PIEZOELECTRIC ENERGY HARVESTING

EVERY HIT GENERATES POWER

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ABSTRACT

Advanced piezoelectric technologies unlock the potential to capture electricity from mechanical energy that would otherwise go to waste. By harnessing stress and vibrations, these technologies offer the remarkable benefits of high-power density, simplicity, and scalability, making them ideal for a wide range of applications. Heavy vehicle traffic, coupled with pedestrian movement on highways, streets, and sidewalks, generates vast amounts of mechanical energy—an untapped resource that can be converted into renewable power. This energy harvesting not only boosts the capacity of distributed renewable energy but also presents an exciting opportunity for sustainable infrastructure. However, a comprehensive understanding of piezoelectric energy harvesting systems and their true potential remains a challenge. This project takes a cutting-edge, multi-disciplinary approach, integrating fields like mechanical engineering, electrical engineering, civil engineering, automobile engineering, material science, and physics. By bringing together these diverse disciplines, the goal is to develop breakthrough technologies capable of harvesting high-density piezoelectric energy—ushering in a new era of energy generation.

Keywords: *-Piezoelectric, Highway traffic, Mechanical force amplification, High energy density, Energy harvesting.*

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1. INTRODUCTION

Electricity has become a lifeline of present-day civilization and thus its demand is enormous and is growing steadily. There seems no end to the different ways one can generate pollution-free electricity. At one hand, rising concern about the gap between demand and supply of electricity for masses has highlighted the exploration of alternate sources of energy and its (energy) sustainable use. On the other hand, traffic on road all over the world is increasing day by day and thus, congestion on roads is becoming inevitable with the fancy of masses towards personal transportation systems for their growing mobility.

Energy demand and heavy traffic correlation motivate to dream about a device in the road that would harvest the energy from the vehicles driving over it. For this, piezoelectric material embedded beneath a road, the piezo-smart road, can provide the magic of converting pressure exerted by the moving vehicles into electric current. The system is based on piezoelectricity, which uses pads of metallic crystals buried over hundreds of meters of road to generate electricity when put under the pressure of quickly moving traffic. With this technology, now, engineers are poised to harvest some of the spare energy of the world's moving vehicles. When a vehicle drives over the road, it takes the vertical force and compresses the piezoelectric material, thereby generating electricity.
This review paper aims to concentrate our vision towards harvesting the energy of moving vehicles and moving people with the help of piezoelectric materials which not only meet the power needs but also meet the criterions of green

energy source that is long lasting in use, safer in operation and provide promising solution to the growing needs of power.

India is aiming to build smart cities …. what if we built smart roads in these smart cities which can generate the electricity for its lighting and other requirements on its own with the help of piezoelectric material.

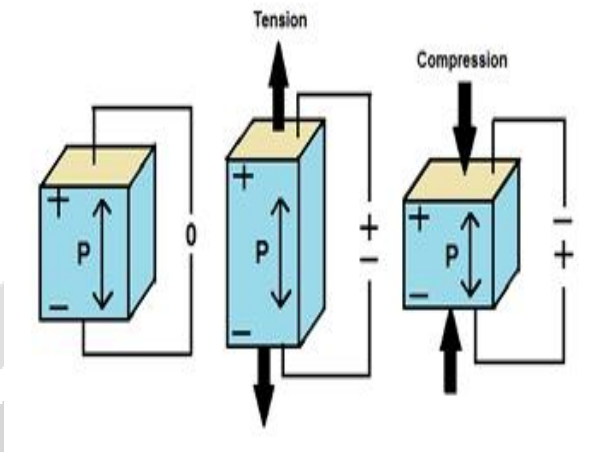


Figure 1: Scheme of Piezoelectricity

2. PIEZOELECTRICITY AND PIEZOELECTRIC EFFECT

The word piezoelectricity means electricity resulting from pressure. It is derived from the Greek piezo or piezein, which means to squeeze or press, and electric or electron, which stands for amber, an ancient source of electric charge.[2] Piezoelectricity was discovered in 1880 by French physicists Jacques and Pierre Curie. This inverse effect causes material to change its physical dimensions e.g. length when an electrical voltage is applied across the material. This actuator effect converts electrical energy into mechanical energy The first real time application of piezoelectric material is in SONAR, which further extended its use in microphone, transducers, signal filters, surface acoustic wave devices, frequency control.

