Power beneath Wheels: Smart Piezoelectric Pavements Empowering Future Transportation Networks

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Abstract -- **This paper presents design and simulation of innovative smart piezoelectric pavements integrated in highway infrastructure to harness mechanical energy from vehicular movement. It also uses the advanced arrays of sensors that exploit the piezoelectric effect to generate usable electrical energy based on the pressure and vibrations made by passing vehicles, without affecting normal traffic flow. The generated energy is projected to serve small-scale functions including street lighting, traffic control systems and environmental sensors and it shows significant potential for future electric vehicles (EV) charging systems on highways. Moreover, the system incorporates a hybrid energy integration approach, combining solar energy harvesting with an intelligent energy management system to enhance the generation, storage, and distribution of power. The feasibility of the system is confirmed by the simulation results and the intention of the means to create sustainable and energy efficient corridors of transportation.**

Keywords: *Embedded sensors, Energy harvesting, Infrastructure integration, Low-power electronics, Piezoelectric materials, Sustainable infrastructure, Traffic energy harvesting.*

I. INTRODUCTION

THE RAPID growth in the demand for clean, sustainable and decentralized energy has raised a vital reconsideration of the traditional infrastructure systems. As the needs of urban population grow and automobile congestion increases, the contemporary cities are increasingly marked by an ever-changing stream of mechanical energy which is only partially utilized and eventually dispersed into the traditional asphalt roads.

This lost energy, primarily in the form of pavement stress and vibration, has a significant potential for renewable energy harvesting. Piezoelectric pavement systems become a game changer in this problem.

They are comprised of piezoelectric materials, which are the substances that produce electrical charge when mechanical pressure is applied in carefully implanted elements in roads infrastructure. Under the dynamic loads exerted by vehicles in motion, these materials can change strains of a mechanical character into electrical energy. The energy collected, even though of small capacity is able to be suitably utilized to supplement distributed low-energy urban networks like LED lighting, environmental sensors and surveillance gear and smart systems. It does this by incorporating energy harvesting directly.

The application of this concept in the real world has proved feasible. Pilot projects such as those conducted demonstrates its implantation on Israel highways, piezoelectric floor tiles in railway stations in Tokyo and test closures in numerous urban corridors in Europe have demonstrated its useful potential. Such endeavours, at once exciting, also show some fatal flaws, such as material wear-out and power conditioning, structural integration and economic feasibility, to transcend experimental applications into the scale of urban deployment.

In this work, a thorough study dealing with piezoelectric pavement-based energy gathering is done. It starts with the fundamentals of the primary physics of piezoelectricity and continues with an interdisciplinary approach to the selection of materials, methodologies of integration of pavement, modeling of loads and estimation of the production of energy by simulation.

Also, the study focuses on power conditioning circuits design, storage system and limits on field deployment. By adopting a system-level approach that blends civil engineering principles with energy, electronics and material science, we aim to position piezoelectric pavement technology as a possible stakeholder in the next generation urban sustainability.

II. METHDOLOGY

Piezoelectric transducers are built in the multilayer paving structure and deployed in high-traffic areas to enhance the mechanical load interception.

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The structural division is as follows:

Surface Layer: This layer comprises of asphalt or Portland cement concrete, which is used to elicit the maximised load transfer and wear-resistance.

Intermediate Layer: This may consist of piezoelectric harvesting modules here which are mechanically bonded to induce the stress to the maximum possible.

Sub-base Layer: These are layers of compacted materials that act as the support structure of the structural layers and the stress is distributed evenly.

