CALIFORNIA
ENERGY COMMISSION

Energy Research and Development Division

**FINAL PROJECT REPORT**

# Force Multiplier Actuated Piezoelectric Energy Harvester for Roadway Energy Recovery

**March 2023 | CEC-500-2023-008**

**PREPARED BY**:

**Primary Author**:
Kevin S. Lu, Ph.D.
Pyro-E
9248 1/2 Hall Rd
Downey, CA 90241
https://www.pyro-e.com/

**Contract Number**: EPC-16-052

**PREPARED FOR**:
California Energy Commission

# 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.
-

*Force Multiplier Actuated Piezoelectric Energy Harvester for Roadway Energy Recover* is the final report for the Force Multiplier Actuated Piezoelectric Energy Harvester for Roadway Energy Recovery project (Contract Number EPC-16-052) conducted by Pyro-E. 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 CEC's research website (www.energy.ca.gov/research/) or contact the CEC at ERDD@energy.ca.gov.

# ABSTRACT

Vehicle traffic can generate large amounts of energy on highways and streets that can be harvested using technology known as piezoelectric devices. Piezoelectric devices take advantage of the inherent ability of specific materials (known as piezoelectric materials) that can take applied mechanical stress – for example, the weight of passing vehicles – and convert it into electricity. Currently, however, there are no such materials that match the vibration caused by automobile traffic and thus are able to convert this energy to electricity in an efficient and cost-effective manner. This project aimed to address this gap in technology and develop piezoelectric devices – that is, regenerative pavement devices – that can efficiently harvest energy from vehicle traffic on roadways using piezoelectric materials at a price that would lower overall energy costs to California ratepayers. To enhance performance under realistic roadway conditions, the approach used state of the art equipment to augment the force applied from passing vehicles and maximize the efficiency and output of the regenerative pavement devices.

The system was tested using a subscale demonstration built on a flexible framework able to scale from hundreds of kilowatts to megawatts in output capacity. The project achieved power outputs greater than 300 watts per square foot and proved the technology worked with lightweight passenger cars as well as heavy-duty trucks. The regenerative pavement devices were demonstrated in a roadway environment and the results can help in assessing the economic merits of using these devices at a scale that can provide energy and other services to Californians.

Keywords: *Piezoelectric devices, vibrational energy harvesting, Solid-state energy, High bandwidth transduction*

Please use the following citation for this report:

Lu, Kevin, Amanda Lin, Wilson Huang, Russell Chung. 2023. F*orce Multiplier Actuated Piezoelectric Energy Harvester for Roadway Energy Recovery.* California Energy Commission. Publication Number: CEC-500-2023-008.

