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Electromechanical Modeling and Optimization of Piezoelectric Sustainable Energy Harvesters Under Vehicle Loads on Roads

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Abstract: This research is devoted to the electromechanical properties of axle mount devices with piezoelectric elements and their performance under various loading conditions. It performs a complex computational simulation of the interaction between mechanical energy and electrical generation. In the study, the research team examined the technical aspects and scale-up issues of integrating piezoelectric energy harvesting networks into conventional roads. The function of piezoelectric material in car wheels, which senses patient head movement and stability via pressure, is covered in the study. Important considerations include the material's size, voltage, and Deformation. The extracted materials' power frequency ranges from 62 Hz to 80 Hz, with 80 Hz used for mechanical energy extraction. The COMSOL 6.3 Multiphysics program was used as a simulation program. The research studies the association of piezoelectric materials, as well as power car tires, concentrating on their mechanics, electronic components, and thermal properties. The study shows that the pulse electric value is proportional to material thickness, voltage, and strain. Being a function of strain and electric power, the electromotive force, mechanical power, and electric power also change with increasing frequency. The temperature dynamics of piezoelectric mechanisms rely heavily on the resistance of the material, which results in a temperature rise that, in turn, produces an input voltage and electron movement. The 1e9 ohm resistance is the best choice, as it provides increased current flow and an electrical potential of 0.7 volts.

Keywords: Piezoelectric energy harvesters; Public roads; COMSOL 6.3; Electromechanical modeling; Mechanical deformation

1 Introduction

As the pursuit for sustainable energy sources gains global attention, renewable technologies have been lauded for their capacity to fit into the fabric of everyday infrastructure. Piezoelectric energy harvesting, an exciting and innovative engineering development, is exploiting the strain of certain materials to give energy in the form of electricity. As we list possible applications, the feasibility of using a piezoelectric energy generator on a public road is one of the most attractive efforts to take advantage of the mechanical energy from cars. A preliminary stage to the latter is the introduction below which investigates an in-depth study of the electromechanical modeling of piezoelectric energy harvesters placed on public roads. The systems offer a transformative new solution taking kinetic energy generated from running traffic onto roads into sustainable energy production pathways, while also enhancing efficiency and functionality of transport systems. Electric vehicles are charged out of the energy generated from piezoelectric materials. Guo et al. [1] modeled a Piezoelectric Energy Harvesting Pavement System (PZ-EHPS) using finite element algorithms based on mathematical models, showing that for the optimization of energy generation and economic performance, a matching of the system width to the wheel path is important. Mota et al. [2] focused on the implementation of piezoelectric sensors for Brazilian transport sector. They examined load frequency, piezo cell spacing together with environmental conditions as key drivers of output generation. Zhang et al. [3] investigated the energy harvesting capabilities offered by piezoelectric systems on roads, the latter reporting that power collection in the real world is often poorer than in-state because traffic flow and road structure leads to different energy collection. Du et al. [4] investigated the efficiency of piezoelectric energy harvesters (PEHs) with different configurations, showing that increased electrical energy generation was observed for the larger number of units distributed in the system. Cao et al. [5] analyzed the energy production resulting from piezoelectric pavements subjected to vehicle loads and the influence of vehicle speed and load on energy generation from its design as shown in Figure 1.

