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Energy Research and Development Division

FINAL PROJECT REPORT

Ultra-High Power Density Roadway Piezoelectric Energy Harvesting System

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation and bring ideas from the lab to the marketplace. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas & Electric Company and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Ultra-High Power Density Roadway Piezoelectric Energy Harvesting System is the final report for the Ultra-High Power Density Roadway Piezoelectric Energy Harvesting System project (EPC-16-049) conducted by University of California, Merced. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the Energy Commission's research website (www.energy.ca.gov/research/) or contact the CEC at 916-327-1551.

ABSTRACT

Advanced piezoelectric technologies can generate electricity from otherwise untapped mechanical energy resources. Piezoelectric technologies provide the opportunity to harvest energy where stress or vibration is generated and have the advantages of high-power density, simplicity, and scalability for a variety of applications. Heavy traffic of ground vehicles and pedestrians on highways, streets, and sidewalks provides considerable mechanical energy. Harvesting this energy can increase distributed renewable energy capacity. However, there is a lack of the comprehensive understanding of piezoelectric energy harvesting systems and their potential. This project takes an integrated multi-disciplinary approach involving mechanical, electrical, engineering, civil, and automobile engineering, material science, and physics to develop technologies for harvesting high-density piezoelectric energy.

The goals of the project were to design a piezoelectric energy harvesting system to achieve an electrical energy density of 333 watts per square foot with the cost of the system reduced to $9,010 per kilowatt and a lifetime of up to 20 years. The project team developed and demonstrated an innovative piezoelectric device for harvesting energy from highway traffic. The results were supported through numerical simulations, experimental investigations, and road tests. Based on the laboratory evaluations and road tests, the application of the piezoelectric energy harvesting system in one lane of a one-mile-long roadway has the potential to generate 72,800 kilowatt-hours of energy per year. For heavy trucks, the annual electric energy over one mile of a one-lane highway can be as high as 907,873 kilowatt-hours, which is equivalent to a reduction of 300 metric tons of carbon dioxide. California has 386,604 lane miles. Outfitting all these lane miles with piezoelectric energy harvesting devices would yield a carbon dioxide reduction of 115 million metric tons annually in California. Other potential applications include warehouses, seaports, aircraft runways, and railroads.

Keywords: *Piezoelectric, energy harvesting, highway traffic, mechanical force amplification, high energy density*

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EXECUTIVE SUMMARY

Introduction

Renewable energy technologies such as wind and solar are weather and time sensitive and therefore intermittent. To achieve California's goal of providing 100 percent of the state's electricity with renewables and zero-carbon energy sources by 2045, the state needs additional sources of energy that are accessible at any time and in any weather. Pavement generation research using piezoelectric materials came as a request from Assemblymember Gatto who saw the potential benefits for California. Piezoelectric generation was an initiative in the 2015-2017 Electric Program Investment Charge Plan to implement recommendations from the Energy Commission's assessment of piezoelectric materials for roadway energy harvesting. Harvesting piezoelectric energy from highway traffic offers just such an appealing alternative as traffic on roadways occurs on a more constant basis. Piezoelectric materials generate electricity with the application of stress, which offers considerable opportunity to harvest energy where stress or vibrations are generated. But this energy source is currently largely untapped. Today's advanced piezoelectric materials and devices have matured to the point that large-scale implementation under highways and streets has become realistic and economic. There have been many attempts to create piezoelectric energy harvesting systems; however, the power level that many of these systems generate has usually been on the order of milliwatts. There is a need to create high-density piezoelectric energy harvesting systems to tap the huge potential source of electricity supply in the nation's highway system and major cities.

Piezoelectric energy harvesters have attracted much attention recently because they can harvest energy from the ubiquitous vibrations (with small displacements -- even down to the nanometer range) in the ambient environment without being affected by the weather. To date, there have been extensive studies of piezoelectric conversion efficiency, individual device reliability, and endurance. Recent technological and research advances offer the opportunity to take a systematic approach to developing a large-scale piezoelectric energy harvesting system by applying current knowledge to economically viable applications to benefit society and move California closer to its energy goals.

This project investigated the energy recovery potential of piezoelectric harvesters by creating a roadway piezoelectric energy harvesting system with ultra-high-power density and efficiency and pilot demonstrating the ultra-high capacity of electric power generation and the feasibility of implementing a large-scale under-pavement system at the University.

Project Purpose

The purpose of this project was to validate the potential of a piezoelectric energy harvesting system in the laboratory and through a pilot demonstration to support meeting California’s long-term energy goals. The main goals of the project were to design a high density piezoelectric energy harvesting system for underneath highways, to demonstrate the high electrical power harvested by the system, and to study the feasibility of implementing such a system on a large scale under public highways and streets in the state. The system includes piezoelectric harvesters, stacked into towers, with load transfer layer and materials to support and protect the system, and interface electric circuitry. Specifically, the project was designed to achieve the following objectives:

1. Develop mechanical designs of the piezoelectric energy harvesting system that can survive weather conditions under continuous dynamic loading of traffic.
2. Demonstrate the effectiveness of the piezoelectric energy harvesting system to achieve high density of electricity harvesting per unit length of the road using an amplification mechanism.
3. Develop a power electronic system to enable battery charging or grid integration by the piezoelectric energy harvesting system.
4. Develop pavement designs that are compatible with the piezoelectric energy harvesting systems, optimize load transfer to the piezoelectric devices and shield the system from the environment.
5. Develop plans for further application and commercialization of the technology to harvest piezoelectric energy from highway traffic and other modes of transportation.

Project Approach

For the research and development of piezoelectric energy harvesting technologies for applications under highway and street pavement, the project team took a multi-disciplinary system approach involving the integration of mechanical engineering, physics, materials science, and electrical engineering. To design piezoelectric energy harvesters embedded in traffic systems more efficiently, the team developed an innovative compression force amplification design to maximize the electric energy generation of piezoelectric materials.

The key to the success of this project rested on the advanced piezoelectric generator design to achieve ultra-high density using an amplification mechanism when harvesting electricity from the highway.

The project team consisted of a mechanical engineering professor, J.Q. Sun; a research scientist and faculty member with higher education training in physics and material science, T.B. Xu; and an electrical engineering faculty member, A. Yazdani.

The director of the Center for Information Technology Research in the Interest of Society and the dean of the School of Engineering at the University of California, Merced served on the Technical Advisory Committee and provided valuable input and administrative support during the project. A state highway contractor in Porterville, California frequently discussed with the project team developing innovative highways integrated with piezoelectric devices.

Project Results

The project achieved its major technical objectives, including the following highlights:

1. A compression force amplification mechanism was designed, analyzed, evaluated in the laboratory environment, and validated in road tests. This mechanism is responsible for generating ultra-high-density energy harvested from traffic.
2. A patent application was filed by the University of California, Merced to protect this proprietary technology. Private investors committed match funding support to further develop the piezoelectric energy harvesting system.
3. A system design methodology of the piezoelectric energy harvesting technology was developed including the compression force amplification mechanism in harvesting units and towers.
4. A multi-objective optimal design approach was developed to determine various parameters of the piezoelectric harvesting unit.
5. Laboratory evaluations demonstrated that the piezoelectric energy harvesting tower under a 1,000 Newton load generates an open circuit voltage as high as 300 volts.
6. The road test results led to an estimated 72,800 kilowatt-hours of electric energy harvested from mid-size car traffic on a single-lane, one-mile-long highway integrated with the proposed devices over the course of one year, equal to a reduction of 24 metric tons of carbon dioxide. The potential energy harvested and carbon dioxide reduced is even higher for heavy truck traffic.
7. The project team further concluded that the application of the piezoelectric energy harvesting devices was not limited to highway traffic. Other potential applications may be found in warehouses, seaports, aircraft runways and railroads.

To implement the ultra-high-density piezoelectric energy harvesting technology on a large scale, the project team recommends completion of the following tasks:

1. Develop modular design of the piezoelectric energy harvesting devices so the devices can be installed below the pavement in an automated manner.
2. Invent a machine to install the piezoelectric energy harvesting devices automatically and consistently.

3. Invent a new pavement technology, together with the construction materials, to accommodate the piezoelectric energy harvesting devices and form integrated smart roads, embedded with energy harvesting capacity.