# TABLE OF CONTENTS


Page

PREFACE ..... i

ABSTRACT ..... ii

TABLE OF CONTENTS ..... iii

LIST OF FIGURES ..... iv

LIST OF TABLES ..... v

EXECUTIVE SUMMARY ..... 1

Introduction ..... 1

Project Purpose ..... 1

Project Approach ..... 3

Project Results ..... 3

Technology/Knowledge Transfer/Market Adoption ..... 4

Benefits to California ..... 5

CHAPTER 1: Introduction ..... 7

Background ..... 7

Why Piezoelectricity? ..... 7

Limits to Current Practice ..... 9

Innovation and Advantages ..... 10

Development Risks and Challenges ..... 11

Project Purpose and Objectives ..... 12

CHAPTER 2: Project Approach ..... 13

Rolling Impact Testing ..... 13

Highly Accelerated Life Testing (HALT) ..... 14

Power Management Circuit (PMC) ..... 15

Initial Field Demonstration ..... 16

Demonstrator Specifications ..... 20

Demonstrator Installation ..... 21

CHAPTER 3: Project Results ..... 23

Demonstrator Pilot and Verification ..... 23

Performance Validation ..... 24

Performance and Cost Summary ........................................................................ 29
Power Projection ........................................................................................ 29
Cost Projection ........................................................................................... 30
CHAPTER 4: Technology/Knowledge/Market Transfer Activities ................................ 32
Go-to-Market Activities ................................................................................... 32
Client – Toll Road Concessions Company ......................................................... 33
Pilot Project Overview ..................................................................................... 33
Client Benefits .............................................................................................. 35
CHAPTER 5: Conclusions/Recommendations .......................................................... 40
Future Developments ...................................................................................... 41
CHAPTER 6: Benefits to Ratepayers ...................................................................... 44
Projected Benefits ........................................................................................... 44
Projected Cost ................................................................................................ 46
Economics and Buildability .............................................................................. 47
Other Benefits ................................................................................................ 47
Adaptability .................................................................................................. 49
Pedestrian Safety ........................................................................................... 50
Advance Traffic Warning ................................................................................. 51
Infrastructure-to-Vehicle (I2V) Communication .................................................. 51
Virtual Parking Assistance ............................................................................... 53
GLOSSARY AND LIST OF ACRONYMS ..................................................................... 54
REFERENCES ..................................................................................................... 56

# LIST OF FIGURES

Page

Figure 1: Piezoelectric Transduction ..................................................................... 9
Figure 2: Regenerative Pavement Devices (RPD) Design Summary ........................... 11
Figure 3: RPD architecture hierarchy .................................................................... 13
Figure 4: Force Impact Testing Data ..................................................................... 14
Figure 5: Power Management Circuit (PMC) .......................................................... 16

Figure 6: RPD Pilot Verification .......... 17
Figure 7: RPD Energy Harvesting Cell .......... 18
Figure 8: RPD Pilot Testing .......... 18
Figure 9: Wheel Impact Data .......... 19
Figure 10: RPD Array Product Specifications .......... 20
Figure 11: RPD Field Demonstration .......... 22
Figure 12: Energy Harvesting RPD module .......... 24
Figure 13: Force Impact Measurement .......... 25
Figure 14: Wheel Impact Feature Identification .......... 26
Figure 15: Impact Type – Short Impact .......... 27
Figure 16: Impact Type Force – Long Impact .......... 28
Figure 17: Demonstrator Battery Charging .......... 29
Figure 18: Projected Economies of Scale .......... 30
Figure 19: Regenerative Pavement Installation .......... 34
Figure 20: Treadle Technology Comparison .......... 35
Figure 21: RPD Levelized Cost of Electricity .......... 38
Figure 22: Cash Flow Analysis for Highway Toll Roads .......... 39
Figure 23: Multi-layered Piezoelectric Capacitors Manufacturing Process .......... 43
Figure 24: Case study of Highway Projects .......... 47
Figure 25: RPD-enabled Smart Crosswalk .......... 49
Figure 26: RPD-enabled Smart Sidewalk .......... 50
Figure 27: On-road Signage for Real-time Alerts .......... 52
Figure 28: Dynamic Driver Alerts using Vehicle-To-Infrastructure communication .......... 53

# LIST OF TABLES

Page

Table 1: Solutions to Technical Barriers .......... 10
Table 2: Solutions to Non-technical Barriers .......... 10

Table 3: Potential Failure Modes of RPD Components .............................................. 14
Table 4: RPD Roadway Testing Result ...................................................................... 19
Table 5: RPD Product Specifications ......................................................................... 21
Table 6: Projected Power From RPD ......................................................................... 29
Table 7: Summary of RPD Fit, Form, and Function for an Interstate Toll Lane............ 36
Table 8: RPD Cash Flow Analysis............................................................................. 38
Table 9: Ratepayer Benefits at Scale ........................................................................ 44

# EXECUTIVE SUMMARY

## Introduction

Americans spend nearly 5.5 billion hours stuck in traffic each year. Hundreds of billions of dollars are spent on the extra fuel and lost productivity from traffic congestion. One remedy to offset the cost is to recover the energy associated with wheel impacts on the pavement. Piezoelectric materials – materials that have the inherent ability to generate an electrical charge from applied mechanical pressure – can harvest the energy from pavement vibrations that would have otherwise been lost as heat. The added generation capacity would not only save on energy costs to California ratepayers, but regenerative pavement technologies can reduce the cost burden of new and retrofit roadway constructions.