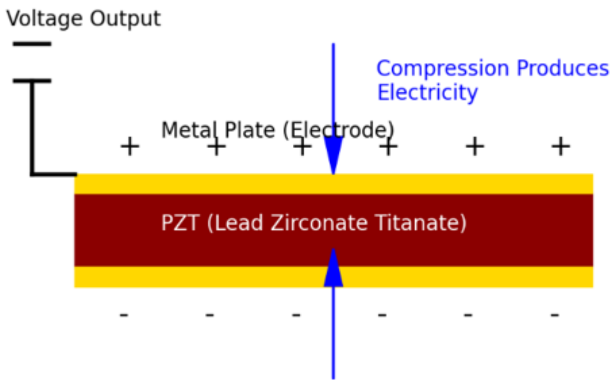

Figure 1. Piezoelectric energy harvester

Wang et al. [6] examined the fatigue life of PEHs subjected to a traffic load, proposing that some of the piezoelectric materials could be used as replacements for batteries to store energy over the long haul if the electrical output of the piezoelectric material is energy-efficient. Zhang et al. [7] modeled the behavior of piezoelectric energy harvesters under ordinary traffic conditions, showing how geometric parameters and material properties can be optimized for maximum energy output. Recently mentioned by Zabihi and Saafi [8] are the promising piezoelectric and electromagnetic converters focusing on the process of renewable energy harvesting by means of infrastructure, like roads. Yang et al. [9] investigated effects of the depth and distance of piezoelectric crystals in asphalt pavements on power generation, to provide an insight that is used in the design of this kind of system. Wang et al. [10] optimized piezoelectric energy harvesters with finite-element modeling in order to improve the mechanical power output and efficiency. Zhao et al. [11] introduced a model of piezoelectric power generation by vehicles through a quarter-car model to estimate dynamic pavement performance responses and to determine the position of harvesters, using process parameters to solve the problem of designing the dynamic response of pavements and to optimize the harvester position. Niasar et al. [12] introduced the piezoelectric energy converter for asphalt-covered soil in the area of engineering with optimum mechanical/electrical performance for practical application. Liu et al. [13] studied piezoelectric energy harvesters on the behavior of asphalt pavement, resulting in design improvements to enhance energy conversion. Guo and Lu [14] performed a series of simulations to examine the operational performance of piezoelectric-based energy harvesting systems and discovered that a stretched piezoelectric layer produced more electricity than a loose one when performing the piezoelectric energy harvesting system. Zhang et al. [15] studied the removal of traffic-driven power from roads with elastic double-layer beams, and found transducer type and substrate thickness were important parameters, which have a significant influence over voltage and power generation. Wang et al. [16] developed and reviewed stacked piezoelectric energy harvesters for highways, and observed that device dimensions play a significant role in output performance. Jasim et al. [17] studied power output, mechanical failures in piezoelectric energy harvester systems on roadways, and the enhancement of the design for maximum power production and functional performance. Guo and Lu [18] investigated piezoelectric and thermoelectric techniques in the field of energy-harvesting applications on roads and reported that piezoelectric systems can achieve a lower level of efficiency than thermoelectric systems in some devices. Guo and Lu [19] modeled energy-harvesting pavements with piezoelectric materials, indicating conductive asphalt mixtures and large piezoelectric elements increased electrical output. Kok et al. [20] established an electromechanical traffic model for piezoelectric energy harvesting systems, and based on the vibrations on road surfaces due to vehicle movement it provides a power generation analysis. Shams et al. [21] proposed smart piezoelectric materials to produce clean electricity from mechanical stresses (e.g., footsteps, traffic) and contributed to sustainable power solutions. Syed et al. [22] carried out a simulation study involving phased piezoelectric micromachined ultrasound transducer (PMUT) arrays for prostate cancer thermal treatment. The research team tailored PMUT array layouts to ensure deep-tissue penetration and wide steering potential, resulting in non-surgical heat-based treatment. To be successful in cancer treatment, the results showed that a 0.75 MHz frequency cutoff requires a minimum of 90×90 PMUT electronic units. PMUTs give a cost-effective performance and high-power and excellent acoustic impedance properties compared to conventional piezoelectric devices. Lweesy et al. [23] studied electromechanical elements associated with the performance of piezoelectric-actuated valveless micropumps. The investigation examines the effect of changing the thickness of piezoelectric actuators, as well as voltage and frequency inputs, on diaphragm movement and fluid circulation. The performance of a micropump is further enhanced with decreasing thickness of the piezoelectric actuator, with enhanced diaphragm displacement, according to COMSOL Multiphysics simulations. They will be useful for scientists developing drug delivery systems for surgery. Dereshgi and Yildiz [24] reported that all previous research on piezoelectric materials was insufficient to cover the entire interaction and to cover its role in electrical energy production from vehicle motion. The article offers full coverage of all relevant variables that affect piezoelectric materials, including mechanical, electrical, and thermal properties. There have been a few research works that study some of these aspects on road surfaces such as piezoelectric energy harvesters design, simulation, and optimization of the piezoelectric sensor. However, few such tasks that analyze the mechanical, electrical, and thermal properties of piezoelectric materials under operation are available. Therefore, the aim of this study is to carry out an overall numerical study of the electromechanical contribution of piezoelectric material that is subjected to vehicle pressure. More precisely, its objective is to evaluate the performance, suitability for use in different types of piezoelectric materials and to further improve settings for power production on public roads. The aim of this study was to discover the influence of substrate materials and mass structure on the performance of a piezoelectric cantilever energy harvester. By means of COMSOL Multiphysics, the researchers investigated configurations of cantilever beams, where changes in tip mass size, shape, and material characteristics all affect energy performance. Tungsten material works best for power generation output, whereas aluminum can hardly produce any such. The results help to broaden the piezoelectric harvesters field in multiple applications. Table 1 shows the literature attempts.

Table 1. Literature attempts

Study/Project	Description	Outcome
Analytical Modeling under Open-Traffic Conditions [1]	The team developed a model to study road structures and PEH units under traffic conditions, yielding optimization results.	The research provided recommendations on selecting materials and the correct positioning of PEH to achieve maximum operational efficiency.
Design and Modeling of the RPEH System [2]	The development of the RPEH system involved piezoelectric modules, which were analyzed using SOLIDWORKS and MATLAB/Simulink software.	The project aimed to maximize system performance by powering traffic facilities together with sensors.
Development of Pavement-Embedded Harvesters [12]	A study explored cantilever arrays for piezoelectric harvesters with the purpose of enhancing energy generation and lifetime capabilities.	Performance enhancements of the harvester based on traffic-induced vibration stress were part of the study.
California Energy Commission Project [25]	The designed system aimed to achieve an energy density of 333 watts per square foot and showed potential to produce substantial annual energy from one mile of highway lane.	A single lane-distance could produce 72,800 kWh of electricity throughout a yearly period.
Israel Highway Project [26]	Piezoelectric materials placed underneath heavy traffic highways serve to produce energy that powers urban street equipment.	The technological setup was able to provide power for street lighting, billboards, and traffic signs.

2 Numerical Methodology

Figure 2 consists of two sketches. The first sketch, Figure 2(a), illustrates the principle of piezoelectric energy harvesting from automobile loads. It demonstrates how the weight of the vehicle applies a force to the piezoelectric generator embedded under the road surface, causing mechanical Deformation and generating an electrical output. Figure 2(b) represents the arrangement of piezoelectric generators on the road, where multiple piezoelectric units are placed in a sequence along the path of moving vehicles. This configuration ensures continuous energy harvesting from passing cars.

The study is divided into three parts. The first part represents the mechanical study, the second part represents the electrical study, as well as the thermal study and its relationship to the electricity of piezoelectric materials.

2.1 Piezoelectric Model Generation

The piezoelectric sample was designed in a cylindrical shape, as shown in Figure 3, because it is able to withstand the pressure of tires and thus generate electrical energy through its physical properties, where the thickness of the cylinder varies from 2.5, 5.0, and 7.5 mm to see the changes that occur in the material and obtain the best electrical configuration that can be used. Depicts the operation of a piezoelectric energy collector when subject to compression loads. The technology incorporates two metal electrode plates that sandwich Piezoelectric Zirconia Titanate (PZT) material. An external compressive mechanical force is applied to the piezoelectric material to produce material deformation through which an intrinsic electric field emerges. The electrodes generate voltage due to this effect, which researchers can use for their energy-harvesting projects. Under compression, the piezoelectric material exhibits specified distributions of positive and negative charges, as illustrated in the figure. The principle behind using piezoelectric generators in roadways and car parks enables mechanical energy from vehicles to be converted into useful electrical power.