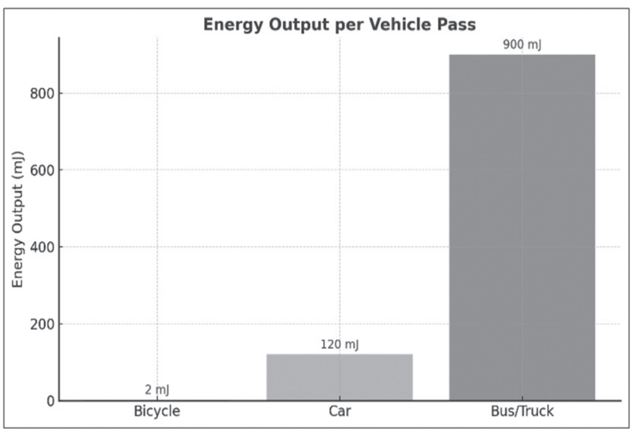

Figure 1. Energy output per Vehicle Pass. The graph shows rough mechanical energy obtained during harvesting the mechanical energy of the various types of vehicles on the basis of the simulations of the vehicular loads and piezoelectric efficiency factors.

We consider two profitably available piezoelectric materials, namely Lead Zirconate Titanate (PZT) and Polyvinylidene Fluoride (PVDF). The selection of these materials is based on their piezoelectric coefficients (d33, d31), mechanical strength, environmental friendliness and the ability to be integrated into the civil infrastructure.

To reproduce natural traffic-induced stresses, pavement structure was modeled under different vehicular loading conditions *i.e.* when vehicle weight was light (1000 kg), or heavy (10,000 kg). The standard civil engineering load models were used to analyze the distribution of the axial forces. Taking into consideration the rate of traffic and the distance between wheels as well as the contact surface areas, the magnitude and the period of dynamic stress put on each of the embedded piezoelectric elements were estimated. With the help of these parameters, the net force delivered to the energy harvesting layer per vehicle pass was computed.

The electrical output generated by the piezoelectric modules under applied stress was modeled as

$$Q = d \times F, \quad V = \frac{Q}{C}, \quad P = \frac{V}{R}$$

where:
Q is the generated charge,
F is the mechanical force,
C is the capacitance of the piezoelectric material and
R is the external load resistance.

The system was simulated under multiple traffic scenarios using MATLAB, providing performance estimates for different material types and configurations.

Due to the low-voltage and alternating output generated by piezoelectric elements, the system will incorporate an energy-conditioning module comprising AC to DC conversion and DC-DC boost converter to ensure voltages to usable values. There were two main units of modeling energy storage:

Supercapacitors: abrupt discharge applications (Instant, *i.e.* streetlights)

Rechargeable Li-ion battery: to provide long-term low power applications (*e.g.* traffic sensors, microcontrollers)

III. BASIC PRINCIPLE

As vehicles move over a road, they create dynamic loads causing pavement deformation and vibration. Instead of being lost as heat, this energy can be captured using piezoelectric transducers embedded beneath the surface. These transducers convert the stress into electrical energy, which can be conditioned and used to power low-energy roadside systems.

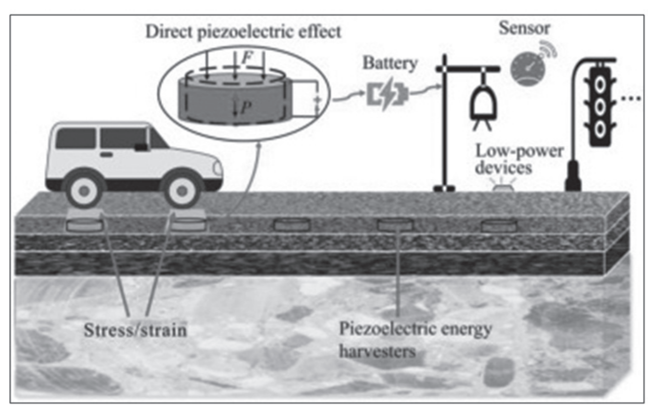

Figure 2. Piezoelectric pavement energy-harvesting system.

Various coupling modes in piezoelectric materials are not important except d33 and d31. Higher conversion efficiency of energy is realized when the applied mechanical force and electric polarization interact in same direction in d33 mode. By contrast, d31 mode exploits force across the polarization axis, and results in reduced performance. d33 mode is the mode of choice in applications on road where use is made of materials that have good piezoelectric coefficient: PZT is the material of choice in this direction.