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. In a larger context, pavement generation supports California's clean energy goals set in Assembly Bill 32 (Nunez, Chapter 488, Statutes of 2006), which mandates statewide reduction in carbon dioxide emissions to 1990 levels by 2020, the Renewable Portfolio Standards (Senate Bill 100 [De Leon, Chapter 312, Statutes of 2018]), which set a target for all electricity retail sellers to serve at least 50 percent of electricity from renewable sources by 2026 and 60 percent by 2030, and the Governor's Clean Energy Jobs Plan, which calls for 12,000 megawatts of localized energy generation. Overall, pavement energy recovery in California could amount to:

- Approximately 862 megawatts of localized capacity in urban areas (7 percent of the Governor's mandate).
- Approximately 2.36 gigawatts per year of renewable electricity (15 percent of California solar generation, 2015).
- Approximately 0.65 million tons of displaced carbon dioxide from electricity generation (10 percent of Assembly Bill 32 goal).

Despite the potential advantages, current piezoelectric materials are limited by performance, related costs, and durability – for example, being able to withstand the repetitive pounding of heavy vehicles. In addition to the technical feasibility, regenerative pavement devices must overcome the operational constraints of roadway environments for safety and reusability. Weatherization and other environmental variabilities also pose significant challenges to a viable product.

## Project Purpose

The goal of this project was to develop and demonstrate a new piezoelectric technology to capture the billions of tire compressions over pavement and convert it into electricity using piezoelectric materials. The deployment of regenerative pavement devices en mass has the potential to provide cost-effective electricity to California ratepayers. For example, a four-lane, 1-kilometer highway could provide electricity for up to 5,000 California homes near 2 cents per kilowatt-hour during peak traffic. Overall, the peak rate reduction, environmental, and social impact to California ratepayers from the use of regenerative pavement devices could include:

- Low-cost electricity generation during peak traffic.
- Improved grid stability to level out power consumption at peak demand.

This project advances piezoelectric technology by demonstrating the technical, product, and market feasibilities of regenerative pavement devices.

For technical feasibilities, the project conducted design, performance testing, and pilot demonstrations of regenerative pavement devices to verify the commercial viability of harnessing pavement vibration for power generation. The project focused on resolving the key feasibility challenges and engineering constraints of the regenerative pavement devices critical to a commercial-scale development of the technology – power, size, efficiency, and reliability. Overall, the key technical objectives included:

- Efficient electromechanical conversion (coupling factor of approximately 70-80 percent).
- Exponential two-stage force amplification (input gain greater than 225 percent).
- Low-frequency power (resonance of approximately 30 Hertz).
- Low-profile design for easing roadway retrofit (height of approximately 1 inch).
- Fail-safe design and weatherized enclosure for robust operation (25-year life).
- Power density exceeding 300 Watts per square feet, attainable for passenger cars and heavy-duty trucks.

For product feasibility, the project extrapolated the research results to estimate the ratepayer benefits at scale. For product feedback, the target clients included transportation agencies for which regenerative pavement presents an opportunity for recovering the capital cost of road construction. The client outreach included early discussions on product performance, safety, and maintenance requirements. Those interviewed had a positive outlook on the regenerative pavement devices if they are deemed safe and non-intrusive to driving and roadwork, respectively. These product aspects informed the regenerative pavement devices development under control test environments.

For market feasibility the project examined other potential benefits of regenerative pavement devices beyond energy recovery, such as using a network of regenerative pavement devices with data connectivity to improve traffic conditions, vehicle throughput, and motorist safety. This adaptation of the technology could improve the lives of Californians with not only clean energy but also infrastructure revitalization with improved mobility and safer driving conditions.