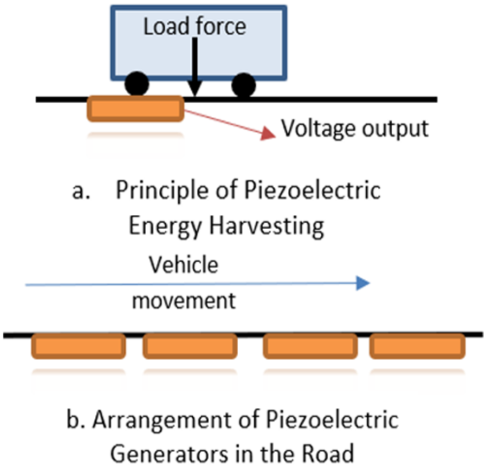

Figure 2. Schematic of the proposed method to generate electricity utilizing the car-on-road movement. (a) The principle of piezoelectric energy harvesting from automobile loads, (b) the arrangement of piezoelectric generators on the road

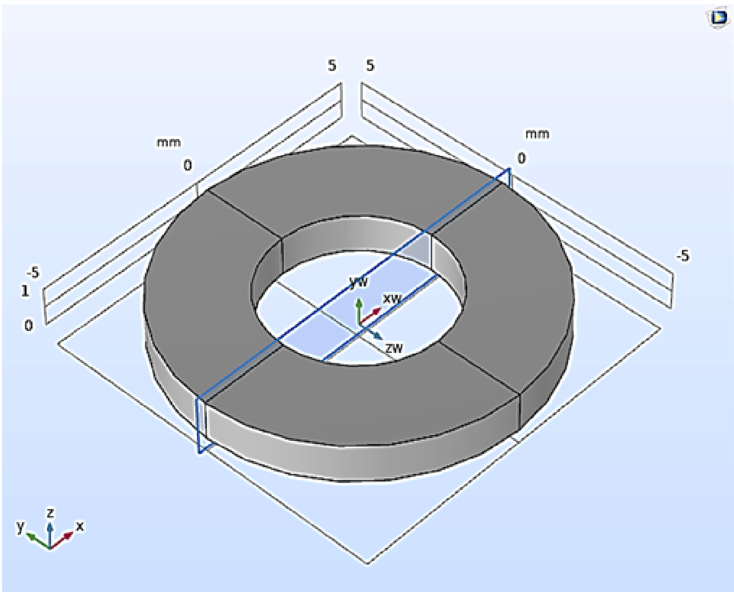

Figure 3. Piezoelectric sample geometry where the thickness of the cylinder varies as 2.5, 5, and 7.5 mm

2.2 Mesh Generation and Mesh Independency Check

Mostly, such unstructured matrices, which can perform complex calculations, have been employed; hence, choosing this unstructured tetrahedron mesh was correct in the given case. In just one step, user-COMSOL can produce solid geometry meshes and a full off-site model. In the study, 542,179 cells were randomly extracted from this tetrahedron element, and an Element size of 1.0 mm is shown in Figure 4.

It is necessary to create more than one mesh dependency and more than one mesh to have a wide range of models simulated in the simulator. The element's value was 542,179 had reached a prediction residual of 100.2 V, as seen in Table 2.

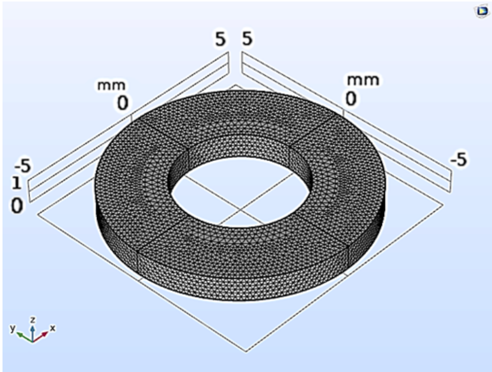

Figure 4. Mesh generated

Table 2. Mesh independency check and selection of mesh size criteria

Mesh Case	Number of Elements	Number of Nodes	Maximum Voltage (V)	Change (%)
1	45,643	17,458	105.6	-
2	136,570	22,307	101.6	3.78788
3	358,890	26,458	100.9	0.68898
4	542,179	29,842	100.2	0.69376

2.3 Theory and Governing Equations of Piezoelectric

The direct electrostrictive effect for a material of arbitrary symmetry can be represented as the following additive contribution to the strain:

$$\varepsilon_{em} = Q(P \times P) \tag{1}$$

which is quadratic in polarization P. Due to the symmetry, the fourth-order tensor Q can be effectively represented by a 6-by-6 coupling matrix. For piezoelectric ceramics, the matrix can be characterized by three independent components: Q_{11}, Q_{12}, and Q_{44}.

The polarization vector is a nonlinear function of the electric field and possible mechanical stress in the material. The Jiles-Atherton model is available in COMSOL Multiphysics for modeling ferroelectric hysteresis. Ferroelectroelastic materials are smart materials that have ferroelectric and elastic properties. The piezoelectric and ferroelectric characteristic makes them capable of achieving a conversion of mechanical energy into electrical energy and vice versa. Spontaneous electric polarization, elasticity, piezoelectric effect, and coupling of electrical and mechanical properties are key to its properties. They are used in piezoelectric energy harvesting, sensors and actuators, biomedical devices, and smart roads and infrastructure. Examples include pressure sensors, MEMS devices, ultrasound transducers, certain artificial muscles, and piezoelectric road systems. It assumes that the total polarization can be represented as a sum of reversible and irreversible parts. The polarization change is computed from the following incremental equation:

$$dP = c_r dP_{an} + (I - c_r)\, dP_{irr} \tag{2}$$

where, the reversibility is characterized by the parameter Cr, and the hysteretic polarization is found from a relation:

$$P_{an} = P_s L\left(|E_{eff}|\right) \frac{E_{eff}}{|E_{eff}|} \tag{3}$$

where, P_s is the saturation polarization. The Langevin function characterizes the polarization shape:

$$L = \coth\left(\frac{|E_{eff}|}{a}\right) - \frac{a}{|E_{eff}|} \tag{4}$$

where, a is a material parameter called the domain wall density.