Technology/Knowledge Transfer/Market Adoption (Advancing the Research to Market)

IDTechEx, an independent market research firm, estimates that the market for piezoelectric energy harvesting will grow to $823.8 million by 2023. Military and aerospace industries could use piezoelectric harvesters to the extent of about $210 million. This innovative project is promising in terms of promoting further market interests in piezoelectric energy harvesting technologies in diverse applications worldwide.

The University of California, Merced filed a patent application to protect the proprietary technology of piezoelectric energy harvesting devices resulting from this project. With the help of the Office of Research and Economic Development at the University of California, Merced, the project team contacted private investors to promote the technology and pursued further funding for larger scale prototype demonstration. One investor committed match funding support for further development and commercialization of the piezoelectric energy harvesting system.

Furthermore, the Office of Research and Economic Development of the University of California, Merced has been actively reaching out to venture capitalists and entrepreneurs to promote the technology developed by this project and transfer the technology to the market.

Benefits to California

The application of the piezoelectric energy harvesting system developed from this project on one lane of a one-mile-long roadway has the potential to generate 72,800 kilowatt-hours of energy per year. For heavy trucks, the annual electric energy over one mile of one-lane highway can be as high as 907,873 kilowatt-hours, which is equivalent to a reduction of 300 metric tons of carbon dioxide. If all of California's 386,604 lane miles were integrated with the piezoelectric energy harvesting devices, the state's annual carbon dioxide reduction would be 115 million metric tons.

What's more, once piezoelectric technology is successfully transferred to the commercial market, a large share of the piezoelectric energy harvesting business will be in California. The ratepayers in the state could see substantial benefits from this reliable green electricity source due to the ever-growing heavy traffic everywhere in the state.

In addition to the commercial market, the project team will also encourage federal government agencies, such as Department of Transportation, Department of Defense, Department of Energy, and National Science Foundation, to investigate energy harvesting technologies in California. The success of the technology will help to improve the nation’s energy security. Also, the success of the technology will significantly raise the academic capability and reputation of the University of California, Merced. Finally, commercial success in this sector would translate to huge potential for new manufacturing jobs in California.

CHAPTER 1: Introduction

Heavy traffic of ground vehicles and pedestrians on highways, streets, and sidewalks provides considerable mechanical energy. Pavement generation research using piezoelectric materials came as a request from Assemblymember Gatto who saw the potential benefits for California. Piezoelectric generation was an initiative in the 2015-2017 Electric Program Investment Charge Plan to implement recommendations from the Energy Commission’s assessment of piezoelectric materials for roadway energy harvesting. This mechanical energy can be generated as electricity with piezoelectric under-pavement harvesters to advance California’s goal to provide 100 percent of electricity with renewables and zero-carbon energy sources by 2045. Today’s advanced piezoelectric materials and devices have matured to a point that large-scale implementation under highways and streets has become realistic and economic. There is an enormous potential source of electricity supply in the nation’s highway system and major cities.

This report summarizes the work at University of California, Merced on the development of an ultra-high power density piezoelectric energy harvesting system (PEHS) for highway traffic. The goal of this project was to demonstrate in the laboratory the ultra-high capacity of electric power generation with piezoelectric devices under pavement and the feasibility of implementing a large-scale demonstration project on highways and streets. The system includes piezoelectric harvesters, stacked into towers, with load transfer layer and materials to support and protect the system, and interface electric circuitry.

Piezoelectric energy harvesters (PEH) have attracted much attention in recent years because they can harvest energy from the ubiquitous vibrations in the ambient environment with small displacements (even down to the nanometer range) without being affected by the weather (Toprak, A. and Tigli, O., 2014). Shenck and Paradiso (2001) demonstrated that a pair of shoes with an embedded PEH can harvest 8.4 milliwatts (mW) of electrical power from walking (Shenck, N.S. and Paradiso, J.A., 2001). Roundy and Wight (2004) showed that a one cubic centimeter cantilever beam-type PEH can harvest 375 microwatts of electrical power at 120 Hertz (Hz) and with 2.5 meters per second acceleration (Roundy, S. and Wright, P.K., 2004). A research group at Pennsylvania State University performed pioneering breakthrough studies by introducing the cymbal, which is a 31-mode flextensional PEH, and harvesting 52 MW with mechanical-to-electric energy conversion efficiency as high as 7.8 percent at 100 Hz under 70 newtons (N) dynamic force (Kim, H.W. et. al, 2004; Uchino, K. and Ishii, T., 2010). Two common modes for PEH operation are 31-mode and 33-mode: operation based on 31-mode occurs where an applied mechanical load is in perpendicular to the polarization direction while 33-mode occurs when the applied mechanical load is in parallel. The 31-mode energy harvesters can typically yield larger strain with smaller forces. This experiment advanced the overall power output for a single PEH from the level of milliwatts to the level of tens of milliwatts, which is the highest value published in literature on the subject. However, those PEH have limited applications because electronic devices and sensors need more than 100 MW to be fully powered (Priya, S. 2007).

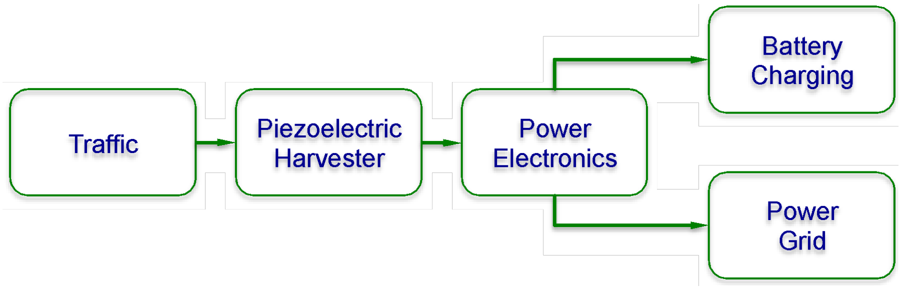
The goal of this project was to develop the technology of ultra-high-density PEHS from highway traffic including advanced designs, power electronics, and methods for integrating the piezoelectric energy harvesters into road construction.

This project advanced the state of the art of piezoelectric energy harvesters. In particular, the project team invented an innovative compression force amplification mechanism that maximizes the electric energy output when a vehicle passes over the device to achieve a high density of electricity harvesting per unit length of the road. Laboratory and road tests confirmed high electric energy outputs of the piezoelectric energy harvesting devices. The estimated electric energy density harvested per unit length of the road is the highest so far in the research.

Concept of the Technology

Figure 1 and Figure 2 illustrate 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.

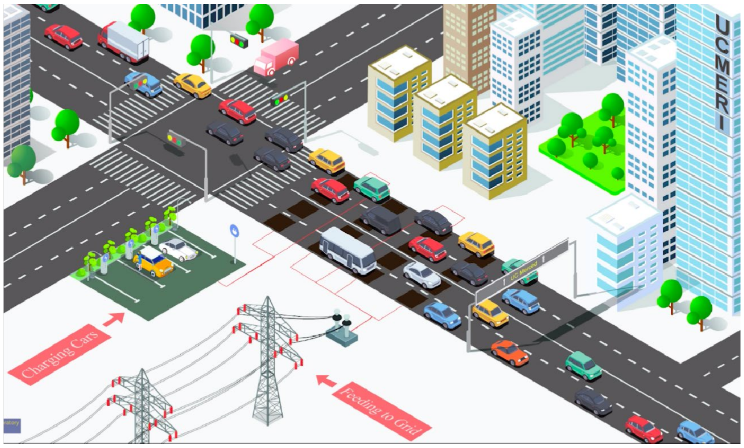
Figure 1: The Concept of Traffic Piezoelectric Energy Harvesting Technology



Conceptual description of the PEHS from traffic.

University of California, Merced

Figure 2: An Artistic Rendering of Traffic Piezoelectric Energy Harvesting



Integration of the traffic PEHS with city utilities.

University of California, Merced

The proprietary piezoelectric energy harvesters generate the mechanical energy in the roadway due to the heavy passing vehicles and convert the mechanical energy into electricity. A power electronic circuit collects the electricity and rectifies it to either charge batteries or electric cars near the road, or to feed a power grid along the highway.