The piezoelectric effect is a linear electromechanical interaction between the mechanical and electrical states in crystalline materials that lack inversion symmetry. Crystals with inversion centres cannot exhibit this effect; thus, piezoelectricity is observed only in materials with non-Centro-symmetric crystal structures. Naturally occurring crystalline materials like quartz and tourmaline, which have mono-crystalline structures, display this property. In single crystals, the piezoelectric effect arises due to asymmetry in the structure of the unit cells [5]. When external forces are applied in specific directions, this structural distortion generates voltage in a defined direction. Artificially manufactured piezoelectric materials include Rochelle salt, ammonium dihydrogen phosphate, lithium sulfate, and a class of polarized piezoelectric ceramics. The most commonly produced ceramics in this category are lead zirconate titanate (PZT), barium titanate, and lead titanate. Ceramic materials exhibit stronger piezoelectric effects due to their asymmetric crystal structures and inherent spontaneous polarization. This polarization occurs as a result of charge separation along the direction of spontaneous polarization within the unit cells. A typical piezoelectric ceramic material features a polycrystalline structure composed of small crystallites, each with a net dipole moment oriented in a specific direction. These dipoles are randomly distributed, resulting in zero net polarization. To align the dipoles in one direction, a strong electric field is applied, inducing remnant polarization in the material. However, the piezoelectric effect can only occur if the material is operated below its Curie temperature (Tc) .

Ceramic piezoelectric materials offer several advantages over single crystals. They are easier to fabricate into various shapes and sizes, whereas single crystals require precise cutting along specific crystallographic directions [4]. Piezoelectric materials are generally classified based on the level of doping into two categories: hard piezoelectric materials and soft piezoelectric materials.
Hard piezoelectric materials are ideal for applications that require resistance to high electrical and mechanical stresses, particularly in dynamic or on-resonance conditions. These materials are difficult to pole or depolarize unless exposed

to elevated temperatures. Conversely, soft piezoelectric materials are used in actuators and sensors designed for static or semi-static applications that demand high precision. However, under dynamic conditions, soft piezoelectric ceramics experience greater dielectric losses and higher dissipation factors, which can lead to overheating during prolonged use.

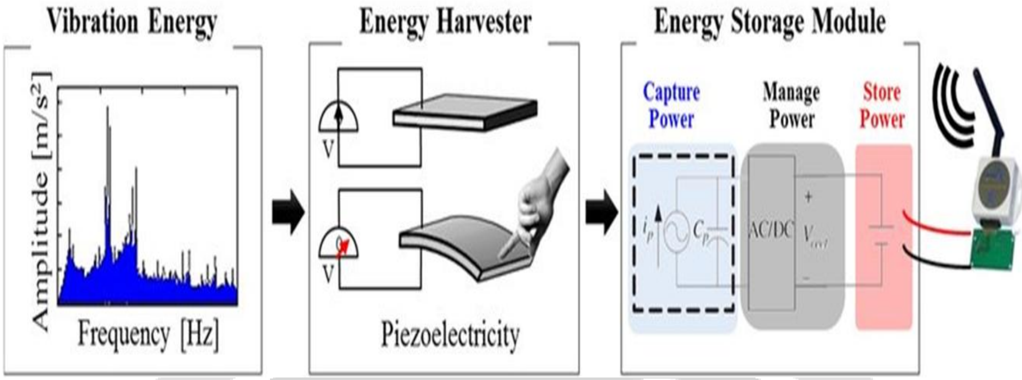
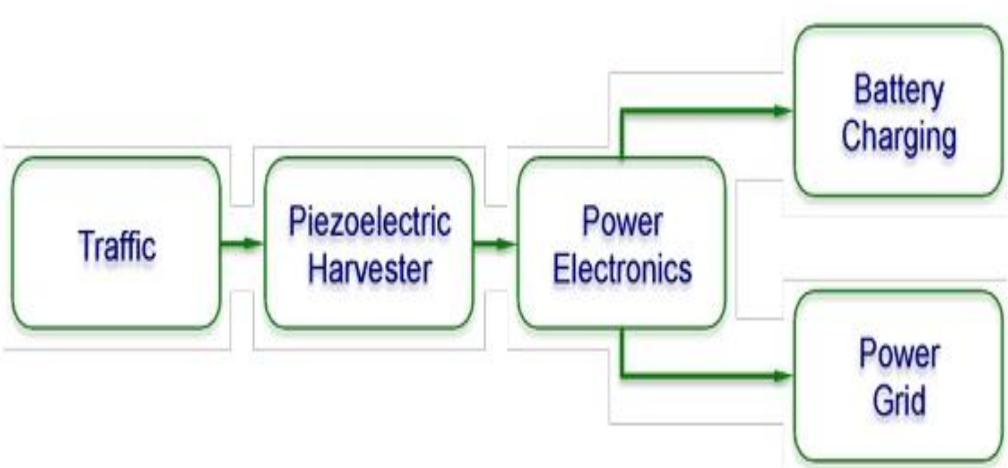