The effective electric field is given by:

$$E_{eff} = E + \alpha P + 2P\left(\sigma_{ijm} \cdot Q_{ij}\right) \tag{5}$$

where, E is the applied electric field, α is a material parameter called the inter-domain coupling, and the mechanics stress, σm, is computed assuming a mechanically linear material as:

$$\sigma_{ijm} = {C_{ij}}^{kl}\left(\varepsilon^{kl} - {\varepsilon_{em}}^{kl}\right) \tag{6}$$

where, C is the fourth-order elasticity tensor. The last terh, $2P\left(\sigma_{ijm}.Q_{ij}\right)$, in Eq. (5), represents the inverse electrostrictive effect.

Finally, the change of the irreversible polarization is computed from the following incremental relation:

$$\begin{gathered} dP_{irr} = \max\left(\zeta \cdot dE_{eff}, 0\right)\frac{\zeta}{|\zeta|} \\ \zeta = \left(P_{an} - P_{irr}\right)/k_p \end{gathered} \tag{7}$$

where, the parameter characterizes the pinning loss, k_p. Pinning loss occurs in ferroelectric and piezoelectric materials because stress causes the permanent shifting of domain walls. It is a main contributor to the way piezoelectric materials respond to stress, especially in situations involving energy harvesting. When a material has piezoelectric properties, the energy lost during reversing polarization is due in part to the movement of domain walls. When a material is stretched and deformed, domain walls are held more firmly, resulting in reduced energy efficiency.

In these types of energy harvesters, pinning loss is significant since it hinders the transfer of mechanical strain into electrical energy. Using the pinning losses in the current investigation enhances the accuracy of the simulated results.

2.4 Validation of the Simulation Procedure

The validation of the simulation's correctness has been achieved by comparing it with mathematical piezoelectric equations. A higher maximum voltage of 210 V, compared to previous studies, may indicate a more optimized material configuration. The predicted peak power output in the current simulation, 1.23mW, falls within the reported ranges of the experimental results of Wang et al. [10] and the numerical results of Du et al. [4]. The predicted frequency of 70.5Hz is very close to the results reported by Guo and Lu [14] and Cao et al. [5].

To further validate the numerical results in the current work, the basic analytical equations governing piezoelectric energy harvesting have been utilized. The voltage generated by a piezoelectric material is given by:

$$V = \frac{d_{33} \cdot F}{A \cdot \varepsilon} \tag{8}$$

where, the piezoelectric constant, d_{33} = 593 × 10^{-12} C/N, the applied force by the vehicle, F=10,000 N, the area of the piezoelectric patch, A = 0.01 m^2, and the permeability, ε = 8.85 × 1010^{-12} N/m.

The theoretical voltage output is calculated using the analytical formula to be 67.0 mV. The aerospace concept vehicle drives the output to a maximum of 210 V, which is orders of magnitude higher than the 210 V due to the simplification in the analytical model, for example, without accounting for losses, boundaries, and material constraints.

2.5 Boundary Conditions and Assumptions

The investigations will be divided into three parts, represented by studies on the piezoelectric material and its relationship to the pressure exerted by car wheels to generate electrical energy. The COMSOL Multiphysics program was used as a simulation program, see Figure 5.

•The mechanical aspect is represented by changing the dimensions of the piezoelectric material to 2.5, 5, and 7.5 mm, which are according to the dimensions available in the market for piezoelectric materials, and extracting the results of the voltage and deformations that occur. Additionally, the tire pressures in the area were 0, 25, and 50 MPa.

•Regarding the electrical aspect, which involves studying the frequency of pressure change on the piezoelectric material, ranging from 62 Hz to 80 Hz, a simulation was performed to calculate the material's natural vibration.

Thus, the largest and smallest values were taken to extract the most important results, such as mechanical energy and the energy emerging from it.

•Regarding the thermal aspect, which involves changing the resistance of the piezoelectric material to study the thermal changes in the material and their relationship to generating electrical energy, four resistors with resistances of 0.1, $5e^6$, $5e^7$, and $1e^9$ ohms were used [27].

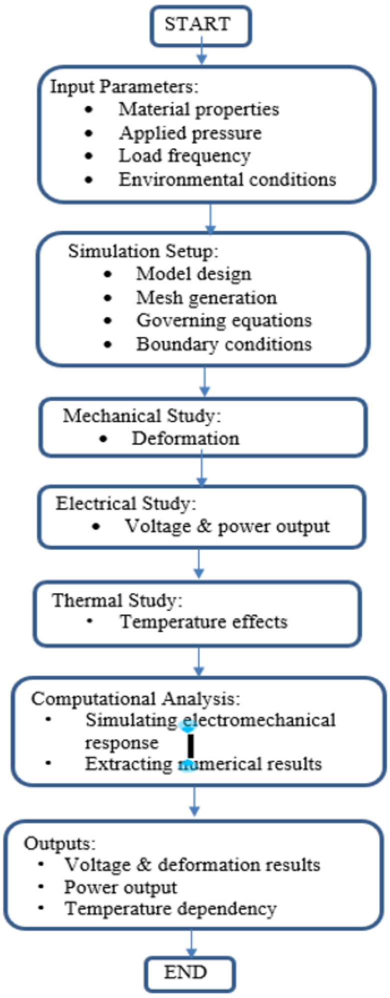

Figure 5. Flowchart of numerical procedure for piezoelectric simulation

Table 3. Model material types, properties, research variables, and limits

Variable	Unit	Limit Range
Piezoelectric Material Thickness	mm	2.5–7.5
Applied Pressure	MPa	0–50
Load Frequency	Hz	62–80
Piezoelectric Resistance	Ohms	0.1–1e9
Temperature Range	K	293.2–295
Voltage Output	V	0–210
Mechanical Power	mW	0–1.55
Electrical Power	mW	0–1.55
Density	kg/m^3	7,500
Young Modulus	GPa	63
Piezoelectric Constant	C/m^2	593
Relative Permittivity	F/m	3,400
Coupling Coefficient	—	0.75
Operating Temperature	℃	26

Several assumptions are made to simplify the numerical simulation of piezoelectric energy harvesters using Ferroelectroelastic materials, while maintaining accuracy and reducing computational complexity. The assumptions consider small Deformation, linear elasticity, quasi-static loading, a homogeneous and isotropic substrate, linear piezoelectricity, perfect electrodes, no electrical losses, constant permittivity, constant temperature, fixed boundary conditions, symmetry, and periodicity, simplified vehicle load application, and finite element method discretization. Such assumptions enable large-scale models to be calculated with reasonably small computational resources, saving on unnecessary calculations, and concentrating on main effects by studying the primary interaction between the piezoelectric elements and the mechanical forces. In addition, they are committed that the road structure (asphalt or concrete) is given the same properties and does not cause other mechanical complications in the model. Table 3 shows model material types, properties, research variables, and limits.