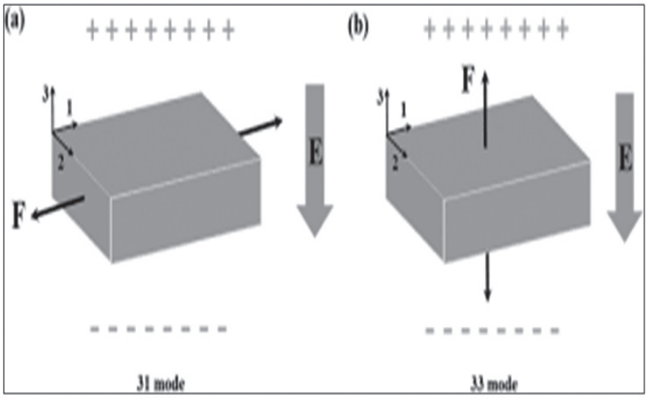

Figure 3. Comparison of working of piezoelectric coupling modes.

IV. MATERIALS USED IN PAVEMENTS

Major materials used are:

PZT (Lead ZirconateTitanate): A common high charge and dielectric strength piezoceramic Lead zirconatetitanate. Though it is brittle yet produces much energy when a heavy load is placed on it.

Polyvinylidene Fluoride (PVDF): It is a ductile and environmental-friendly polymer that is good in fatigue and the environment. Though it produces less power than PZT, it lasts long in high-cycle environments.

Lead-Free Ceramics (Barium Titanate): Lead free alternatives that are in active development stages.

The mechanical integrity of the layers of the pavement needs to have the capacity of transmitting sufficient stresses to the integrated sensors.

Classic layout takes the following form:

Top Layer (Wearing Surface): This layer is the layer that touches directly with the traffic which is made of Hot Mix Asphalt (HMA) or Portland Cement Concrete (PCC). It should be rigid enough to relay stress and safeguard the modules underneath.

Intermediate Layer (Sensor Housing): It consists of recesses or even cavities inside Sintex, thermoset resins or even engineered composite, which accommodates the transducers. An effective force transmission is provided by proper bonding.

Base and Sub-base Layers: Base and sub-base layers are collections of granular materials or soil treated layers and act to distribute loads evenly and avoid the formation of local area of peak stress. Drainage control is also important to avoid water lapping and chances of sub grade collapse.

Figure 4. The layered structure of the piezoelectric pavement.

Surface of every module is sealed with thermal stable epoxy or polymers. Depending on application depth additional housing can be stainless steel or FRP. Internal terminals are attached to external control units by means of shot lined conduits. Rectifiers, filters and voltage regulators form part of power conditioning. Tiles are tested after installation by subjecting the tiles to controlled loads.

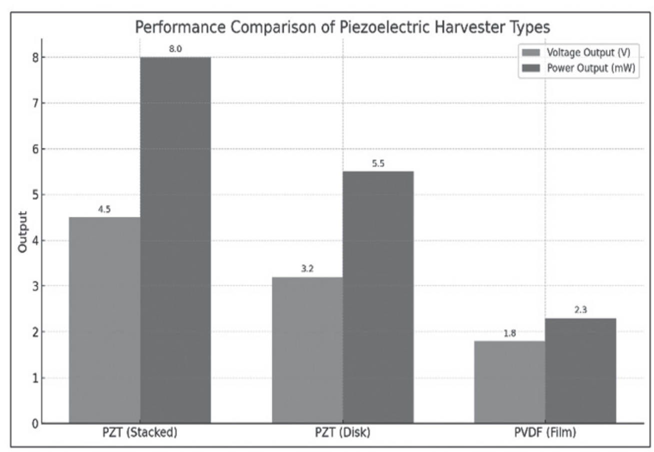

Figure 5. Piezoelectric harvester voltage and power. PZT in stacks produces greater output as compared to disk-type PZT and PVDF film.