Figure 2: Stages of Piezoelectric energy harvesting

3. Concept of the Technology

The concept of the piezoelectric energy harvesting technology for harvesting energy from traffic, including traffic on highways, airport runways, or even warehouses, as well as pedestrian traffic. This project initially focused on the ground vehicle traffic on highways.



Piezoelectric energy harvesters work by utilizing the mechanical energy produced by heavy vehicles passing over roadways. This mechanical energy is converted into electrical energy, which is then collected by a power electronic circuit. The harvested electricity can be rectified and used to charge batteries or electric vehicles near the road or supplied directly to a power grid along the highway.

Unlike solar panels, which depend on sunlight and can only generate power intermittently, piezoelectric energy harvesting systems operate continuously as long as there is traffic. This feature makes them a reliable alternative source of electricity under any weather conditions. However, implementing piezoelectric energy harvesting systems (PEHS) on a large scale, such as on public highways, poses certain challenges. These include the need for innovative designs to integrate piezoelectric devices into roadways while maintaining a smooth and safe surface for vehicles.

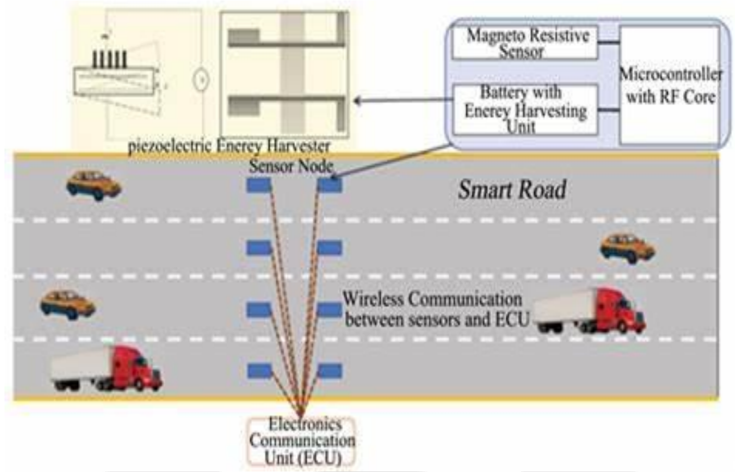


Figure.4: Piezeoelectric Roads

4. METHODOLOGY

Material Selection: The first step is choosing suitable piezoelectric materials like lead zirconate titanate (PZT), barium titanate, or polyvinylidene fluoride (PVDF). These materials are selected based on their piezoelectric constants, mechanical strength, and durability. Additionally, substrate materials such as flexible polymers or composites are chosen to support and protect the piezoelectric elements.