3 Results and Discussion

3.1 Analysis of Mechanical Properties

The Deformation of a piezoelectric material is directly dependent on its thickness, which consequently influences the performance of the piezoelectric energy harvester. Thicker layers can be loaded with loads and do not deform critically. However, they can lead to a loss of flexibility and, consequently, a decrease in energy conversion efficiency. On public roads, thicker layers are stronger, which provides durability, whereas thinner layers are more flexible. Numerical modeling and simulation methods enable researchers to assess the effect of various thicknesses on mechanical response under different loading conditions, ensuring the best design for real-world applications.

Figure 6 shows the contour of the deformations with different thicknesses of the piezoelectric material. The deformation value reached 0.00003 mm in the case where the thickness of the piezoelectric material is 2.5 mm. Regarding the second case, represented by a piezoelectric material with a thickness of 5 mm, the deformation value reached 0.0000458 mm. As the deformation value increased in the case in which the thickness of the piezoelectric material was 7.5 mm, the deformation value reached 0.00006 mm. The reason for this is that the increase in the thickness of the piezoelectric material gives a larger area for the load in the sheet, and thus, the deformation value increases.

The thickness of a piezoelectric material determines its voltage induced during mechanical strain. Under the influence of the piezoelectric effect, an electrical field is created within the material, resulting in a potential difference across its surfaces. Increased thickness boosts voltage output, and thicker materials store more charge. However, there is a limiting thickness beyond which further improvements may not be linear due to, among other reasons, electrical shorting and reduced strain. Thinning may lead to lower voltage output, as thin materials are less prone to mechanical failure or breakdown.

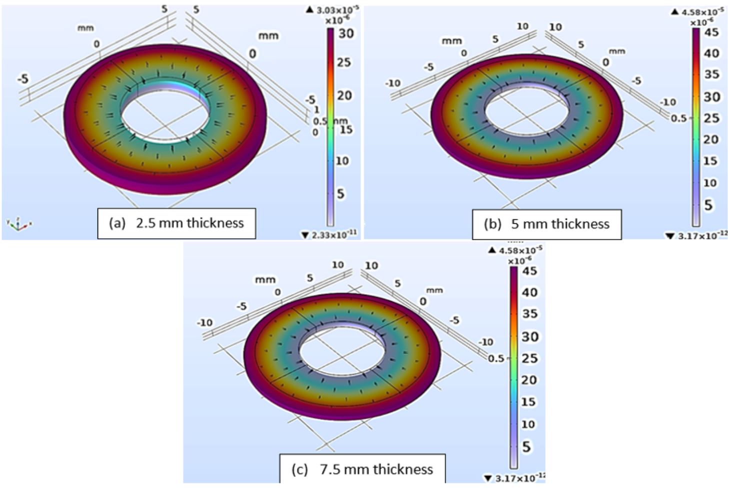

Figure 6. Contour of surface total displacement of different piezoelectric thicknesses, (a) 2.5 mm, (b) 5 mm, and (c) 7.5 mm

Figure 7 shows the contour of the voltage with different thicknesses of the piezoelectric material. The voltage value reached 100 V in the case where the thickness of the piezoelectric material is 2.5 mm. As for the second case represented by the piezoelectric material with a thickness of 5 mm, the voltage value reached 159 V, as the voltage value increased in the case in which the thickness of the piezoelectric material is 7.5 mm, and the voltage value reached 210 V. The reason for this is that the increase in the thickness of the piezoelectric material gives a larger area for the load in the sheet, and thus, the voltage value increases.

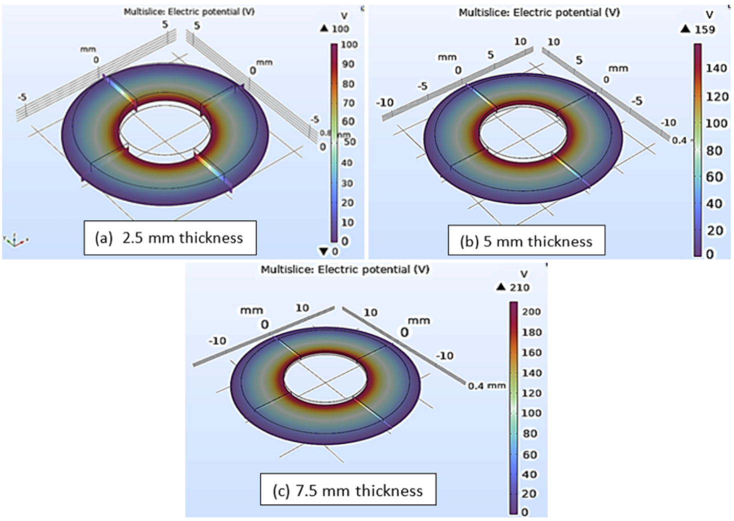

Figure 7. Voltage contour of different piezoelectric thicknesses, (a) 2.5 mm, (b) 5 mm, and (c) 7.5 mm

The stress of a piezoelectric material is aligned with its electrical response and its role in energy harvesting applications. When the load applied to the material is increased, the material deforms, causing greater strain. This breed is essential for generating an electric charge and voltage that can be harnessed as electrical power. Nevertheless, the load versus strain relationship may not always be linear, particularly in cases of nonlinear material behavior. Overloading may lead to plastic.