## Project Approach

Pyro-E, founded in 2012, is based in Los Angeles, California. The project team has experience working with piezoelectric materials, their electrical and mechanical characterization, and solid-state devices – those without moving parts. The company's work in the field has market potential for using piezoelectric devices in smart city infrastructure, water conservation, machine health, and ocean observation. During this project, Pyro-E conducted end-user interviews with the California Department of Transportation and the San Francisco Municipal Transportation Agency. To advance the piezoelectric-based technology, Pyro-E conducted both laboratory and field testing, including:

- Dynamic impact to simulated vertical and horizontal loading
- Electronic testing to optimized power-takeoff efficiency
- Field testing under normal vehicle driving and braking

To advance the technology readiness, Pyro-E focused primarily on fine-tuning the regenerative pavement devices to harvest energy at a frequency range consistent with vibrations in pavement resulting from automobile traffic. The challenge is that the natural frequency at which the piezoelectric material resonates is significantly higher (by as much as a 100-fold). This mismatch severely limits the efficiency of off-the-shelf piezoelectric devices. To resolve this mismatch, the design reduces the natural frequency of the regenerative pavement devices and enhances performance under realistic roadway conditions. The resulting regenerative pavement devices tested during this project obtained both higher power densities and greater efficiency than current commercially-available piezoelectric devices.

The project also found ways to simplify the regenerative pavement devices and reduce the number of components and movable parts involved, improving reliability and power output of the devices. The simplified design would also be beneficial for manufacturing at the scale necessary to lower the cost at volume. The product development aligns with suggestions from the technical advisory committee to focus on improving the scalability of innovation.

## Project Results

The project demonstrated an efficient design for regenerative pavement devices that could be scaled up to provide cost effective electricity for widescale implementation. The key innovations of the project included:

- **Robust output via dual-stage force amplification** – The regenerative pavement devices integrate the use of strain-flexors to augment the input force from passing vehicles. The design reduced the height of the regenerative pavement devices by 30-percent while improving output. Simulation and experimental results indicated that these design changes lead to a 10-fold larger power output than current devices.

- **High efficiency from broad bandwidth** – The regenerative pavement devices passively improves the low-frequency response to varying input without complex tuning schemes. Early experiments achieved up to 45 percent bandwidth at half-power, compared to typical electromagnets of less than five percent.
- **Passive power management circuit** –The passive power management circuit was designed and developed to minimize losses and increase the output power produced by the piezoelectric elements. The project demonstrated that the electrical input-output efficiency of the regenerative pavement devices is greater than 65 percent at 10 milliwatt output. The passive load-matching circuit has low parasitic losses, able to reach 82 percent efficient at 100 milliwatt (four-times higher than commercial power management circuits).

The work demonstrated the technical feasibilities necessary to justify commercial viability, including generation and conversion of the energy produced by vehicular traffic. Overall, the project achieved success through demonstrating that regenerative pavement devices at scale could:

- Provide 80 percent savings to grid electricity with a projected levelized cost of 0.02 cents per kilowatt-hour.
- Serve 5,000 homes with electricity generated by piezoelectric technology from a 4-lane, 1-kilometer highway during peak traffic hours (approximately 4.2 million average homes serviceable with renewable electricity).
- Displace 1.2 kilotons per year of carbon dioxide emissions from thermal plants.
- Save 16.8 mega gallons per year of fresh water alleviated from thermal plants.
- Save $1 billion per year through improved mobility, motorist safety and traffic decongestion.

## Technology/Knowledge Transfer/Market Adoption

The target entry market for adoption of Pyro-E's regenerative pavement devices is the $13 billion United States road tolling industry. Every year, 5.7 billion vehicles make crossings on nearly 6,000 toll roads across 35 states. In the process, significant revenue is lost due to inaccurate vehicle identification and inefficient weight-limit enforcement. Pyro-E had early partnership discussions with privatized toll concessions companies for conducting a pilot study to install regenerative pavement devices at a select toll plaza. The preliminary plan calls for an 18-month pilot project using regenerative pavement devices to complete a 30-foot test section for testing and evaluation. The project would be divided into two phases: a 12-month field deployment and a six-month validation for traffic data analytics and performance.

The pilot seeks to replace diesel generators as backup power to counter blackouts instead using electricity is stored in batteries to meet intermittent demand. In addition to capturing energy, the regenerative pavement devices would provide data as a service. It allows toll companies to track traffic patterns and provide data to improve congestion and motorist safety. The regenerative pavement devices can measure vehicle speed, track the width and weight of passing vehicles, and provide data directly to customers.  It is a scalable solution that can expand beyond private toll roads to public infrastructure once the solution gains the client support.