As long as there is traffic, the energy harvesting system generates electricity under all weather conditions, which is a major advantage compared to solar panels that have intermittent generation and are dependent on the sun. As a result, the piezoelectric energy harvesting technology can provide an alternative, reliable source of electric power. However, there are challenges to implementing the PEHS on a large scale, such as on public highways, including innovative design to integrate piezoelectric devices into roadways while providing a smooth road surface for traffic.

This project developed a PEH that enhances the energy output density of the system per unit length of road. The high energy output density is an important feature of the PEHS that will make the harvested electricity commercially viable.

Specifically, the project was designed to achieve the following objectives:

1. Develop mechanical designs of the PEHS that can survive weather conditions under continuous dynamic loading of traffic.
2. Demonstrate the effectiveness of the piezoelectric energy harvesting system to achieve high density of electricity harvesting per unit length of the road.
3. Developing a power electronic system to enable battery charging or grid integration by the PEHS.

4. Develop pavement designs that are compatible with the PEHS, optimize load transfer to the piezoelectric devices, and shield the system from the environment.
5. Develop plans for further application and commercialization of the technology to harvest piezoelectric energy from highway traffic and other modes of transportation.

CHAPTER 2:
Project Approach

The first step to developing an ultra-high-density PEHS was to design and fabricate dual-mode, multi-layer PEH. In addition, the project team needed to consider how to package piezoelectric stacks in a mechanical housing that would protect the stacks from side loading, which could damage the stacks, and weather conditions. The second step investigated how to integrate the piezoelectric energy harvesters into a system together with power electronics to enable the electricity to be used, such as through battery charging.

Mechanical Design and Analysis

The project team developed a mathematical model for the piezoelectric devices, analyzing their ability to generate electricity and optimizing the design.

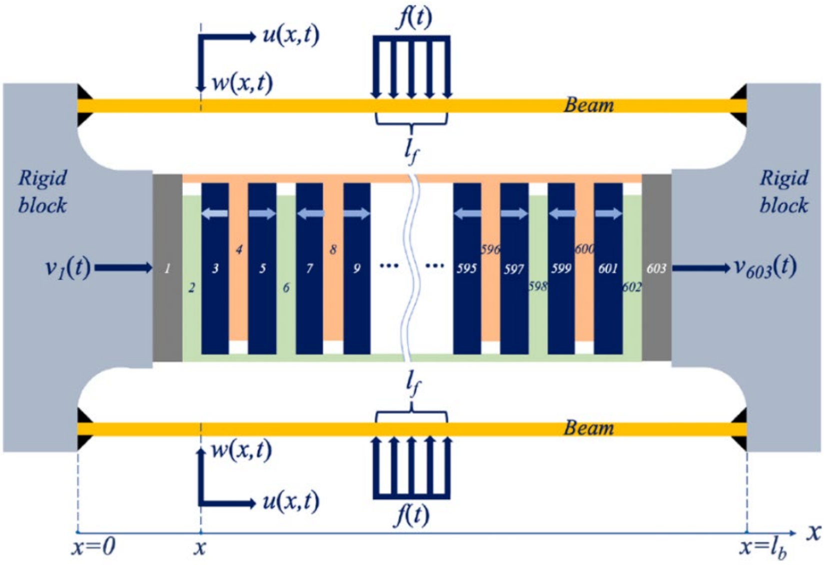
Piezoelectric Energy Harvester Design

The PEH were optimized for beam thickness, length, width, and material through developing theoretical models and analyzing the compression force amplification mechanism. In addition, the team developed a multi-objective optimal selection procedure of various parameters for the PEH to maximize the harvested electric energy and reliability.

Through extensive numerical simulations, within the practical ranges of all these parameters, the project team found that the first order resonant frequency of the integrated mechanical-piezoelectric system was in the order of hundreds of Hz, which was much greater than the frequency of the traffic-induced pulse forces, which was in the order of Hz. This allowed the project team to conduct the design based on the static analysis and force amplification mechanism.

Figure 3 shows the design of the PEH, which consists of a frame holding the 33-mode lead zirconate titanate (PZT) stacks in the middle. The 33-mode was chosen due to higher mechanical to electric energy conversion efficiency compared to other modes. The ends of the frame, the rigid metal blocks, completely prevent the PEH from moving during both extension and deflection of the stacks.

Figure 3: Schematic of a Piezoelectric Energy Harvester



The design detail of the PEH is shown here. The PZT stack is sandwiched between two metal blocks, which are connected by two elastic beams on the top and bottom.

University of California, Merced

The extension and deflection of the elastic beams are coupled so that the dynamics of the beams are nonlinear. A mathematical model of the beams was needed to develop optimal designs of the piezoelectric energy harvesting device. The mathematical model and analysis of the nonlinear elastic beams were completed as part of the project.

The PZT stack consists of many thin layers of the PZT material as well as thin layers of copper. The project team used finite element modeling of the stacked thin structure and decoupled and coupled analyses of the beam and the PZT stack to better understand the forces within the stack. The internal force balance and displacement continuity of the frame and the PZT stacks were imposed to couple the beams and the PZT stacks.

Dynamic Analysis of Piezoelectric Energy Harvester

The project team assumed that the wheel of a passing vehicle provides a triangular shape impulsive compressional force on the PEH. The duration of the impulse was equal to the time the vehicle takes to pass over the PEH, and the peak value of the impulse was determined by the weight of the vehicle as well as the dynamic reaction of the vehicle suspension.

The amplitude of the impulsive force on the PEH was taken to be 1333 N, the same as the force considered in the static analysis for the purpose of comparison. The project team designed the road surface so the tire of the wheel exerted the force of 115 millimeters on the PEH over a short span, assuming that the vehicle speed was 65 miles per hour (104.61 kilometers per hour). Hence, it took about 8 milliseconds (ms) for the vehicle to pass the PEH. The duration of one impulse was, thus, 8 ms.

In the dynamic analysis, the finite element model of PZT stacks was used. For the nonlinear beams, the dynamics of the axial displacement were ignored because the frequency of the axial vibration was much higher than that of the deflections. The project team applied the Rayleigh-Ritz method and expressed the deflection of the beam in terms of the first five modes of a clamped-clamped beam.

The static design used a force amplification factor of 10. The dynamic loading appeared to be beneficial as far as the force amplification was concerned, while the damping did not seem to lower the force amplification factor.

Harvesting Tower Design

To scale up, the project team needed to design and fabricate holding structures to house and protect the PEH. The PEH were integrated into a tower structure called the piezoelectric energy harvesting tower (PEHT), which provided a housing and water-proof environment. This vertical design improves the energy density. The units were stacked in a cylinder and behaved like multiple nonlinear springs mechanically connected in series. If the stress wave generated by a moving vehicle could travel downward through all the PEH during the short interaction time, the number of PEH in each column was reasonable for power generation. However, two important factors were considered to determine the value of the number of PEH in a column, the first being driving comfort and safety. The cost of improving the system's energy density by increasing the number of PEH in a column included not only the higher economic expenditure, but also the increase of total sinking displacement. This displacement had to be limited well within the deflection range of suspension system to ensure driving comfort and safety.

The second concern was mechanical stability. The accumulated manufacturing error could have caused the PEH stack not to be centered vertically. This geometric error could generate unwanted bending moments on PEH under compression. When the number of PEH in a column is too large, the PEH stack could become unstable. Furthermore, the enhanced friction due to the interaction between PEH could result in more mechanical losses. Hence, poor tower design could lead to a multi-objective optimization problem. After some rudimentary search in the parameter space and based on the above considerations, the project team found that three PEH in a column was a well-balanced choice. The middle PEH forms a 90-degree angle to the upper and lower PEH for enhanced mechanical stability.

Furthermore, three PEH stacked in the PEHT were connected in parallel electrically. Rubber cover was used to prevent dust and gravel from falling into the gap between shaft and bearing. To achieve waterproof consistency, silicone sealant was used to seal the inner corner at the bottom and the seam under the rubber cover below the stainless-steel clamp. Mechanical protection to avoid damage from heavy load was achieved by setting a proper distance between upper top surfaces of the shaft and tube wall. This limited the maximum sinking distance.