System Design: The design phase focuses on optimizing energy harvesting. This includes configuring the geometry and layout of piezoelectric elements (e.g., tiles, strips) based on traffic patterns and vehicle weights. Electrode design is crucial for efficient charge capture, typically using conductive materials like copper or silver. Encapsulation techniques are developed to protect the piezoelectric elements from environmental factors such as moisture, temperature, and mechanical wear. Simulation and Modelling: Finite Element Analysis (FEA) is used to simulate mechanical stress and deformation on the piezoelectric elements under different traffic loads, optimizing the system design for maximum energy output. Electrical modelling is also performed to understand the voltage and current characteristics under varying conditions.

Prototyping and Testing: The next step involves creating lab-scale prototypes to test basic functionality and system efficiency. Field testing is then conducted in controlled environments, like test tracks, to assess performance in real-world conditions, focusing on energy output, durability, and environmental resistance. These steps ensure the development of a robust, efficient piezoelectric road system capable of harnessing energy from traffic.

5. WORKING

A significant portion of the energy produced from vehicle fuel combustion is lost due to engine inefficiencies, with only a part of it utilized for moving the vehicle or powering auxiliary systems like air conditioning. The energy required for vehicle movement is primarily spent overcoming rolling resistance, which occurs as the wheels move forward on the road surface. Additionally, some energy from fuel combustion is wasted in deforming the asphalt, a consequence of the loaded wheel's interaction with the road surface.

Asphalt roads are typically visco-elastoplastic materials, with elasticity being their dominant characteristic. When a vehicle drives over the road, the surface undergoes vertical deflection. This deflection depends on the vehicle's weight and the asphalt's stiffness. A small fraction of the vehicle's total energy—specifically, the mechanical energy related to the vertical deformation of the asphalt—can be harnessed for electricity generation.

The vertical load from the vehicle's wheels creates compression stress in the road, which decreases with depth. Piezoelectric generators are embedded approximately 5 cm beneath the surface, where compression stress is at its peak. The external load causes deformation of both the asphalt layer above the generators and the piezoelectric columns within the generators. This deformation generates charges in the piezoelectric material, producing electric energy.

The amount of energy required to deform the road depends on factors such as road surface quality, asphalt composition, environmental temperature, and other variables. By embedding piezoelectric generators at the optimal depth, this otherwise wasted energy can be effectively converted into electricity.

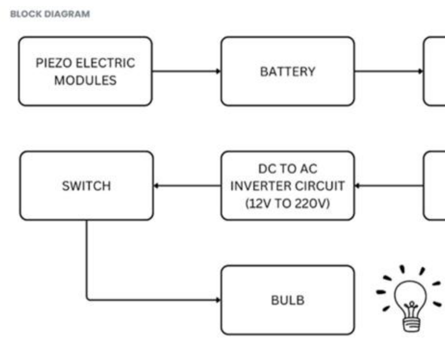


Figure-5: Block Diagram

6. APPLICATIONS

- Design mechanical systems for PEHS that can withstand varying weather conditions and the continuous dynamic loads generated by traffic.
- Showcase the efficiency of piezoelectric energy harvesting systems in generating a high density of electricity per unit length of roadway.
- Create a power electronic system to facilitate battery charging or seamless grid integration for energy collected by the PEHS.
- Engineer pavement structures compatible with PEHS, optimizing load distribution to the piezoelectric devices while protecting the system from environmental factors.
- Formulate strategies for the broader application and commercialization of piezoelectric energy harvesting technology, targeting highway traffic and other transportation systems.

7. EFFICIENCY AND MECHANISAM

The concept of piezoelectric roads revolves around utilizing crystals with piezoelectric properties, which are embedded approximately 5 cm beneath the road surface. As vehicles travel over the roadway, they cause the surface to deform slightly. Each time a vehicle passes over these crystals, they undergo minor deformation. The energy expended on this deformation is captured by piezoelectric generators, which convert the mechanical energy of road deformation into electrical energy. This harvested energy can be stored in batteries or fed directly into the electrical grid.

The electricity generated from the piezoelectric effect can be used to power road lighting, traffic signals, speed sensors, roadside billboards, and other applications. As shown in Figure 5, piezoelectric crystals are strategically embedded in designated areas. For instance, when a truck passes over these embedded crystals, deformation occurs, producing a corresponding electrical potential. This energy can be used to light nearby street lamps. Studies indicate that if vehicles move continuously along a 1 km stretch of road embedded with these crystals, generating energy every second, approximately 240.12 kW of power can be produced. Considering a typical mercury vapor lamp consumes about 500 W, the energy from piezoelectric crystals is sufficient to illuminate these roadside lamps.