For long-term target markets, regenerative pavement devices can be adopted at a broader scale to improve the efficiency of United States road infrastructure. In recent years, the Federal Highway Administration has indicated a declining revenue from fuel tax due to more fuel-efficient vehicles. The Congressional Budget Office further projects that outlay from the Highway Trust Fund will exceed its reserves by a cumulative $119 billion (highway portion) by 2028. The improved tolling accuracy from the use of regenerative pavement devices could provide added revenue that could help bridge the gap in the impending budget shortfall and mitigate additional excise taxes.

The barrier to entry for regenerative pavement devices is the reluctance of adopting new technologies in renewable energy. For conservative industries such as transportation, the primary concern is safety. The wide-ranging driving speeds and weather conditions make any pavement modifications potentially dangerous to motorists. One mitigating strategy is to begin adoption in a low-speed section such as a toll plaza. Though less productive, low-speed impacts would greatly improve safety over potential hazards of road-embedded systems. In addition to safety, another primary concern is the added complexity of removing the regenerative pavement devices during scheduled road works and resurfacing. These are valid concerns that must be addressed early in the hardware development process. In response, the project team consulted public works engineers on the removability of regenerative pavement devices during the pilot installation.

## Benefits to California

Adopted at a larger scale on roadways across the state, regenerative pavement devices could benefit all Californians by serving local communities with low-cost electricity. Unlike other infrastructure modernization projects, regenerative pavement devices could be implemented in timelines that are faster than permitting for new roadway construction. Likewise, retrofitting regenerative pavement devices into select high-traffic corridors, the speed of reduction from the transportation sector is faster than electrifying the current stock of gasoline vehicles. That is, regenerative pavement devices-retrofitted roadways could provide electricity during peak traffic hours. They include early mornings and late afternoons to offset the ramp up to peak energy demand. And during blackouts, provide power for lighting and signaling. Adopting regenerative pavement devices can also greatly improve convenience, safety, and mobility (the three tenets of effective transportation) though real-time data services. These and other various stakeholder benefits include:

- *Public health improvement* from reduced carbon dioxide and oxides of nitrogen emissions by offsetting power generation from fossil fuels.

- *Capital effective traffic remediation solution* at one percent overall cost of roadway expansion.
- *Accelerated timetable* with direct 'drop-in' retrofit during pavement resurfacing.
- *Lower operational cost* with self-powered, maintenance-free operation.
- *Energy sustainability* by capturing lost energy from road pavement vibration without adversely impact normal driving *Taxpayer appeal* for having an equitable solution as a low-cost, revenue generating infrastructure upgrades.

# CHAPTER 1: Introduction

## Background

Americans spend 5.5 billion hours annually stuck in traffic. Along the 400,000 lane-miles of California highways (Caltrans, 2020), the extra fuel and lost productivity from traffic congestion costs approximately $120 billion to the national economy annually (Build America Investment Summit, n.d.). One way to offset or recover these costs is to harness part of the energy associated with traffic congestion. Thus, this project aims to harvest some of the lost energy using a special class of materials called piezoelectric materials – those that have the inherent ability to convert mechanical stress into electricity. 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.

The goal of the project is to convert the billions of tire compressions from automobiles traveling over pavement every day into cost effective electricity using devices based on these piezoelectric materials called regenerative pavement devices (RPDs). The project also identified other end-user benefits of RPDs to enable intelligent roadways. One aspect of intelligence is data to monitor, diagnose, and report roadway incidents autonomously. The needs met is by providing power to a network of sensors. Network sensors placed in remote or covered areas require power for data connectivity, and solar energy may not be an option in many cases (for example, covered areas limiting access to solar). The RPDs can be used to harvest energy from sources such as pedestrians walking on sidewalks or crosswalks or cars on streets and highways near the sensors.

Additionally, RPDs can be used to address congested roadways and improve transportation and mobility. The standard mitigation for traffic congestion is lane expansion, which is costly and time-consuming RPDs can be built into roads during resurfacing operations at minimal additional costs and little delay to the resurfacing projects. Once installed, a network of RPD-powered pavement-embedded network sensors may be able to remediate traffic congestion by providing real-time data on traffic patterns to improve throughput and safety.

