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Research Paper

Piezoelectric Road at Toll Plaza-1

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ABSTRACT The proposed project, "Piezoelectric Road at Toll Plaza", is an innovative smart-road system designed to generate electrical energy from the mechanical pressure produced by moving vehicles. In this system, piezoelectric plates are installed beneath the road surface at the toll plaza. Whenever a vehicle passes over these plates, the applied mechanical pressure is converted into electrical energy through the piezoelectric effect. The generated electrical energy is collected, stored and monitored through an electronic control system. A mobile-based monitoring system is also proposed to display the amount of electricity generated by the vehicles in real time. Along with energy generation, the system can automatically detect and record the number of vehicles crossing the piezoelectric road. This information can be transmitted to the mobile application, allowing the user to monitor both vehicle count and electricity generation from the toll plaza remotely. The proposed system combines renewable energy generation, smart transportation monitoring and IoT-based data communication. It can help utilize the continuous movement of vehicles at toll plazas as a potential source of electrical energy while providing useful traffic and energy data. The project demonstrates the potential of integrating piezoelectric technology with smart-road infrastructure for sustainable and intelligent transportation systems.

The increasing demand for clean and sustainable energy has encouraged researchers to investigate unconventional sources of renewable energy. One promising approach is the use of piezoelectric technology in road pavements to convert mechanical energy produced by moving vehicles into electrical energy. A piezoelectric road consists of piezoelectric transducers embedded beneath or within the pavement. When vehicles pass over the road, their weight and the resulting pavement deformation generate mechanical stress in the piezoelectric material. Through the piezoelectric effect, this mechanical stress is converted into electrical charge. The generated electrical energy can subsequently be rectified, regulated, stored in batteries or supercapacitors, and used for low-power applications such as road sensors, traffic monitoring systems, warning lights, wireless communication devices, and street lighting.

Research during the last two decades has demonstrated the technical feasibility of pavement-based piezoelectric energy harvesting. However, practical deployment remains challenging because of relatively low and variable power output, high installation costs, mechanical durability requirements, environmental exposure, energy-conditioning requirements, and

uncertainty concerning long-term economic performance. Recent reviews emphasize that piezoelectric roads are most realistic as a supplementary energy source for localized transportation infrastructure rather than as a replacement for conventional electrical grids.
Keywords: Piezoelectric road, piezoelectric effect, energy harvesting, smart road, renewable energy, pavement, PZT, PVDF, traffic energy.

1. Introduction

Transportation infrastructure consumes substantial amounts of energy for lighting, traffic management, sensing, communication, surveillance, and other functions. At the same time, roads experience repeated mechanical loading every day because of vehicle movement. Conventional road pavement primarily treats this mechanical loading as a structural load that must be resisted. Piezoelectric road technology proposes an alternative concept: part of the mechanical energy associated with vehicle-induced stress and vibration can be converted into useful electrical energy.

The piezoelectric effect is the ability of certain materials to generate an electrical charge when mechanical stress is applied. The effect can also operate in reverse, where an applied electric field produces mechanical deformation. Piezoelectric materials therefore provide a direct method of electromechanical energy conversion.

In a piezoelectric road, suitable transducers are installed in locations where vehicle-induced stress or deformation can be effectively transferred to them. As a vehicle travels over the pavement, the applied load causes the transducers to deform. The resulting electrical output is collected through an electrical circuit and can be conditioned and stored for later use.

Recent research shows that the field has progressed from laboratory-scale experiments toward field testing and advanced structural designs. A 2025 review in the *Journal of Traffic and Transportation Engineering* examined road piezoelectric harvesting in terms of materials, harvester structures, finite-element analysis, protective packaging, power-management circuits, and applications.

The main objective of this research paper is to study the working principle, construction, materials, energy-conversion process, applications, benefits, limitations, and future potential of piezoelectric roads.

2. Objectives

The major objectives of this research are:

1. To understand the fundamental principle of piezoelectric energy conversion.
2. To study the concept and construction of a piezoelectric road.
3. To identify the piezoelectric materials suitable for roadway applications.
4. To explain the process of converting vehicle-induced mechanical energy into electrical energy.
5. To investigate potential applications of harvested electrical energy.
6. To examine the advantages and limitations of piezoelectric road technology.
7. To review recent developments and experimental research.
8. To identify challenges that must be addressed before large-scale implementation.
9. To discuss the future potential of piezoelectric roads as smart and sustainable transportation infrastructure.

