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# Energy harvesting from asphalt pavement roadways vehicle-induced stresses: A feasibility study

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## HIGHLIGHTS

- Piezoelectric power is sensitive to frequency, vertical load and number of disks.
- Effect of temperature on output power was found to be negligible.
- A statistical model developed to quantify output power under stress and frequency.
- Piezoelectric can be used to harvest energy from roadway under certain conditions.

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## ABSTRACT

Roadways are major infrastructure for connecting people and providing access and mobility. The traffic-induced strains and stresses generated by the vehicles can be potentially used for energy harvesting purposes. Piezoelectric devices are ideal candidates for harvesting energy in asphalt pavement roadways as they convert mechanical strain energy into electric voltage. In this study, an experimental program was conducted to evaluate the potential of harvesting energy from roadways using piezoelectric materials. A prototype consisting of piezoelectric disks sandwiched between two copper plates was assembled in between asphalt mixtures. A uniaxial compression test was performed to measure the output power under different numbers and arrangements of piezoelectric disks. Moreover, the sensitivity of the power to loading frequency, vertical load, test temperature, and loading time was also studied. The experiment results show that the quantity and arrangement of the piezoelectric sensors alter the applied stresses leading to variations in the generated output power. The effect of temperature on the output power was found to be negligible. In addition, the magnitude and loading time significantly affect the output power. Considering the best combination of variables, the piezoelectric devices could be ideal candidates for harvesting energy in asphalt pavement roadways.



## 1. Introduction

Energy harvesting, or energy scavenging, is a process that captures unused ambient energy that would otherwise be lost as heat, light, sound, vibration, stress or movement. The United States transportation system consists of about 6 million kilometers of roadways. These roadways are exposed to energy in the form of vehicle vibrations, traffic loading strains, and thermal gradients that can be harnessed. These resources can be potentially converted into usable energy such as electric power. Capturing the unused energy is the major and challenging aspect in the harvesting process. Successful energy harvesting from roadway pavements can lead to sustainable transportation infrastructure systems. The ability to capture this energy cheaply with great efficiency is considered an area of great interest. The concept of energy conservation and development of alternative energy resources becomes urgently needed due to the high cost and environmental impact associated with fossil fuels. Consequently, the search for environmental-friendly, low-cost energy resources becomes more and more necessary [1–4].

One of the main sources of the unused ambient energy is the induced vibration and stresses caused by vehicles movements on the roadways. Assuming a fully loaded 18-wheeler truck is moving at 50 mph, the average dynamic displacement in the asphalt pavement under each tire is about 0.04 in. [5]. By considering 100 psi for truck tire pressure, footprint of 55 in$^2$ (6.67 in. × 8.25 in.) for a commercial truck dual-tire with 5 axles, and the average daily

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truck traffic of 100 per lane, the total daily induced energy on roadway is about 4.18 GJ/lane. Taking advantage of a portion of this amount of energy could be a great area of interest for the transportation industry. This energy can be harvested by using piezoelectric disks [6,7]. The piezoelectric materials are capable of generating electric voltage due to the application of loading stresses and vibrations. The piezoelectric is activated if the load application oscillates with time. As the magnitude of load changes with time, the piezoelectric will polarize to form two distinct surface charges. These charges are the source of the electric voltage [8]. The piezoelectric materials are extensively available in several shapes and forms including single crystal (e.g. quartz), piezoceramic, thin film (e.g. sputtered zinc oxide), screen printable thick-films based upon piezo-ceramic powders and polymeric materials such as polyvinylidene fluoride [9]. Accordingly, they could be widely used to harvest vibration and strain energy caused by vehicles on roadways [6,10].

Several attempts have been recently made to evaluate the possibility of using roadways to generate useable energy. A large number of them have been undertaken with the aim of harvesting solar energy from asphalt pavement. In 2006, researchers designed and developed solar panels equipped with integrated heating component that maintain a temperature above freezing for roadway infrastructures in cold climate [11]. The concept of solar roadways is to harvest solar energy with imbedded (surface) photovoltaic technology incorporated directly into roadways and replacing the conventional asphalt pavement layer currently used. In similar attempt in the Netherland, the engineers of SolaRoad® implemented installed solar panels in a 230-feet bike lane. The fragile parts were encased in thick glass layers to be able to withstand the heavy loads caused by traffic. SolaRoad® claims that the output power during the first six months is around 3 MW h which is approximately equal to the amount of electricity required for a single occupancy house for one year [12]. The problem facing these panels on roadways is the effect of shading or partial shadowing from obstructions such as buildings, trees, and cloudy conditions. However, a solar roadway would have further hindrance on its efficiency by the shadows of passing vehicles. Analysis has shown that the two most important factors to be considered to calculate the time the shade of a passing vehicle will be covering a solar panel is the vehicle's speed and the length of the vehicle [13].