### Why Piezoelectricity?

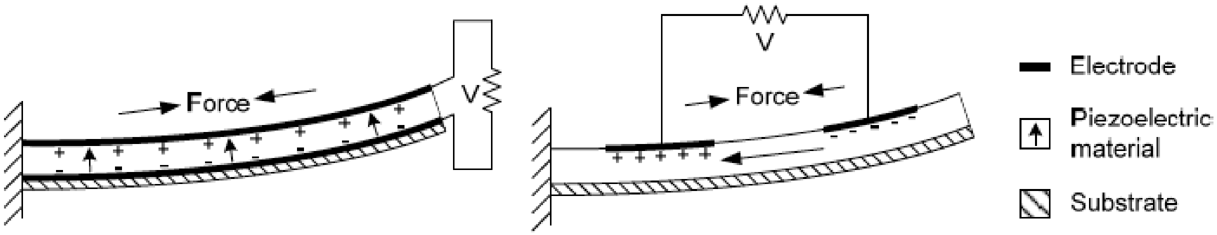
Piezoelectric technologies use a special class of ceramic materials that can generate an electric charge in response to applied mechanical stress. The phenomenon is both precise and predictable, and the practical use of these materials has been demonstrated in many electronic applications, including microphones, speakers, and camera zooms. Its ubiquity is noted in the electronic industry where billions of multi-layered ceramic capacitors are produced and sold every year around the world. For piezoelectric energy harvesting, the electricity is generated from cycles of applied pressure on the material. Given its ceramic composition, extreme pressures are needed – that is, approximately 100 Megapascals (Mpa) (14,500 pounds per square inch). A novel device design is invariably needed to overcome this extreme operating requirement.

The basic piezoelectric device resembles a rectangular stack (typically, 1.0 cm x 1.0 cm x 2.4 cm), consisting of hundreds of layers of piezoelectric ceramics sandwiched between metal electrodes. When under planar stress, the total electric charge collected, $Q = \mathrm{N}Ad_{33}E_y\varepsilon_3$, is determined by the number of layers, *N*, piezoelectric (charge) constant, $d_{33}$, film surface area, *A*, elastic Young's modulus, $E_y$, and strain, $e_3$, in the normal direction to the layer area. Then, the resulting electrical energy across a multi-layer stack through one compression-release cycle would be given as $E = 2Q^2/C$, with capacitance, *C*, of the piezoelectric ceramic.

Since energy scales quadratically as material strain, $E{\sim}{\varepsilon_3}^2$, a device that could amplify the input vibration to produce larger piezo strains would recover a greater portion of the input into useful energies. In response, a strain-amplified piezoelectric device is designed to maximize electrical output from a wide range of external force magnitudes and excitation frequencies.

Currently, there are two basic technologies capable of energy harvesting – piezoelectric (cantilever-type) transduction, and ferromagnetic (permanent-type) induction. In the piezoelectric cantilever-type, the devices work by incorporating a resonant bending beam tuned to a specific operating frequency (Mide Corporation). Figure 1 shows an example of the operation and key components of the piezoelectric cantilever-type harvester. This type of energy harvester has two main limitations: 1) a very limited bandwidth; and 2) tendency to be fragile due to the uneven bending stresses experienced during vibration. In the strain-amplified version used in this project, both limitations are overcome using stack-type piezoelectric materials operating with low frequency, pressure-drive excitations.

**Figure 1: Piezoelectric Transduction**




**Operation and key components of the cantilever-type harvesters, with alternate material polarization schemes.**

Source: Pyro-E

Currently, commercially available piezoelectric energy harvesters are inadequate for roadway harvesting. As resonant devices, they operate in the kilo-Hertz (kHz) frequency range, far outside of the frequencies of vibrations generated by vehicle traffic (typically <50 Hz). Moreover, in practice, resonance tuning for each specific application is needed given that a deviation of less than 5% would lower the power output by more than 50%. In response, Pyro-E has developed a new family of strain-amplified vibrational energy harvesters that overcome the limitations in bandwidth and robustness of existing devices.