The energy output is directly proportional to roadway activity—the busier the road, the more energy is produced. This concept can also be extended to other areas such as pedestrian walkways, airports, and railway tracks. Additionally, piezoelectric technology can harness energy from human movement, such as walking or running, making it suitable for indoor locations like public transportation hubs, shopping malls, and entertainment venues. This approach effectively captures energy that would otherwise be wasted during movement, transforming it into a sustainable power source.

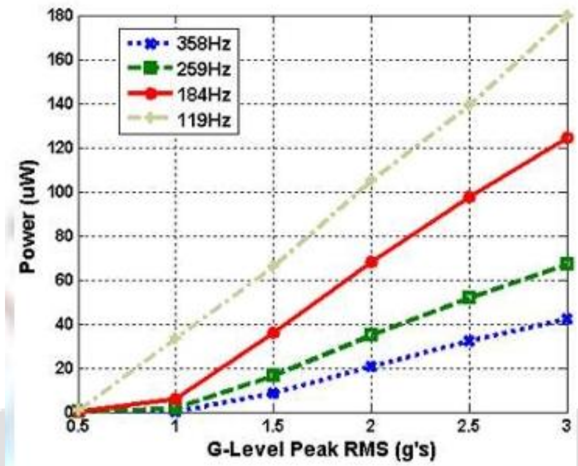


Figure 6: Shows the efficiency graph

One design for piezoelectric roads involves placing a thin box containing piezoelectric material beneath a layer of asphalt. When vehicles, especially trucks, drive over plates embedded in the asphalt, they compress a hydraulic system underneath, which pumps fluid to drive a generator and produce electricity. For cars, the vertical force compresses the piezoelectric material directly, generating electricity. This energy, about 80 kilowatt-hours per kilometre of road traffic, can be stored in batteries or supercapacitors or used immediately to power streetlights and other roadside devices.

The electricity generated comes from the motion of vehicles and the deformation of the road, energy that would otherwise be lost as heat. Since the piezoelectric layer is stiffer than the asphalt it replaces, it may also slightly reduce the energy needed to move the vehicle.

Another design captures energy when vehicles slow down, using a mat installed on highways, off-ramps, or near toll booths. As vehicles drive over the mat, it transforms some of the energy from braking into electricity, reducing wear on the vehicle's brakes. This system uses mechanical or hydraulic cells and can be adjusted for different vehicle types. Tests of this design have shown potential, producing up to 40 kilowatt-hours of electricity, but the panels faced issues like damage from dirt, extreme temperatures, and vehicle movements. Engineers are working to improve these systems.

Another innovation involves piezoelectric generators under the road that turn vibrations from passing vehicles into electricity. This electricity can be stored in roadside batteries and used to power traffic lights or street lamps. For instance, one truck can generate up to 2,000 volts. This method, known as parasitic energy harvesting, can also be applied to airport runways and railway systems.

On railways, piezoelectric systems are especially effective because trains consistently apply pressure in the same location, making energy harvesting more reliable. Additionally, the system can provide real-time data on the weight, speed, and spacing of vehicles or trains passing over it, offering added functionality alongside energy generation.

8. RESULTS

The energy harvested by piezoelectric energy harvesting systems (PEHS) depends on factors like the weight and speed of passing vehicles, causing the power output to vary at any given moment. To better understand the energy harvesting capability, calculations were based on the energy collected from a midsize vehicle weighing 16,000 N traveling over a one-mile-long lane equipped with this technology. Using test results and assuming the capacitance of the system was measured or estimated from a model, the energy density was found to be 15.37 joules per meter per vehicle per lane. This means that for every meter of road, a single vehicle passing once could generate this amount of energy.