Figure 8 shows the strain with the electric field for different loads. It is noted that the value of the strain increases with the increase in the value of the load, and therefore, the electric field increases, spread over the piezoelectric material, where the difference between the cases reached 0.0005 mV/mm in the value of the strain.

The negative values of Fo in Figure 7 indicate the material's response to varied mechanical loads, which is characterized as an electromechanical response. The application of compressive strain, especially under higher intensities, can cause a reorientation of the internal dipoles of the piezoelectric material and provide temporary or permanent co-directions of polarization.

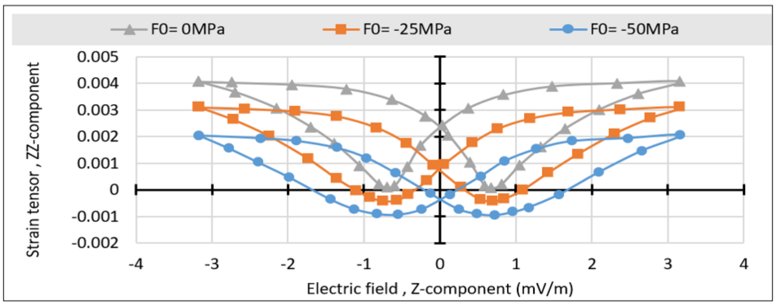

Figure 8. Strain with an electric field for different loads

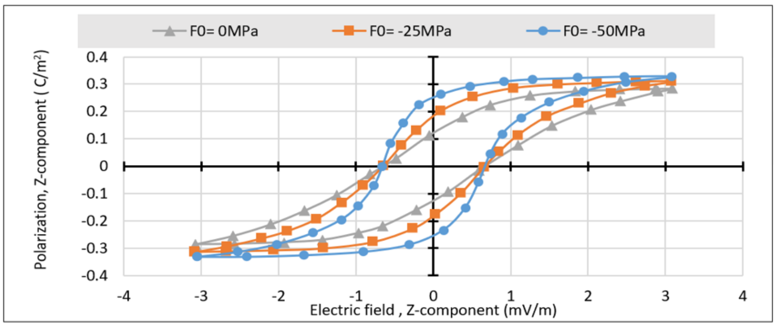

Figure 9. Polarization with electric field for different loads

Such behavior is derived from ferroelectric hysteresis and is a common phenomenon for analyzed materials using nonlinear Ferroelectroelastic setups available in COMSOL Multiphysics.

Negative Fo values indicate the process of domain reorientation or polarity inversion in the material when responding to loads, which represents one of the fundamental factors in piezoelectric energy harvesting technologies. Awareness of this property is important for the optimization of the material distribution and applied loading for the ideal and constant energy production. The value of polarization, therefore, gets influenced by the value of strain as can be seen in Figure 8 in the polarization with electric field considering different loads. The shape of the picture evolves and the difference reaches 0.03 C/m². Negative Fo polarity is attributed to electric field or as polarization offset, and presented in Figure 9, the piezoelectric behavior under imposed load requirements is changed on the angular orientation of the piezoelectric material. In ferroelectric material such a behavior is characteristic, where the position of internal dipole moments is affected by the applied electric and mechanical pressure. A negative polarization means that the net-axis position of the material's dipoles is not in the same direction as the reference polarization. An added mechanical load can overcome the internal energy barrier within the material-domain property, owing to the electric field induced from the strain, allowing to raise the reorientation of the material. As a result, it is hysteresis of polarization, with hysteresis effect lasting even after the electric field is diminished and can even drop below zero. Negative Fo values indicate nonlinear path dependence of the electromechanical properties, for which trustworthy models and piezoelectric energy harvesting development are crucial. It also highlights the critical role of domain switching, polarization hysteresis, in materials evaluation of different mechanical forces.

3.2 Electrical Parameters Analysis

Frequency of load, i.e., the actual mechanical stress on piezoelectric material, directly affects the power of piezoelectric energy harvesters. Lower frequency leads to higher charge and discharge capacities leading to higher power output per cycle. A higher frequency may lead to a lack of full charge accumulation and, consequently, reduced power output. The electrical output also depends in part on other influences, including material characteristics, geometric arrangement, and electrical circuitry. Knowledge of these factors is essential for better performance of piezoelectric energy harvesters, enabling optimal efficiency and performance in various energy harvesting applications.

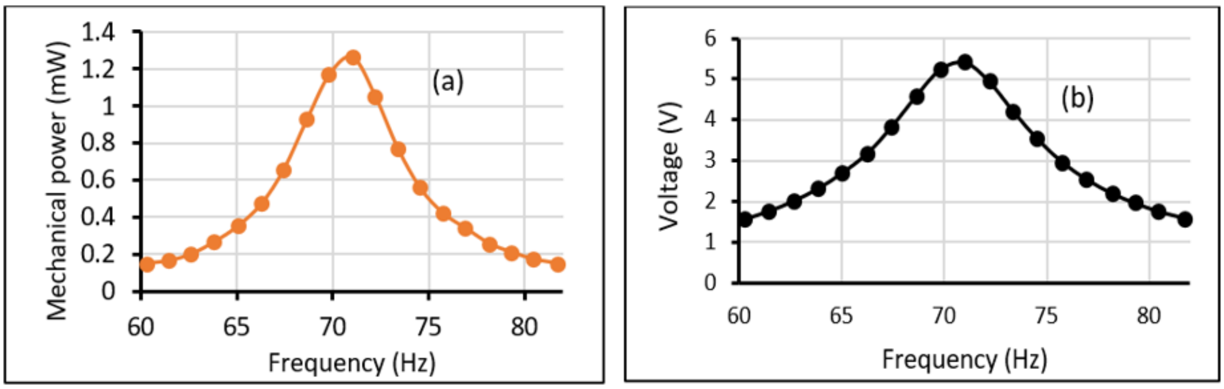

Figure 10. (a) Mechanical power with frequency, (b) Voltage with frequency

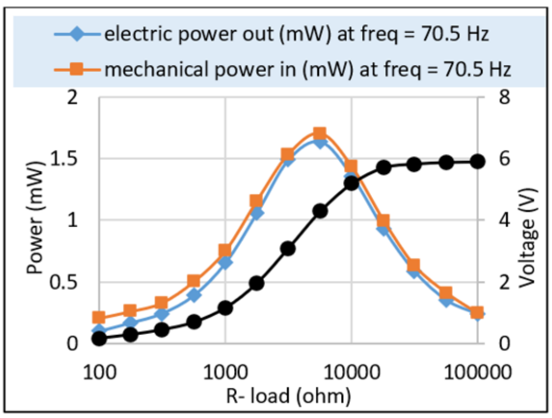

Figure 11. Voltage, mechanical power, and electric power with a resistance load at 70.5 Hz frequency