## Limits to Current Practice

There are both technical and non-technical barriers to using piezoelectric energy harvesting for power generation at grid parity. Namely, for the technical aspect, existing piezoelectric materials are limited by their extreme operating range in frequency of greater than 1 kHz, much higher than vibrations from road traffic at less than 50 Hz. Pyro-E's approach makes it possible to match the speed and force of cars and trucks while achieving 30-times greater power densities than currently available technologies. Pyro-E's approach specifically addresses the following shortcomings:

- Frequency mismatch (off-resonant) resulting in low efficiency.
- Small load bearing capability for vibrating structures.
- Non-uniform stress distribution across a plurality of generating units.
- Non-strain tolerant electrodes in vibrational bending harvesters.

For the non-technical aspect, product feasibility is driven by customer return on investment. Today, vibrational energy harvesting has not yet found broad adoption. Overcoming early adoption barriers would launch piezoelectric energy towards grid-parity. Having a more robust supply chain of the raw materials for the piezoelectric devices is equally important at obtaining the economy of scale to achieve cost reduction with greater throughput.

Table 1 and Table 2 give a summary of technical and non-technical barriers and the respective solutions.

**Table 1: Solutions to Technical Barriers**

| Barrier | Solution |
| --- | --- |
| **Power** | Increase input force through strain amplification using compliant mechanism and obtain greater piezoelectric material excitations and output power. |
| **Bandwidth** | Broaden the frequency response of a resonant mechanism by removing friction, eliminating the backlash, and reducing the stiffness of the device. More energy is harvested across a large range of input frequencies. |
| **Efficiency** | Reduce parasitic losses with direct force transfer to multiple piezoelectric elements in a parallel array, while collecting the output electricity using a passive, high-impedance transduction circuit that prevents back-charging. |
| **Reliability** | Distribute applied stresses uniformly across individual piezoelectric elements to reduce shear stress loading and extend material life and operational reliability (approximately 3 billion cycles, as manufacture suggested). |

**Competitive features of the RPD technology.**

Source Pyro-E

**Table 2: Solutions to Non-technical Barriers**

| Barrier | Solution |
| --- | --- |
| **Supply chain** | Ensure robust raw material supply through direct supplier contact and in-house manufacturing. |
| **Broad application** | Ensure competitive pricing with multi-functional use and expensive power market mitigation. |
| **Grid-parity** | Ensure positive cashflow through small-scale pilots with private businesses. |

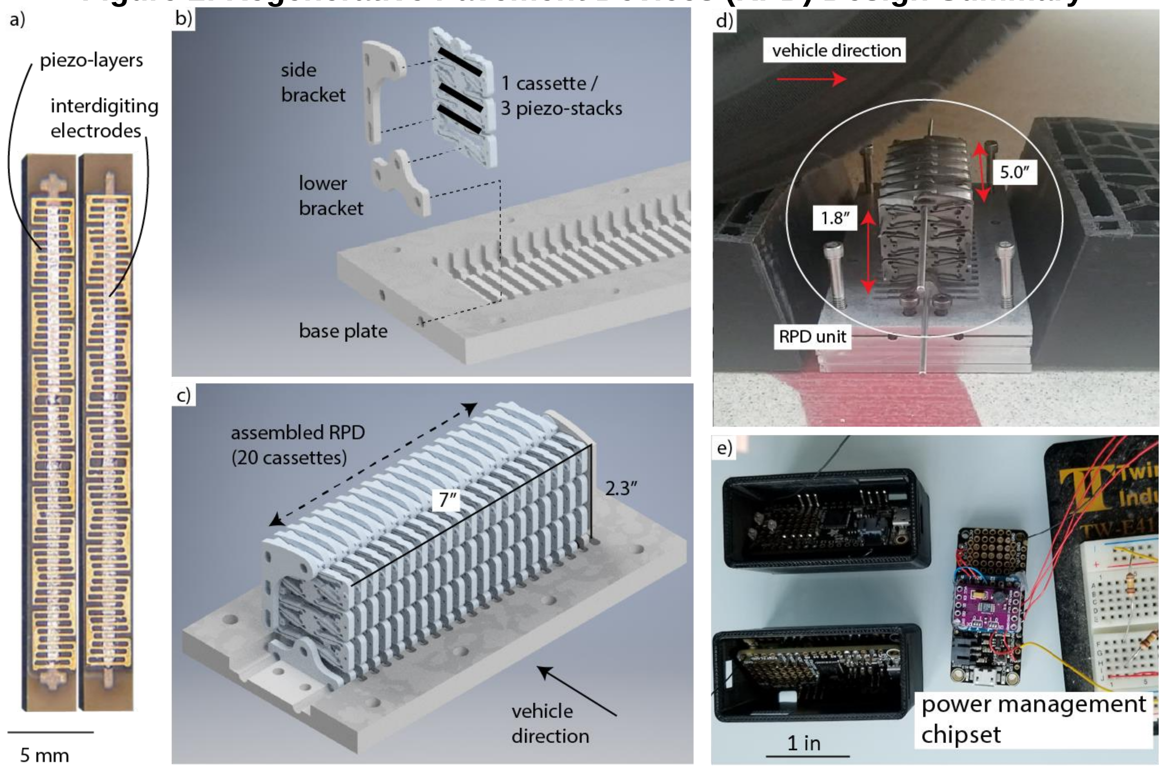
**Competitive features of the RPD technology.**