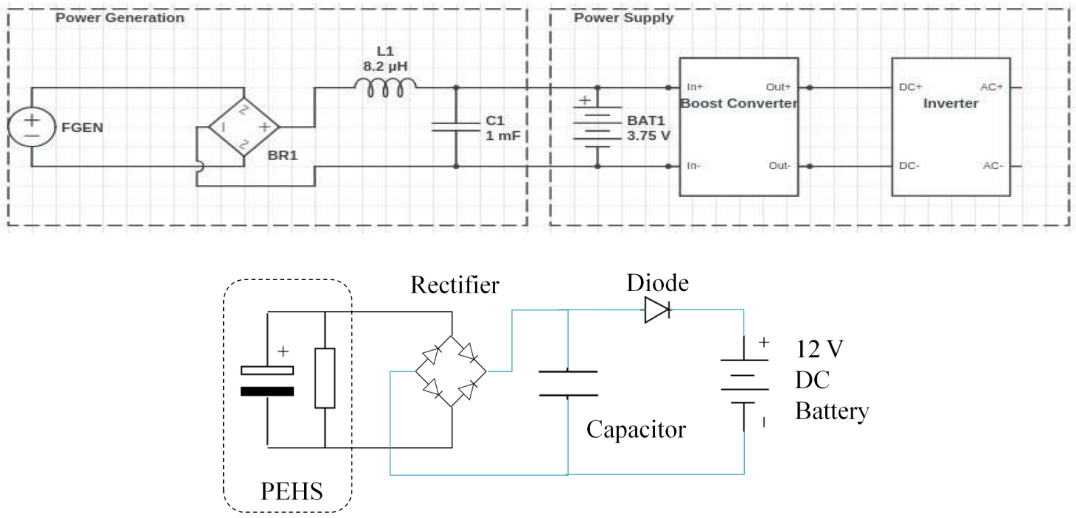
Power Electronic Design and Analysis

The goal of this task was to design and fabricate a power electronic system to manage the electricity from the piezoelectric energy harvesting system. To accomplish this, the project team developed a circuit layout design and performed an analysis.

Circuit Layout

The circuit shown in Figure 4 was developed for the PEHS. Only one piezoelectric energy harvester is shown in Figure 4 for illustration purposes. When many piezoelectric energy harvesting towers were implemented on the road with a mix of series and parallel electric connections, a full bridge rectifier was used for each tower to avoid electric interactions. Since each row of piezoelectric energy harvesting towers was activated by the passing vehicle sequentially, the rectifiers prevented discharging and charging among the towers in different rows.

Figure 4: Circuit Layouts for PEHS



The full bridge rectifier can be integrated with each tower to avoid energy loss when many piezoelectric energy harvesting towers are connected in series or in parallel. The output of the circuit can be used to charge a battery, which can power a converter to invert the DC current to AC current to feed to the power grid.

University of California, Merced

Circuit Analysis

Since the electric output of the PEHS was in the form of sharp electric pulses generated by the passing vehicles, the circuit had to be able to capture the pulses. The captured electric energy was primarily stored in the capacitor, which had to discharge the electric energy quickly to charge the battery before the next pulse arrived.

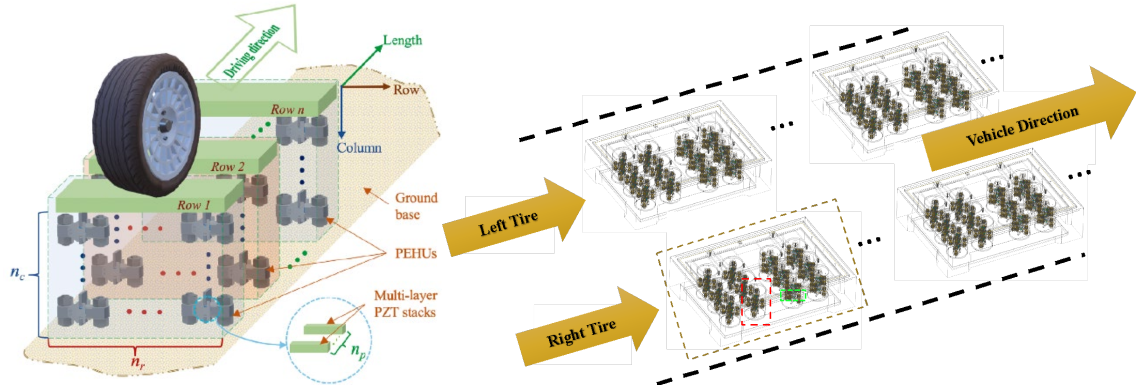
For laboratory testing, a diode was added before the battery to prevent backward charging of the capacitor when the battery had more electric energy stored than the capacitor. This circuit was able to be integrated into the PEHS to enable electricity usage.

Energy Harvesting System Design

The goal of this task was to test and validate the PEHS on a test road on the campus of the University of California, Merced. To meet this goal, the project team developed pavement designs compatible with the PEHT, with optimized load transfer and housing to shield the PEHS from the environment.

Figure 5 shows a layout of the PEHT installed on the road. Since the energy source was the mechanical work done by the vehicles passing over the PEHT, the tower was designed to convert as much of the mechanical energy to electricity as possible and have as small an interruption to traffic as possible.

Figure 5: Road Test Layout



Detail of implementation of the PEHT underneath the pavement for the road test. The piezoelectric generator towers were arranged along the road.

University of Calfornia, Merced

Many parameters influence the electric energy harvested at the system level. The effects of the parameters such as the number of PZT stacks in one PEH, the number of columns of PEHTs in one row to share the load of the vehicle, and the number of PEH stacked up in each tower and the total sinking displacement of a row were studied.

First, the study was done by numerical simulations of the PEHTs. Since the mathematical model of the piezoelectric devices was sufficiently accurate, a numerical optimization study was conducted. With consideration of various parameters and their effect on the devices, the system and energy harvesting capacity led to a multi-objective optimal design problem. The multi-objective optimal design should have minimized the sinking displacement and maximized the electric energy of a PEH subject to various material strength and geometric and economic constraints.

CHAPTER 3:
Project Results

Chapter 3 presents the results of extensive laboratory evaluations of the PEH and PEHS, including the effect of the circuit components on the energy harvesting and results from the road test on the campus of the University of California, Merced. The chapter also presents an energy harvesting estimation by the technology developed by the project team.

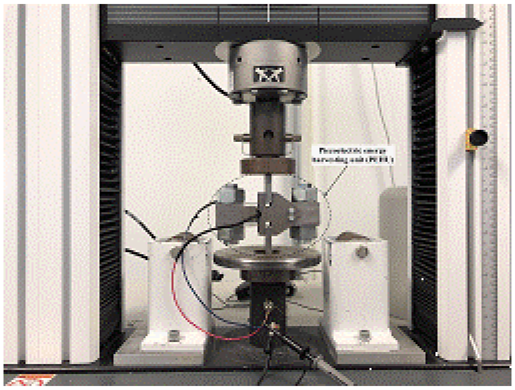
Laboratory Evaluation and Road Test

Laboratory Evaluation of Harvester

In the laboratory evaluation, the project team fixed the design of the PEH to have a compression force amplification factor approximately equal to 10. That is, when a vertical compression force of 1333 N is applied to the unit, the compression force on the PZT stacks is 13.3 kilonewtons (kN) and the horizontal stretching force at the ends of both beams was more than 6.6 kN. The project team made prototypes of different designs for testing. The external dimension of a PEH was 142x42x84 cubic millimeters (mm^3).

Although the ultimate goal of harvesting piezoelectricity is to store the harvested energy in a battery or to feed the energy to the power grid, in the laboratory test, the project team only measured the open circuit voltage of the PEH to evaluate its performance. The quasi-static compression Instron Machine test setup is shown in Figure 6.