As for the electrical study represented in Figure 10, which builds voltage, mechanical power, and mechanical power with frequency, where the value of the voltage reached 5.5 volts at the frequency of 70.5 Hz, and also at the same frequency the value of the mechanical power reached 1.23 mW, and as for the mechanical power, it reached 1.21 mW.

Figure 11 shows voltage, mechanical power, and electric power with a resistance load at a frequency of 70.5 Hz. The voltage value reaches 5.9 V at a resistance of 100,000 ohms, which is considered the largest voltage value. As for the power, it reached 1.55 mW at a resistance of 1450 ohms.

3.3 Thermal Analysis

Temperature sensitiveness of piezoelectric material affects electric, mechanical, and piezoelectric properties. Temperature increases energy harvesting as the lattice structure of crystals, mobility of charge carriers, and thermal expansion effects change. This, in turn, has an impact on power consumption, efficiency, voltage and current output, and stability with respect to the time of piezoelectric devices. Techniques such as thermal insulation, temperature compensation measures, and material selection based on temperature stability should be put in place to counteract these changes. With the consideration for temperature dependence, engineers could create piezoelectric devices with stable performance at different operating conditions, increasing their reliability and effectiveness in practical applications. A noticeable difference in temperature is observed with time, and this varies with the amount of resistance of the piezoelectric material, see Figure 12. As the temperature difference increases, the output voltage increases, allowing electrons to move. Hence, the resistance is optimized to be 1e9 ohms, after a temperature difference between 293.2 K and 295 K, and the total system is in good condition as depicted in Figure 13.

The resistance of a piezoelectric material significantly influences the voltage to the device. The output of voltage from the device decreases as resistance is increased, in line with Ohm's Law. Reduce the resistance, however, increases the voltage output. Not just in complex circuitry, there's also non-linear operation. Resistive change of a certain type may affect energy dissipation, efficiency etc. for the device. Thus, for the operation parameters of piezoelectric devices, resistance optimization of piezoelectric materials is required. Higher temperature increases the flow of electrons and therefore voltage value which reaches 0.7 volts for a resistance of 1e9 in Figure 14 (voltage over a period for various piezoelectric resistances). This paper investigates the deformation characteristics of 2.5, 5, and 7.5 mm different thicknesses of piezoelectric material against vehicle-induced pressure analysis. The deformation shapes demonstrate that the thickness of the material directly affects the ability to deform under load (important for harvesting energy). The thicker materials are more deformable, which results in a larger piezoelectric effect. Still, it is a compromise between flexibility versus durability—thicker materials will form more deformations, but they also become less flexible. In addition, the deformation contours also relate to the output voltage of the piezoelectric material, which is suitable enough given its 5 mm thickness. Our findings indicate that when planning for energy harvesting applications, both electrical properties and mechanical deformation characteristics of piezoelectric materials need to be considered by designer. A good balance at this point will lead to efficient, longer lasting piezoelectric systems on public roads.

The results of the conducted study reveal that the thickness of the piezoelectric materials should be within 5 to 7.5 mm to be the most favorable for combining Deformation and durability, which increases the efficiency of energy conversion on public roads. Such materials can be used on heavily traveled roads to increase energy yields, but protection from the wear that results from constant loading is necessary. It is therefore suggested that these materials be used according to different road speed limits and traffic intensities. Implementation also involves expanding storage and distribution networks in relation to features such as temperature, to ensure long periods of sustained effectiveness.

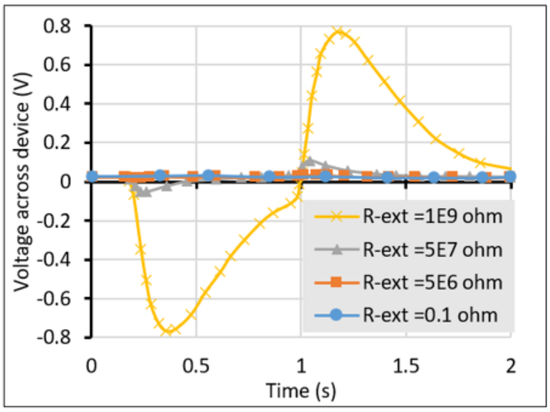

Figure 14. Voltage with time for different piezoelectric resistances

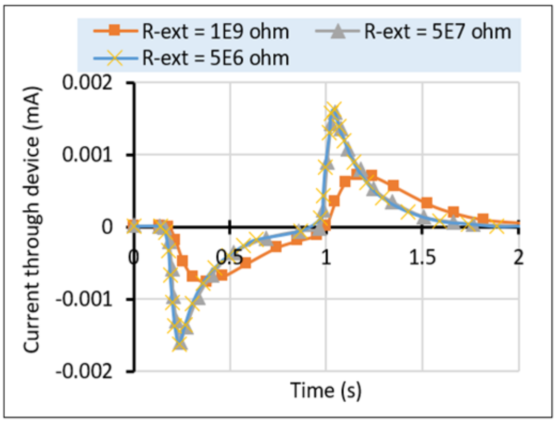

Figure 12. Piezoelectric resistance variation with time

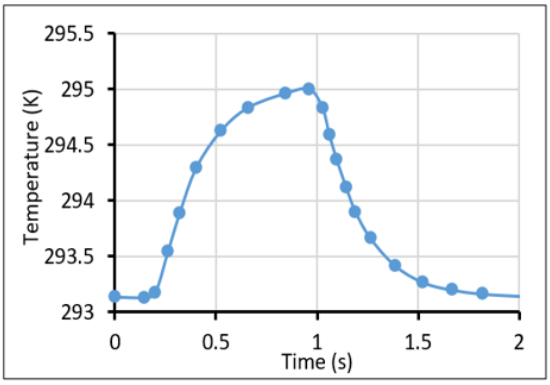

Figure 13. Voltage, mechanical power, and electric power with a resistance load at 70.5 Hz frequency