The battery storage efficiency was considered to be 30.7%, and traffic was assumed to follow the "three-second safety rule" (vehicles spaced three seconds apart) throughout the day. Based on these assumptions, the total energy harvested and stored in batteries from one lane of a one-mile-long road was estimated. This provides a practical measure of how much energy such a system could produce under real traffic conditions. Electric energy estimates at various levels based on the laboratory as well as the mathematical model of the PEH. The electric energy estimates based on per unit length as well as on per unit area are presented.

Figure 6: Practical model of the circuit

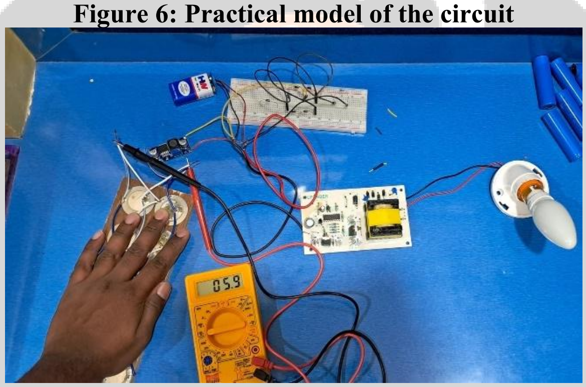


Figure 7: showing practical results

This design uses piezoelectricity, which is generated when certain materials like crystals or ceramics are subjected to mechanical stress. The idea is to place piezoelectric sensors under the road surface to capture the vibrations caused by vehicles. This technology could generate up to 44 megawatts of electricity per year from a one-kilometer stretch of road, enough to supply power to about 30,800 households.

Table 1: Harvested Electric Energy Estimates

Conditions	Numbers	Electric Energy Estimate
Measured electric energy density from two rows, 48 piezoelectric towers with one (Nissan Altima) car passing on a 1.32 meter one-lane road	No. of towers 24x2 Road length 1.32 m	15.37 J /(m.pass.lane) 17.43 J /(sq.m.pass.lane)
One year traffic following three-second rule Over one mile or 1609.34 meters Equivalent area 0.882x1609.34 sq meters	365x24x3600/3 1609.34 m 1419.4 sq m	260,040,668,487 J 72,811.4 KWh 51.25 kWh /(sq m year)

9. ADVANTAGES OF PIEZOELECTRIC ENERGY HARVESTING

- Sustainable Energy Generation: They capture energy from vehicle movement, turning wasted mechanical energy into electricity. This provides a renewable energy source without relying on the weather, unlike solar or wind energy.
- Reduced Energy Waste: Instead of energy from vehicle vibrations and road deformations being lost as heat, piezoelectric roads convert it into usable electricity.
- Low Maintenance: Once installed, piezoelectric systems require minimal maintenance compared to traditional power generation methods, such as power plants.
- Supports Smart Infrastructure: The energy harvested can power streetlights, traffic signals, sensors, and other roadside devices, creating a more energy-efficient and connected transportation system.
- Environmental Benefits: By harnessing energy from everyday vehicle movement, piezoelectric roads help reduce the reliance on non-renewable energy sources, contributing to a cleaner environment.
- Scalable: The technology can be applied to various transportation routes, such as highways, pedestrian walkways, railways, and even airports, making it versatile.
- Energy Storage: The electricity generated can be stored in batteries or supercapacitors, which can be used during peak demand or supplied directly to the grid.
- Reduced Vehicle Wear: Some designs also capture energy when vehicles slow down, reducing the wear and tear on car brakes.
- Innovative Data Collection: These systems can also collect data on vehicle traffic, such as speed, weight, and spacing, offering valuable insights for traffic management and road maintenance.

10. CONCLUSION

Piezoelectrified roads represent a promising intersection of infrastructure development and renewable energy generation. By leveraging the mechanical energy from vehicular traffic, these roads have the potential to contribute significantly to sustainable urban environments. Continued research and development are essential to overcoming technical challenges and realizing the full potential of piezoelectric energy harvesting in road infrastructure. Piezoelectric energy harvesting devices can be used in various types of traffic. The most suitable traffic for harvesting energy is highway traffic, which includes passenger vehicles, trucks, and heavy-duty semis traveling at high speeds. This type of traffic offers the greatest potential for generating energy.

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