Stacking or layered arrangements: The stacked harvesters order multiple piezoelectric elements in series (to provide higher voltage) or parallel (to provide higher current). They have special applicability in a high-vehicular-load area to achieve a maximum of energy density and low mechanical vulnerability.

Disk and tubular modules: Small disk shaped or cylindrical modules are laid directly under the wheel track. They can absorb vertical stress and are usually placed in canisters to protect them.

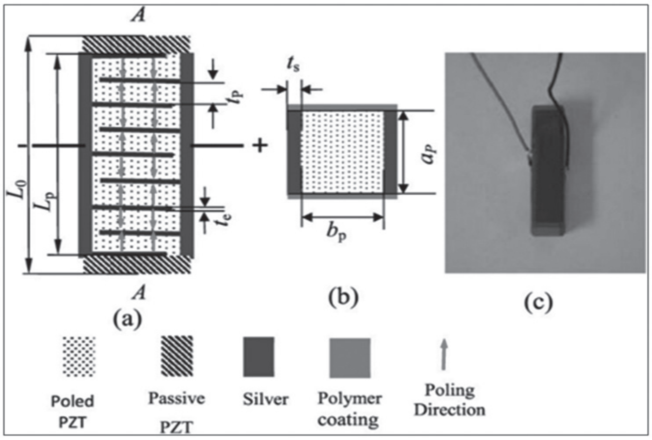

Figure 6. Schematic and physical structure of a stacked PZT piezo-electric harvester. (*a*) Exploded sectional view showing layers of poled and passive PZT with poling direction, (*b*) Cross-section with coating and electrode materials, (*c*) Actual fabricated stacked module.

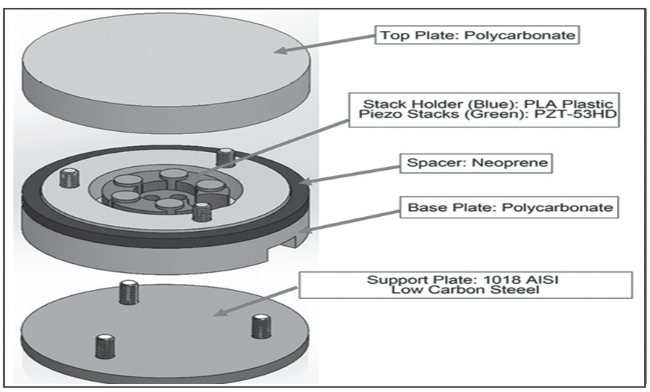

Figure 7: Design of Modular piezoelectric harvester. Exploded view of piezo stacks PLA holder, polycarbonate casing, neoprene spacer and the support base of steel.

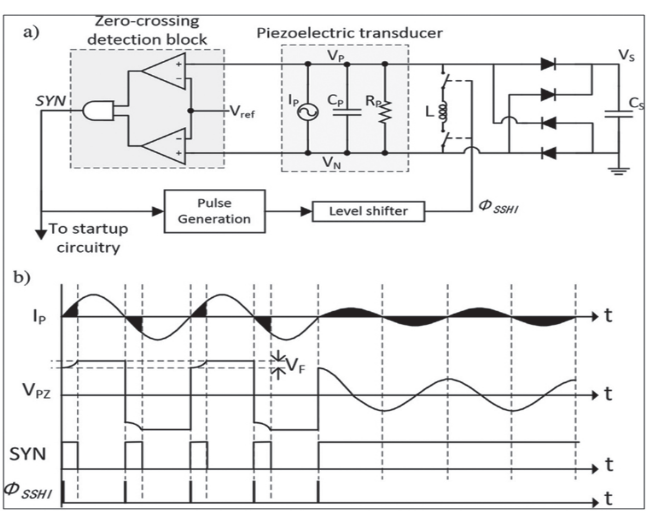

Figure 8 Circuit schematic and timing diagram of ‘Synchronized Switch Harvesting on Inductor’ interface to piezoelectric energy harvesting, displaying detection at the zero-crossings, action of switch-control and waveforms of voltages/currents.