Kang-Won et al. investigated the feasibility of using solar cell or photovoltaic technologies as an energy harvester in roadways. Current challenges in solar system are their susceptibility to sustain harsh conditions in asphalt pavement from excessive traffic loading and environmental condition changes [14]. The photovoltaic energy systems are capable of improving asphalt pavement performance and durability as they decrease temperature in summer and increase it during winter seasons. This leads to reduce temperature-related distresses in asphalt pavement such as rut damage and thermal cracking, respectively [15–17]. From an environmental point of view, using the photovoltaic systems in urban roadways and parking lots can decrease the urban heat island effect [18].

Xiong et al. in 2010 [19,20] compared the generated power of different energy harvesting methods (piezoelectric, thermoelectric, electromagnetic and photovoltaic) based on the works conducted by DuToit et al. [21] and Voigt et al. [22]. According to the comparison results, the photovoltaic energy harvesting provides more output power followed by piezoelectric energy harvesting, but due to the fact that the solar energy harvesting is highly dependent to direct sunlight and its efficiency becomes low in a cloudy day, it does not constitute a good candidate for all environmental conditions and locations such as tunnels. On the other hand, compared to other methods, piezoelectric energy harvesting is capable of generating power in any conditions and supply electricity for transportation facilities.

Recently, the application of piezoelectric materials has been attempted by Technion Institute of Technology in Israel. Researchers embedded the piezoelectric materials under the asphalt pavement layer. They investigated the potential of these materials through field-testing sections [23,24]. Xiong conducted a field experimental study using in-house fabricated piezoelectric prototypes in an attempt to harvest energy from roadways. The prototype was capable of generating 3.1 mW of energy harvesting per passing vehicle [25]. Xiong et al. also investigated the coupling configuration and material selection in piezoelectric energy harvesting from traffic-induced deformation. They reported that for roadways applications using the 33-mode of coupling configuration is more efficient compared to 31-mode [19,25].

In 2011, Baldwin et al. conducted an attempt to harvest energy from the traffic-induced loading on bridges using a piezoelectric prototype. The maximum reported energy output was 1.2 μW h. They reported that the implementation of the prototype was successful but the amount of output energy was not enough to drive a modest electrical load [23]. Zhang et al. conducted a comprehensive numerical modeling on harvesting energy using piezoelectric materials in asphalt pavement roadways. The results depicted more energy output if roadways are built over soft subgrade foundation. In addition, they remarked that key variables such as depth of embedded disks, position of the wheel with respect of energy harvester, and vehicle speed influence the output power [26]. The energy harvesting using traffic induced vibration in bridges as an energy source was also studied. Cantilever piezoelectric harvester was used to convert the random short-time pulses of vibration to electrical energy. The researchers were able to generate 0.03 mW during the rush hour that is able to power wireless health monitoring sensors [27].

The use of piezoelectric in harvesting energy from asphalt pavements is practically a new approach that has not been studied thoroughly yet. Various factors such as the effect of traffic speed, traffic volume and vehicle type on piezoelectric materials are still unknown. Therefore, there is a press need to study the impact of these factors on the potential of energy harvesting from roadways.

In recent years, several companies attempted to harvest strain energy in asphalt pavement and convert it into a usable source of power using commercial piezoelectric devices [24,28,29]. In those attempts, the effects of traffic loading and pavement conditions on the generated power out of piezoelectric materials were not fully understood due to the lack of a comprehensive laboratory evaluation. Moreover, most of these attempts lack realistic quantification of the feasibility of their commercial devices. This study aims to fill in the gap through laboratory evaluation of the energy harvesting concept from asphalt pavement and its feasibility compared to the cost associated with traditional power sources. The results can help researchers to explore new sources of harvesting wasted energy from roadway and to understand the key factors for improving their devices design and efficiency.

## 2. Piezoelectric theory

The piezoelectric effect has been observed in a number of ceramic materials such as lead-zirconate ($PbZrO3$), lead-titanate ($PbTiO2$), barium-titanate ($BaTiO3$), and lead-zirconate-titanate (PZT). These materials show a polarized electrostrictive effect [30]. There are two forms in which piezoelectric functions; the first is the direct piezoelectric effect in which the materials are able to transform mechanical strain into electrical charge. The current applications of direct piezoelectric effect are in the form of sensors manufacturing and energy harvesting. The second form is the