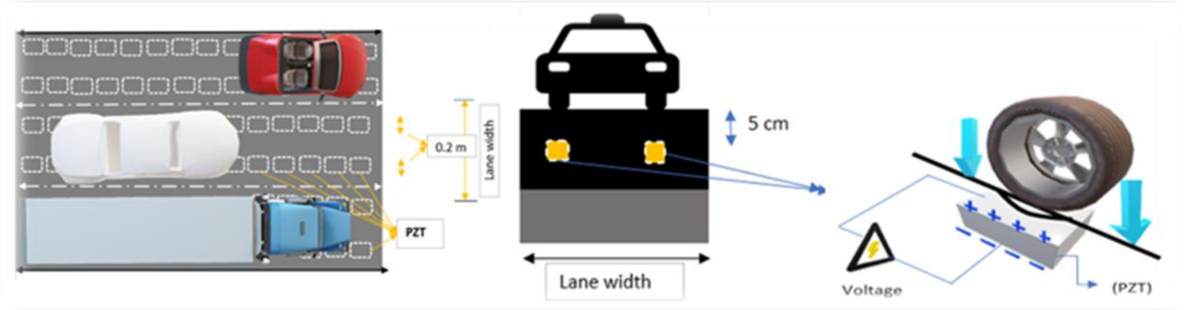

Fig. 3. illustration of piezoelectric harvesters embedded beneath the pavement surface in a typical roadway configuration

Table 1. summary of piezoelectric harvester characteristics from literature

Attribute	Roshani et al. [20]	Guo & Lu [22]	Papagiannakis et al. [36]
Area (m²)	0.0225	0.0500	0.0012
Transducer Type	PZT Disks	EHPS (PZT)	Rectangular PZT
Price	$200.00/unit	$18.60/unit	$150.00/unit
Service Life (years)	10	5 –15	20
Max Output Power per Pass	0.49 mW	1.20 mW	1.80 W
LCOE ($/kWh)	18.60	19.15 – 57.46	4.80 – 19.40

7. Analysis

Based on the defined input parameters, assumptions, and cash flow model, a comprehensive Life Cycle Cost (LCC) was computed for each selected piezoelectric energy harvesting prototype. The analysis evaluated long-term economic viability, accounting for initial capital investment, operational efficiency, replacement costs, and projected energy revenue over the system's lifespan. The results summarized in Table 2 indicate that all evaluated systems currently require significant upfront investments, which considerably outweigh expected revenues from generated electricity under typical traffic conditions. This disparity suggests that current piezoelectric technologies may not be economically viable without external financial support or further technical enhancements. Among the examined prototypes, the system by Roshani et al. [20] had the highest present worth cost (approximately $1,036,129), while the Energy Harvesting Pavement System (EHPS) by Guo and Lu [22] exhibited the lowest LCC.

Table 2. LCC of the piezoelectric energy harvester prototypes

Prototype	LCC
Roshani et al. [20]	$1,036,130
Guo & Lu [22]	$ 63,797
Papagiannakis et al. [36]	$ 433,985

8. Conclusion

This study demonstrates that, despite the currently high initial costs and relatively modest energy revenues of piezoelectric energy harvesting prototypes, these systems offer significant promise as sustainable energy solutions contingent upon future technological advancements. The economic feasibility of piezoelectric energy harvesting systems is strongly influenced by key parameters, including initial investment, device efficiency, traffic volumes, axle loads, and electricity rates, with initial capital investment identified as the most critical factor. Progress in material science and device design, especially improvements aimed at increasing energy yield per tire pass and reducing manufacturing and installation costs, has the potential to substantially enhance the economic viability of these systems, analogous to historical advancements observed in photovoltaic technologies. The outcomes presented herein provide essential foundational insights into the economic viability of piezoelectric roadway energy systems. Future research efforts should emphasize comprehensive life-cycle cost analysis (LCCA), incorporating indicators such as net savings, benefit-to-cost ratio, savings-to-investment ratio, adjusted internal rate of return, and sensitivity analysis. Such analyses would facilitate identification of the most critical parameters affecting the economic feasibility of piezoelectric transducers, ultimately guiding effective decision-making for practical implementation in high-speed transportation infrastructures.

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