Figure 6: Experimental Setup on Instron Machine



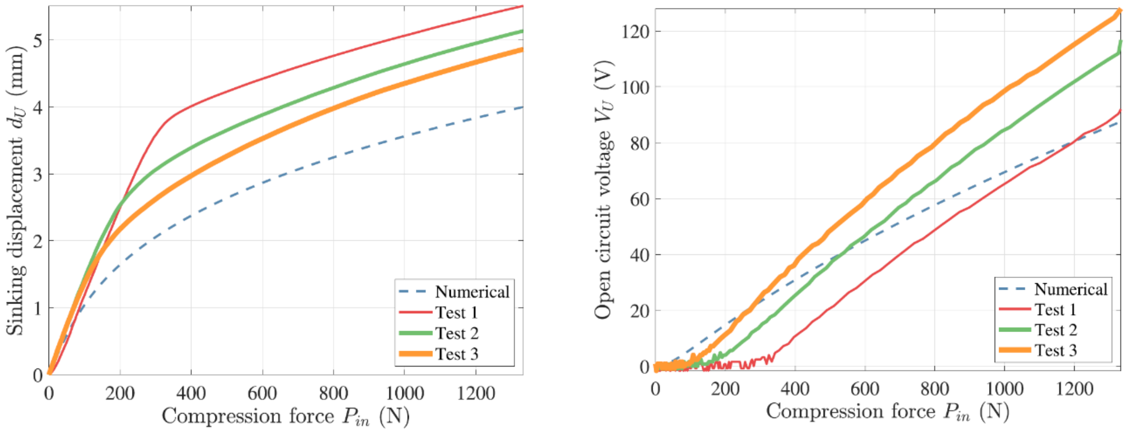
Experimental setup of the quasi-static compression test on Instron machine.

University of California, Merced

The Instron machine applied compressive forces from 0 to 1333 N at the displacement rate of 25 mm/min. The voltage output of the PEH was measured with an oscilloscope. Three different thicknesses of shims were used inside the PEH to adjust the preload on the PZT.

The comparisons between numerical and laboratory test results of sinking displacements, applied load, and generated voltage are presented in Figure 7 (left and right). The numerical results were obtained by sweeping different input forces based on the simplified static model of the PEH. The experimental results are repeatable.

Figure 7: Displacement and Voltage of PEH Compressive Tests



Left: Input compressive force vs. sinking displacement of the piezoelectric energy harvesting device. Right: Input compressive force vs. open-circuit voltage.

University of California, Merced

The laboratory tests qualitatively validated the static prediction based on the theoretical model of the PEH. Many cyclic compressional tests have also validated the static strength analysis of the PEH.

The dynamic fatigue tests are needed to study the fatigue life of the PEH to predict the service time. This will be an effort in the future.

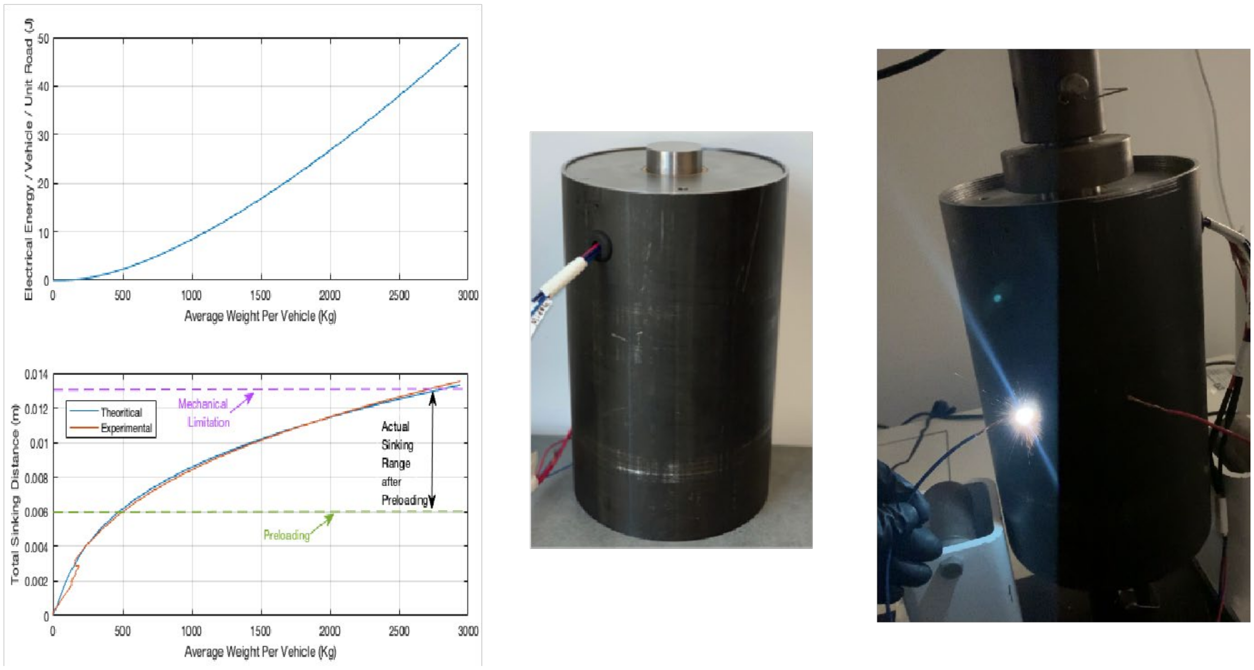
Once the mathematical model of the PEH had been validated qualitatively, the dynamic analysis of the PEH under the traffic load could be carried out by making use of the model.

Laboratory Evaluation of the Harvester Tower

A quasi-static test setup and results of the PEHT are shown in Figure 8. The outer dimensions of the tower were 6 inches in diameter (15.24 centimeters) and 10 inches (25.4 centimeters) in height. As the load level reached the designed load, about half the weight of the Toyota Camry used for the experiment (about 3,500 pounds), the circuit was shorted so that the harvester produced a loud and bright electric spark. The open-circuit voltage of the PEHT was later measured at about 300 volts (V).

Another approach to improve the performance was to apply a vertical preload to the PEHT. This reduced the total sinking displacement while simultaneously providing the preload on the PZT stacks.

Figure 8: Quasi-Static Laboratory Test of the PEHT



The left figure shows the mechanical performance of the PEHT under quasi-static repetitive compressive loadings. The middle figure shows the PEHT. The right one shows bright electric sparks when a load about half the weight of a Toyota Camry was applied.

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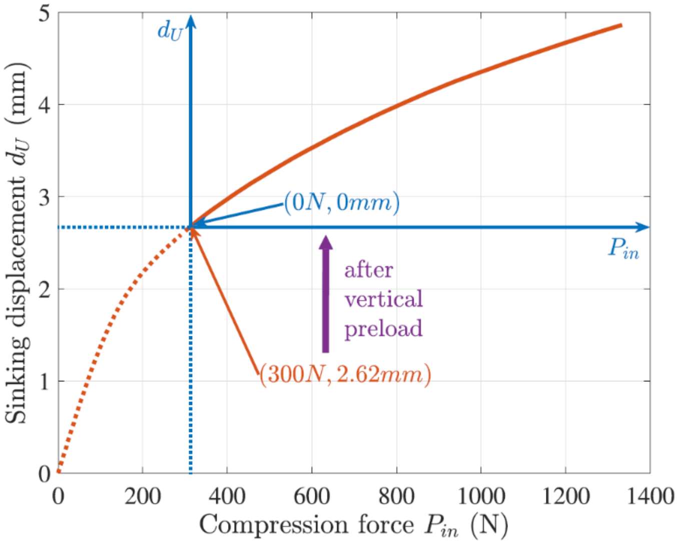
Figure 9 shows a summary of the experimental results, which suggest that application of a vertical preload of 300 N would remove the soft region. The initial state of the PEH was under compression so that the PEHT had an initial sinking displacement 2.62 mm. Hence, the total sinking displacement of the PEHT was reduced from 4.86 mm to 2.54 mm when the compressive load of 1333 N was applied.

Furthermore, the vertical preload also improved the energy conversion efficiency. Since the total sinking displacement was almost halved, the work done by gravity was also halved. Since the generated electric energy was nearly equivalent without the vertical preload when the load reached 1333 N, the mechanical-to-electric energy conversion efficiency was approximately 10 percent in the dynamic case at a speed of 65 miles per hour (104.61 km/hr).

The preload increased the stiffness and therefore the natural frequencies of the PEH. Hence, the static design became even more reliable, and the dynamic response at low frequencies caught even fewer effects of high frequency resonances.

Figure 9: Effect of Pre-Loading



The experimental result of the sink displacement of the tower as a function of the pre-load. This curve provided a guideline for assembly of the PEHT to apply for proper pre-load.