Adaptable film based harvesters are made of piezoelectric polymers which are flexible and conformable such as PVDF. They produce less power, but they are beneficial in lightweight traffic areas and the pedestrian paths because they are easy to install and have environmental survivability. Harvesters are commonly embedded on a 30-50 mm depth below the surface.

V. SIMULATION RESULTS

To access the voltage response of the embedded piezoelectric modules under dynamic vehicular loads, a simulation was conducted using MATLAB. It was aimed to model the electromechanical behavior of the transducer under varying applied forces corresponding to different weights of vehicles on the road. We have considered a piezoelectric sensor of area 1 cm^2 and thickness 1 mm , encapsulated beneath asphalt layer. Material parameters used include:

- Piezoelectric coefficient: $d = 2.3 \times 10^{-10}$ C/N
- Permittivity of free space: $\varepsilon_0 = 8.85 \times 10^{-12}$ F/m

A range of axial loads from 0 to 2000N was applied, simulating varying vehicular weights. The mechanical stress (σ) and corresponding output voltage (V) were computed using:

$$\sigma = \frac{F}{A}\ ,\ V = \frac{d \cdot \sigma \cdot t}{\varepsilon_r}$$

where:

- *F*: Applied force (N)
- *A*: Area of sensor (m²)
- *t*: Thickness of sensor (m)
- *d:* Piezoelectric constant (C/N)
- ε_r: Dielectric constant

The resulting voltage was plotted as a function of the applied load using MATLAB. The plot is a linear voltage response with increasing load.

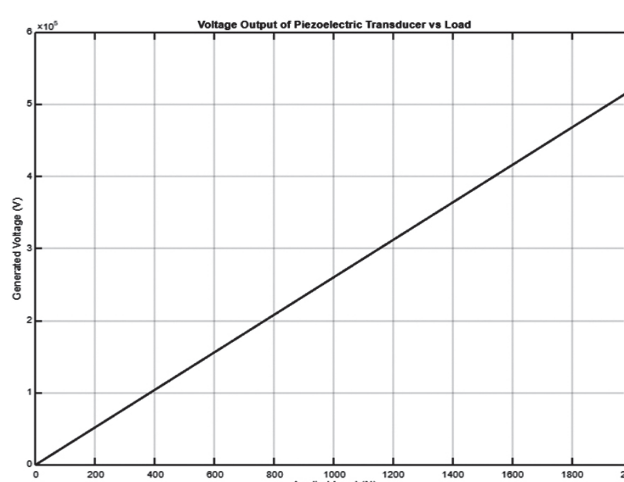

Figure 9. Simulated voltage output of the piezoelectric transducer under varying applied load conditions.

At 2000 N, the voltage output reached approximately 5.19774 volts, indicating a strong electromechanical coupling. This trend supports the feasibility of embedding such modules in pavement structures for energy harvesting applications and real-time traffic sensing.

V. CHALLENGES AND LIMITATIONS

Though piezoelectric pavement systems show potential of being an excellent system of capturing sustainable energy, various challenges that are currently facing the system outside the lab, such as practical and technical issues, remain significant barriers to the application at the large scale.

Mechanical and structural durability: Repetitive dynamic loads caused by passer-by vehicles doubly hit piezoelectric modules installed in the bottom of road surfaces. It may provoke the mechanical fatigue, cracking or delamination, over a long period. However, despite the enhancement of the mechanical strength by encapsulation procedures, long-term durability in different stress conditions is a major issue that requires necessary attention.

Constraints on the environment and climate: Road environments lead to exposure to the harvesters on moisture, thermal variations, oil, and particulate, which may corrupt piezoelectric and circuitry. A significant environmental variation in locations can be extreme, necessitating particularly heavy packing and safeguards, which can just make the overall system more complex and expensive to buy.

Energy conversion efficiency: Due to the efficient increase in circuitry by using the solid state design over the past years, the overall effect of conversion of mechanical stress to electrical energy that can be used is still relatively low. A total loss through parasitic capacitance, dielectric losses, and diode voltage drops affects useful energy delivery capacity that restricts usage of the system in high-demand applications.