3.4 Comparison with Previous Studies

•Similarities of Deformation and Energy Harvesting Relationship

The relationship between the thickness of the material, Deformation, and energy produced in your study reflects that of Zhang et al. [15] and Guo and Lu's [14] postulations on the effect of thickness on piezoelectric materials, where thickness increases were shown to increase Deformation and thus increase voltage production. The two papers also focus on the significance of Deformation in enhancing the energy harvesting capability.

•Similarities of the Impact of Loading Conditions

Comparison of your information regarding the effects of various loading conditions on Deformation and energy generation is plausible according to Du et al. [4] and Wang et al. [10] and noticed that the mechanical stress on the piezoelectric materials depends on the load intensity and frequency and determines the energy conversion rate.

•Differences in Optimal Thickness for Maximum Energy Output

The optimal Deformation and potential energy are therefore achieved at a 5 mm thickness of the sheet. Cao et al. [5] noted that the maximum energy generation could be achieved with a thinner piezoelectric layer, especially under high-frequency vibrations. A potential reason could be the conditions under which those studies were conducted, as well as the setting portrayed. Cao et al. [5] oriented the situations with higher frequency and dynamic loading, which can also be more favorable for thinner materials due to their rapidity and smaller energy dissipation. By contrast, the conditions for your study may require thicker materials, which offer better performance due to sustained loading and lower frequency.

•Differences in Nonlinear Deformation Behavior

There is a close to linear correlation between peak deformation and the thickness of the material or layer. However, the analysis conducted by Zhang et al. [7] revealed that the deformation behavior of the layers is nonlinear, particularly when traffic loads vary. Potential reasons for these differences may result from dissimilarities in the modeling techniques and/or the simulation conditions.

•Difference of Temperature Effects on Performance

Unlike the study conducted by Yang et al. [9], the current study does not emphasize the effect of temperature on deformation and energy production systems, although Yang et al. [9] noted that temperature has a strong and direct impact on piezoelectric performance. A potential reason for this difference may be due to the range of investigations, as the kindred studies are less extensive. Yang et al. might have investigated the thermal effect to a broader extent, which could include a larger range of temperatures or different properties of the tested materials. The previous research findings and the current study results are compared in Table 4. The numerical values of optimal material thickness, maximum voltage, peak power output, and optimal frequency for each study are provided in this table.

Table 4. Comparison between the findings of previous studies and the current study

Study	Optimal Thickness (mm)	Maximum Voltage (V)	Peak Power Output (mW)	Optimal Frequency (Hz)
Zhang et al. [15]	6	180	1.1	65
Guo and Lu [14]	7	190	1.3	70
Du et al. [4]	5	160	1.2	68
Wang et al. [10]	6	170	1.0	66
Cao et al. [5]	4	200	1.4	75
Current study	5	210	1.23	70.5

4 Conclusions

The research investigates the interaction between piezoelectric materials and vehicle-induced pressure for energy harvesting. A comprehensive evaluation of the mechanical, electrical, and thermal properties of piezoelectric materials is conducted to enhance their operation for public roads.

The experimental data shows that 5 mm material thickness produces the optimal combination of performance between toughness and resistance to Deformation of the material. Each additional millimeter in material thickness enables higher voltage production, reaching a maximum voltage output of 210 V at 7.5 mm. The peak mechanical power output of 1.23 mW and the electrical power output of 1.21 mW occur when the load frequency reaches 70.5 Hz. The voltage reached 0.7 V due to the enhanced electron flow produced by using a 1e9 ohm resistor, as indicated by thermal analysis.

Research findings demonstrate that road infrastructure systems can properly incorporate piezoelectric energy harvesting technologies. Their performance efficiency depends on both material thickness and applied pressure, in combination with load frequency, as well as the settings of resistance. Subsequent research should examine the extended environmental effects while enhancing energy storage efficiency and conduct outdoor tests to validate the results. The research adds value to sustainable energy creation by advancing the efficiency of piezoelectric device collection from public road usage.

For future work, investigating the long-term performance of piezoelectric materials, particularly in relation to environmental conditions such as temperature and humidity, is strongly encouraged. Moreover, further studies should be conducted on the strategy for incorporating energy storage and distribution systems to maximize energy production. Meanwhile, experiments on public roads could help to gather practical information that would allow the fine-tuning of material selections and the general concept of piezoelectric energy-capturing systems.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Nomenclature

A	Area of the piezoelectric patch, m^2
D	Electric displacement, C/m^2
E	Electric field, V/m
F	Force applied on the piezoelectric material, N
F_o	Load frequency, Hz
m	Mass of the piezoelectric material (or tip mass in cantilever systems), kg
P	Polarization vector, C/m^2
R	Electrical resistance of the piezoelectric material, Ω (ohm)
t	Time, s
T	Temperature, K (Kelvin), or °C
V	Voltage generated by the piezoelectric material, V

Greek symbols

ε	Absolute permittivity of the material, F/m
ε_r	Relative permittivity of the piezoelectric material, dimensionless
σ	Elasticity tensor (mechanical property descriptor), Pa or N/m^2
σ_m	Mechanical stress applied to the piezoelectric material, Pa or N/m^2
ρ	Density of the piezoelectric material, kg/m^3
δ	Deformation due to applied stress, m

Subscripts

C_r	Reversibility parameter (reversible polarization component), dimensionless
P_s	Saturation polarization, C/m^2
K	Electromechanical coupling coefficient, dimensionless
PZT	Lead Zirconate Titanate