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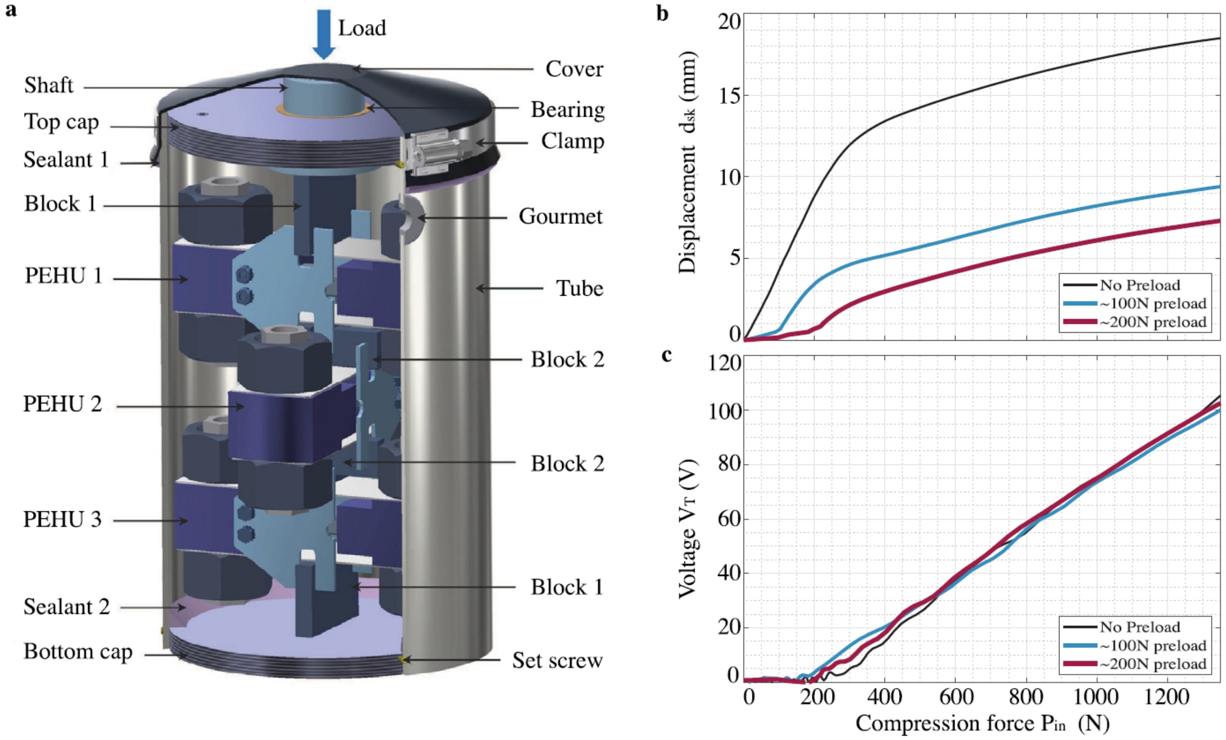
The performance of a PEHT prototype in a quasi-static compression test is illustrated in Figure 10. As the load was increased to 1333 N, a maximum open circuit voltage of 106 V was generated with a sinking displacement of 18.5 mm. Stiffness hardening was observed as predicted by theoretical analysis. It is worth noting that a large portion of the sinking displacement occurred in the soft region of nonlinear stiffness. However, this initial deformation did not contribute to power generation. This observation indicates that total sinking displacement could be significantly reduced by applying vertical preload through rotating the top cap downward. With a preload of about 100 N, the total sinking displacement was sharply decreased to 9.4 mm while the open-circuit voltage was maintained at higher than 100 V. By increasing the preload to about 200 N, total sinking displacement was further reduced to 7.3 mm with negligible electric energy loss.

Figure 10: Performance of PEHT in Quasi-Static Tests



Piezoelectric energy harvesting tower and its quasi-static performance. A. 3D model of the piezoelectric energy harvesting tower. B. Under quasi-static compression of 1333 N, a prototype of PEHT demonstrated nonlinear stiffness. Vertical preload of about 100 N and 200 N were applied to reduce total sinking displacement. C. In the same tests, the generated open circuit voltage, V_T, did not change significantly with or without preload.

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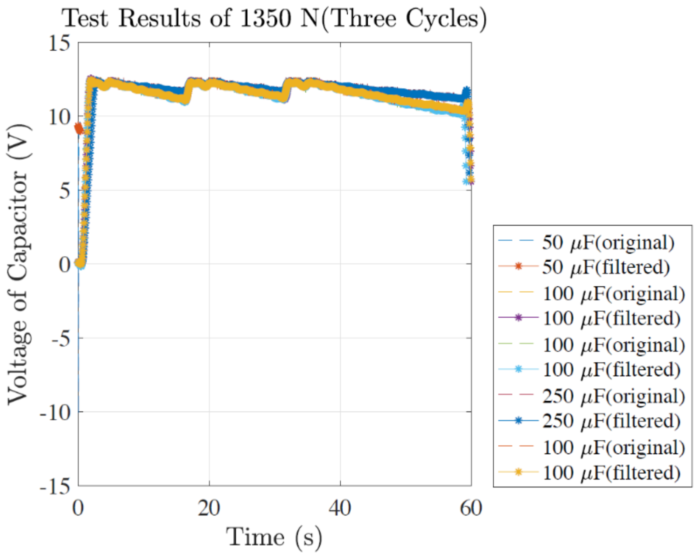
Forty-eight PEHTs were tested in the laboratory before installation in pavement for road tests. The results were documented in a recent publication by the project team (Chen, C. et. al, 2021). The mechanical behavior of 48 piezoelectric energy harvesting towers under 1333 N in the first 50 quasi-static tests exhibited the nonlinear stiffness of PEHT as predicted. During the first 50 quasi-static tests, the internal gaps inside PEHT were eliminated. Then the mechanical behavior of PEHT became steady, which could also be confirmed from the decreased variance of the results. Under compression of 1333 N, the mean total sinking displacement was 17.96 mm, with 25th and 75th percentiles of 17.78 mm and 18.20 mm, respectively. Overall, the mechanical behavior of 48 PEHTs was stable and repeatable.

Laboratory Evaluation of the Circuit

Effect of Capacitor

The laboratory evaluations and optimization of the circuit for collecting the electric energy were carried out. Several of the full bridge rectifiers and the size and quality of capacitors were evaluated. Figure 11 displays the charging and holding patterns of various capacitors when one PEH was tested on an Instron machine.

Figure 11: Influence of the Circuit Capacitor on Energy Harvesting



The voltage across the capacitor in the circuit when one PEH was tested on an Instron machine.

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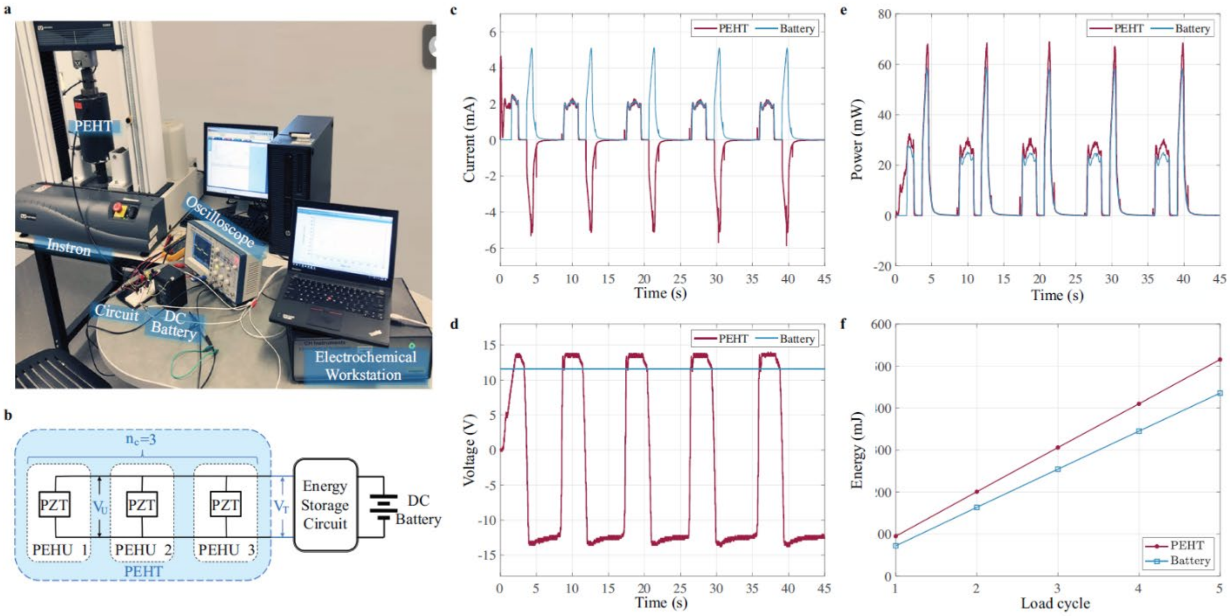
Battery Charging