3. Research Methodology

This paper is based on a review of published scientific and engineering literature concerning piezoelectric energy harvesting from roads and pavements.

The research methodology consists of:

- Reviewing scientific literature on piezoelectric energy harvesting.

- Studying different piezoelectric materials and transducer configurations.
- Comparing laboratory, simulation, and field-test results reported in the literature.
- Examining the electrical and mechanical components required for a practical system.
- Identifying major technical and economic limitations.
- Evaluating potential applications in smart transportation infrastructure.
- Reviewing recent research to identify future development directions.

Recent literature is particularly important because roadway piezoelectric technology has developed considerably since the earliest experimental investigations. A 2025 systematic review analyzed 61 peer-reviewed studies covering approximately two decades of research.

4. Principle of the Piezoelectric Effect

4.1 Definition

The word "piezoelectric" originates from the Greek word *piezein*, meaning "to press." Piezoelectric materials produce an electrical response when mechanical stress is applied.

When mechanical force is applied to a piezoelectric element:

Mechanical stress → Electrical charge → Electrical voltage

The opposite phenomenon is:

Electrical voltage → Mechanical deformation

This property is called the direct piezoelectric effect and is the principle used for energy harvesting.

5. Concept of a Piezoelectric Road

A piezoelectric road is a roadway in which piezoelectric energy-harvesting devices are incorporated into or beneath the pavement.

A simplified system consists of:

Vehicle load
↓
Pavement deformation/vibration
↓
Piezoelectric transducer
↓
AC electrical output
↓
Rectifier
↓
DC/DC power-management circuit
↓
Energy storage
↓
Electrical load

The electrical load may include:

- Roadside sensors
- Traffic signals
- LED lighting
- Warning signs
- Wireless communication systems
- Vehicle-detection systems
- Environmental monitoring equipment
- Structural-health-monitoring systems

Discussion

Piezoelectric road technology represents an innovative connection between civil engineering, electrical engineering, materials science, and renewable energy.
Its most important advantage is the direct relationship between the energy source and the transportation infrastructure. Vehicles already impose mechanical loading on roads, and piezoelectric technology provides a method for recovering a portion of this energy.
However, the technology should be viewed realistically. A piezoelectric road should not necessarily be expected to replace conventional electricity generation for large-scale applications. Current evidence more strongly supports its use for localized, low-power transportation applications such as sensors, communication nodes, monitoring equipment, and selected lighting systems. This conclusion is consistent with recent reviews emphasizing the promise of the technology while identifying output, cost, durability, and economic evaluation as major barriers.
The most promising future approach may therefore be a smart hybrid road, where piezoelectric energy harvesting is combined with solar generation, energy storage, wireless sensors, traffic monitoring, and intelligent control.

Conclusion

Piezoelectric road technology is an emerging approach for harvesting mechanical energy generated by road traffic. By embedding piezoelectric transducers into pavement structures, mechanical stress caused by passing vehicles can be converted into electrical energy.
The technology has several advantages, including local renewable-energy generation, compact installation, compatibility with smart-road systems, and the possibility of powering autonomous sensors. PZT, PVDF, and piezoelectric composites are among the important materials investigated for roadway applications.
Nevertheless, large-scale implementation faces significant challenges. These include installation cost, limited and variable power output, mechanical fatigue, environmental protection, electrical losses, maintenance, and uncertain long-term economic performance. Research has demonstrated technical feasibility, but laboratory output cannot automatically be assumed to represent full-scale road performance.
Therefore, the most realistic near-term application of piezoelectric roads is as a supplementary energy source for low-power intelligent transportation infrastructure. Continued research in materials, structural design, protective packaging, power electronics, energy storage, and field testing can improve the feasibility of the technology. In the long term, integration of piezoelectric harvesting with other renewable-energy technologies could contribute to the development of sustainable and intelligent transportation infrastructure.

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AI and machine-learning methods could analyze traffic and pavement data to predict energy production and optimize the operation of smart-road systems.

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