Load matching and output variability: The measure of piezoelectric systems is such that the output is not uniform and intermittent in nature depending on the traffic condition, type of vehicle and axle weight. This fluctuation makes the storage and real-time consumption of energy harder, especially when loads necessitate constant and steady power. Harvested energy can fail to be utilized effectively in case of poor power conditioning.

Freedom of economical sustainability: PZT and other high-performance piezoelectric materials and the advanced encapsulations methods escalate the cost of initial set-ups. There are also other costs involved which comprise the maintenance, the integration of circuits and the long term reliability. These aspects place considerable obstacles on cost-effectiveness particularly when used in broad applications.

Integration of infrastructure: Installation of piezoelectric modules, in existing roads will involve retrofitting of the roads, and limited disturbance to the traffic. These interventions are logistically challenging and sometimes cannot be exploitable in crowded or areas with high traffic unless there is planning and a big investment.

To recap it all, the massive implementation of piezoelectric pavement systems is presently limited by mechanical, environmental, electrical, financial and infrastructural constraints. These challenges require interdisciplinary research and engineering solutions to turn laboratory success in a direction and make it viable to scale up and useful outside the laboratories.

VI. APPLICATIONS

The piezoelectric pavement systems are an experimental initiative of the conversion of mechanical energy through vehicular or foot traffic to electric energy. The fact that they can run without the need of outside fuel or the fact that they have a negligible carbon footprint also makes it a very viable resource in upgrading to smart and sustainable infrastructure. They have operational flexibility as shown by the following applications:

Signage and street lighting in urban areas: LED-based streetlights can be powered by the harvested energy and this happens mostly in less traffic or off-grid regions where the traditional electric infrastructure might be constrained. This does not only facilitate the energy saving but also contributes to enhanced night-time visibility and safety on the road. On the same note, road signs which are dynamic, speed indicators and the lane guidance systems can run automatically with the stored piezoelectric energy.

Vehicle counting and traffic monitoring system: This is possible because piezoelectric pavements allow self-powered sensor network traffic analysis. These systems have the abilities and can:

- Record traffic that goes through certain lanes
- Maintain balance on car loads and speed
- Identify vehicle types (*e.g.* light vehicles and heavy vehicle), that helps in planning urban traffic as well as collection of toll, and automation of law enforcement.

Environmental sensing networks: The energy of piezoelectric modules in combination with low-energy microcontrollers can accommodate environmental sensors which can monitor: Humidity and the temperature of the roadway, pollution level and quality of air The levels of noise and vibrations. Such sensors can be applicable in climate responsive infrastructure and real time smart city dashboards.

Smart foot paths and pedestrian zones: The foot-steps of pedestrians on a walkway, a railway platform, a terminal building in the airport, or even at the entrances to a stadium, can produce enough energy to: Electrify your wall lamps, information boards or shop signs, turn on the touchless access control or the emergency alert systems, Charge portable electronics of low-power on specific widely available hubs.

IOT and smart grids integration: Piezoelectric pavements are able to play a role in the IoT framework by providing energy to: Edges, Distributed edge devices, Intelligent traffic lights, Modems of wireless communication (Zigbee, LoRa, NB-IoT).

Such integration enhances data connectivity and supports real-time decision-making in intelligent transportation systems.

Energy harvesting in remote or disaster prone areas: Piezoelectric pavements create a self-sustaining source of power in disaster areas or areas with no grid power supply that can be used to: Emergency lighting, Communication equipment, Advance warnings (earthquake or flood warning). This adds resilience and autonomy to infrastructure in critical or sensitive regions.

Finally, it is possible to state that piezoelectric pavements can be seen as an essential element of the smart cities, transport infrastructure, and green energy ecosystems of the next generation due to their versatile application. They may turn common passive surfaces into proactive, smart systems that make the world more sustainable and efficient, as well as safer.

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