Laboratory experiments were conducted to investigate PEHT's performance in charging a DC battery with a nominal voltage of 12. Experimental setup and schematic circuit diagram of battery charging are described in Figure 12a and Figure 12b, respectively. Voltage and current of PEHT and DC battery during five quasi-static loading cycles with amplitude of 1333 N are shown in Figure 12c and Figure 12d, respectively. The output from PEHT was rectified by a full bridge rectifier in the circuit to charge the DC battery during both compression and releasing. The voltage of the PEHT oscillated between ±13.80 V, while the DC battery held a constant voltage of 11.56 V during tests. The difference between these two voltages was due to the voltage drop across the diode in the circuit. The maximum current of the PEHT and battery during releasing were higher than those during compression due to the faster unloading speed in contrast to loading.

Figure 12: Battery Charging by a PEHT



Charging a 12 V DC battery by a PEHT in five quasi-static load cycles with amplitude of 1333 N.
a, Experimental setup. b, Schematic circuit diagram. c, Current. d, Voltage. e, Power. f, Energy.

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The output power of the PEHT and input power of the battery were estimated by multiplying voltage and current. The maximum output power of the PEHT was 31.02 mW and 68.93 mW in compression and releasing, respectively. In the meantime, the maximum power charging the battery was 25.10 mW and 58.27 mW. This difference showed that loading speed had significant influence on maximum power. As loading from roadway traffic is much faster than that of quasi-static tests, the maximum power generated from a mid-size vehicle would be much higher.

The accumulated output energy generated by the PEHT and energy stored in the battery were obtained through integration of power. The linear relationship shows that the performance of the PEHT was stable and repeatable. In each cycle, the output energy from the PEHT was 105.13 millijoules (mJ) and the stored energy in the battery was 90.87 mJ on average. According to the open circuit voltage of 116 V and capacitance of 22 Farad of the PEHT in tests, the open-circuit electric energy was 296.03 mJ. This indicated that the storage rate of harvested energy based on the circuit is 30.7 percent.

The laboratory evaluations indicated that the circuit design was adequate for application to the piezoelectric energy harvesting from traffic.

When the PEHS consists of many units and towers that are electrically connected in a mixed series and parallel arrangement, it is best to install a full bridge rectifier for each PEHT.

Road Test Results

When a vehicle travels at high speed it generates a dynamic reaction force on the road surface through the suspension. The dynamic reaction force can have much larger amplitude than the vehicle weight. To obtain the dynamic reaction force, one must have a full dynamic model of the vehicle. The road tests were conducted to evaluate the mechanical designs and investigate the effect of vehicle speed on the energy output of the piezoelectric harvesters.

Figure 13a illustrates the open circuit voltage of the piezoelectric harvesters under both wheels of the vehicle at a speed of approximately 24.85 mi/hr (40 km/hr). The corresponding open circuit electric energy was about 20.29 Joules. The maximum voltage observed was as high as 484 V. The effective value of tested PEHS was 1.32 m determined by 8 times the outer diameter of the PEHT. As a result, an energy density of 15.37 Joules per unit length of the instrumented road per lane and per passage of vehicle (J/(m.pass.lane)) was obtained.

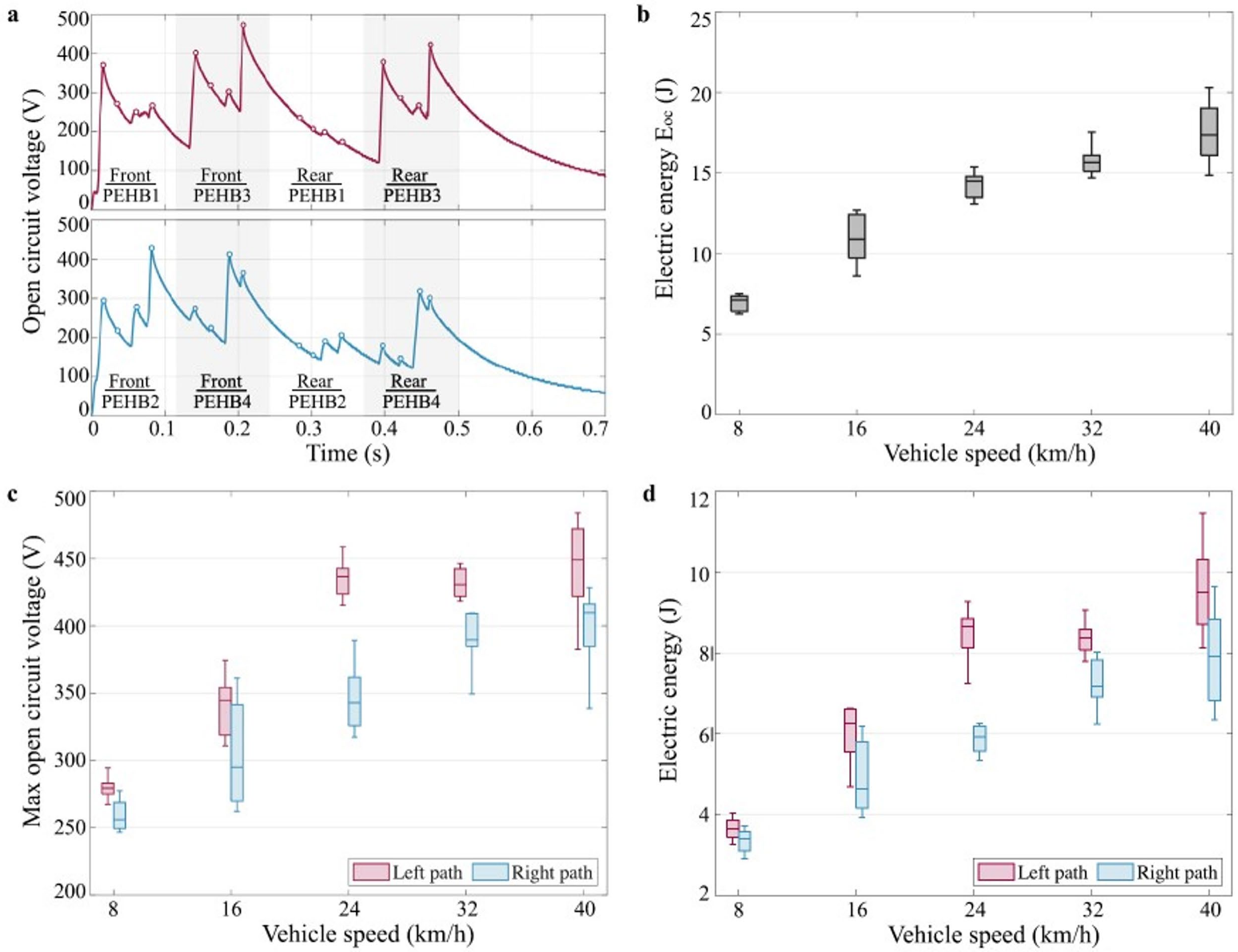
There was a difference in energy production among the rows of PEHTs. One cause for this difference was the roughness of the road. The differences between PEHTs in terms of height and mechanical stiffness could also have contributed to the difference in energy production.

To investigate the effect of vehicle speed on energy production, road tests were conducted at speeds from 4.97 mi/hr (8 km/hr) to 24.84 mi/hr (40 km/hr) at intervals of 8 km/hr. Figure 13b shows the harvested electric energy per passage at different speeds. Ten measurements were taken for each speed group. Harvested energy in left and right paths are shown in Figure 13d. The median harvested energy increased from 7.11 J at 8 km/hr to 17.36 J at 40 km/hr, which demonstrated a positive effect of vehicle speed on energy harvesting in the tested range. Higher vehicle speeds are to be tested in the future.

In the same road tests, maximum voltage in the left and right paths at different speeds were recorded, as shown in Figure 13c. Voltage in the left path was greater than the right side in general because the left side of the vehicle is heavier than the right side. A key factor resulting in the observable variation in open circuit voltage and harvested energy was the wheel track. When a vehicle passed the boxes of PEHTs along the center line of the rows, the energy production was the highest.

Additionally, the vehicle speed from the time differences of the electric pulses generated by passing vehicles could also be estimated. Since the voltage level generated by passing vehicles was correlated to the weight of the vehicle, the PEHS could be part of the smart highway with the capabilities to monitor traffic flow, vehicle weight, and speed.

Figure 13: Road Test Results



Road test results of the PEHS a. Open circuit voltage of PEHS during passage of a Nissan Altima at a speed of 40 km/hr. Each PEHB was activated twice, by the front and rear wheels. b. Harvested electric energy in tests at different speeds statistically indicated a positive effect of vehicle speed on energy harvesting. c. The maximum open circuit voltage in left and right paths at different speeds. d. Harvested electric energy in left and right paths at different speeds.

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Energy Density Estimate

Since the electric energy was harvested in a discrete manner, the instant power output varied with the weight and speed of the vehicles. To better describe the capability of energy harvesting, the energy density per unit length of the instrumented road was computed based on the PEHS harvested electric energy that could be stored in a battery with one passage of a midsize vehicle with weight 16,000 N over a one-mile-long lane where the energy harvesting technology was implemented. To compute the harvested energy by PEHTs from the open circuit voltage measurements, it was assumed that the capacitance of the PEHTs could be directly measured or was equivalently calculated from the model.

The efficiency of the battery storage was assumed to be 30.7 percent. The energy density per unit length of the instrumented road per lane and per passage of vehicle was calculated by using the road test results and found to be 15.37 J/(m.pass.lane).

The traffic was assumed to follow the three-second safety rule all day long. The energy that could be harvested and stored in batteries from one lane of a one-mile-long (1609.34 meters) roadway was estimated.

The road test results are summarized in Table 1.

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)

Electric energy estimates at various levels based on the laboratory and road test results 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.

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Note that the effective width of six towers in a row was 0.882 meters, less than one meter. Hence, the electric energy density per unit area generated by the PEHS was higher than the density per unit length.

CHAPTER 4: Technology/Knowledge/Market Transfer Activities

Proprietary Technology

In August 2019, the University of California, Merced filed a patent application to protect this proprietary technology (docket number 3891.012PRV).

The patent, titled High-Power-Density Piezoelectric Energy Harvesting System," covers the mechanical design of the piezoelectric power generating unit and tower with the amplification mechanism and electronic circuit for rectifying the high-power electric pulses generated by vehicles. The listed inventors are Cheng Chen, Amir Sharafi, Jian-Qiao Sun, Tian-Bing Xu, and Atousa Yazdani.

Technology Transfer

The project team has been actively disseminating the knowledge and technology created by this project by publishing research articles in professional journals and presenting the project at professional conferences. Two publications came from this project:

- Chen, C., Sharafi, A. and Sun, J.Q., 2020. *A high density piezoelectric energy harvesting device from highway traffic–Design analysis and laboratory validation.* Applied Energy, 269, p.115073.
- Chen, C., Xu, T.B., Yazdani, A. and Sun, J.Q., 2021. *A high density piezoelectric energy harvesting device from highway traffic—System design and road test*. Applied Energy, 299, p.117331.

The project team has also disseminated the results of the project at an American Society of Mechanical Engineers technical conference. The conference publication is:

- C. Chen, A. Sharafi, J. Flores, R.L.D. Pena, P. Mendoza, H. Ayala, S. Ortiz-Donato and J.-Q. Sun (2020) *Proceedings of ASME International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*. St. Louis, Missouri - On-line. IDETC2020-22205. "Design and Laboratory Validation of a Force-Amplified Piezoelectric Energy Harvesting Unit."

The Office of Research and Economic Development at the University of California, Merced has been working to connect the project team to private investors and entrepreneurs. The project team found a private investor who committed matching support of $800,000 to the further development of the PEHS. This is an important step of the technology transfer effort.

CHAPTER 5: Conclusions/Recommendations

Potential of Electricity Harvested from Traffic

This research has proven that technology for harvesting piezoelectric energy with high power density is feasible and promising and that it offers significant benefits to California ratepayers. The barrier to large-scale implementation relates to aspects of civil engineering construction of the instrumented roads.

Modular design of the piezoelectric harvesting device should be integrated with automated road construction machineries. Quite possibly, new machines will be invented to enable large-scale road construction with embedded piezoelectric devices.

Based on the estimate from the limited road test, the annual production of electricity by traffic passing over one mile of a single-lane road instrumented with the piezoelectric energy harvesting technology is 72,811 kilowatt-hours, which translates to 4,7655 watts per square foot per year. With 386,604 lane miles in California, multiplication of these two large numbers suggests a huge potential for the electricity that can be harvested for ratepayers in the state.

Ideal Traffic Modes for Harvesting

The developed piezoelectric harvesting devices can be implemented in a variety of traffic conditions. Highway traffic with passenger vehicles, trucks, and heavy-duty semis traveling at high speed was the original target. This mode of traffic has the highest potential for energy harvesting.

The traffic at seaports consists mostly of slow-moving heavy trucks and semis. This traffic is ideal and offers significant potential for energy harvesting. Entrances and exits of busy parking lots in cities provide another opportunity.

A third mode of traffic consists of weight-lifting forklifts in large warehouses. As e-commerce continues to grow in the foreseeable future, this indoor traffic is an ideal source for energy harvesting.

Recommendations

The main achievements of this project lie in the development of a high-density piezoelectric energy harvesting device and the system design. For this technology to be economically and technically feasible for implementation on a larger scale without interfering with the traffic, the following technical issues must be addressed.

1. Develop modular designs of the piezoelectric energy harvester that are compact and connectable. Such a modular design would allow automated installation without much manual operation. The project team did the mechanical design for

heavy semis resulting in a lower profile, one-layer structure involving a larger number of piezoelectric devices.

2. To assess the system lifetime, conduct extensive fatigue tests on the devices and the devices and the system. The limited cyclic tests of piezoelectric energy harvesting units in laboratory showed high repeatability of the device performance, which infers to a potential long lifetime of the mechanical design.
3. Invent a machine to lay down the modular piezoelectric energy harvesting devices.
4. Identify new vendors to acquire large quantities of piezoelectric devices and other mechanical components at affordable and competitive prices.
5. Develop new pavement materials to provide a cushion between the tires and the piezoelectric energy harvesting devices.
6. Write new building code for highways with imbedded piezoelectric energy harvesting devices.

CHAPTER 6: Benefits to Ratepayers

Development of technology to harvest high-power piezoelectric energy has the potential to offer tremendous environmental and economic benefits to California ratepayers, especially when adopted on all roadways. Although the financial outlay to outfit roadways with the technology is significant and the return-on-investment long term, harvesting this readily-available energy source advances California's environmental goal to provide 100 percent of electricity with renewables and zero-carbon energy sources.

- Harvesting piezoelectric energy from highway traffic provides an appealing alternative to intermittent wind and solar as it is available 24/7 in any weather condition.
- Consistent energy availability can increase distributed renewable energy capacity and reduce demand-side load.
- Carbon dioxide reduction associated with annual electricity energy production over one mile of single-lane road is 300 metric tons. Outfitting all 386,604 lane miles of California highways with piezoelectric energy harvesting devices would yield an annual carbon dioxide reduction of 115 million metric tons.
- Ratepayers could enjoy lower energy bills resulting from the greater availability of on-demand electricity.

LIST OF ACRONYMS

Term	Definition
Hz	Hertz
kN	Kilo Newton
kWh	kilowatt-hour
mm	Millimeter
ms	Milliseconds
mW	Milliwatts
N	Newton
Pa	Pascals
PEH	Piezoelectric energy harvesting or piezoelectric energy harvester
PEHS	Piezoelectric energy harvesting system
PEHT	Piezoelectric energy harvesting tower
PZT	Lead zirconate titanate
V	Volts

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