Source Pyro-E

## Innovation and Advantages

The barrier to broad adoption of piezoelectric devices is cost. One way to reduce cost is to increase performance efficiency of the devices through increased power density at off-resonant frequencies. To accomplish this, Pyro-E used a flex-tensional actuator to generate large force leverage, augmenting the force applied from passing vehicles. As shown in Figure 2, the energy harvester consists of: 1) a multilayer stack of piezoelectric thin films; and 2) a force multiplier actuator frame. The piezoelectric stack is pressed and bonded into the prefabricated metal frame under compression. When the device is excited by a compressive force, $F_c$, a larger extensional force, $F_e$, is transmitted to the piezoelectric-stack. The relationship, $F_e = c\ F_c$, is governed by the force multiplier factor, c=dz/dx, which is equal to the ratio of deflection travel between the two orthogonal directions.

**Figure 2: Regenerative Pavement Devices (RPD) Design Summary**




**(a) Multilayered piezoelectric stack for energy harvesting, three of which are installed inside a (b) single flexor cassettes secured to an exposed RPD module (c). A photograph of the RPD module in above-ground demonstration (d) and power electronics. The construction consists of 3 piezo-stacks to a cassette, and 3 cassettes to a unit, and 3 units to a module). Commercial off the shelf (COTS) inverter and battery are not shown.**

Source Pyro-E

## Development Risks and Challenges

Pivotal to the mechanisms of force and strain amplification, the flexors in the RPDs are intended for converting vertical compression into orthogonal piezoelectric strain. This requires the use of compliant hinges that pivot rotationally without sliding components. The RPD development therefore focused on mitigating the following undesirable device properties:

1. Large rotational spring loads imposed on the transfer of orthogonal displacements. This reduces the ratio of amplification across stage 1 and 2 flexors, thereby reducing device performance.

2. Large material flexibility when exposed to large longitudinal forces along the beam direction. This creates buckling between the flexure hinges, thereby attenuating force transfer and reducing device performance.
3. Large translational displacements that occur at the flexure hinges when the geometries are optimized to reduce rotational hinge stiffness. This creates the same problem as beam buckling in the thick sections, thereby reducing device performance.

## Project Purpose and Objectives

The purpose of this project is to demonstrate a commercially viable technology, the RPD, that can harvest energy from pavement vibrations via the piezoelectric effect. Achieving the objectives in power, size, efficiency, and reliability would represent significant progress towards demonstrating project success. Overall, the key technical objectives include:

- Efficient electromechanical conversion (coupling factor ≈70-80 percent).
- Exponential two-stage force amplification (input gain ≈225 percent).
- Low-frequency power (resonance ≈ 30 Hz).
- Low-profile design for easing roadway retrofit (height ≈1”).
- Fail-safe design and weatherized enclosure for robust operation (25-year life).
- Power density exceeding 300 W/ft$^2$ (cars and trucks).

The advantage of displacing grid electricity to benefit ratepayers is by lowering the electricity costs and reducing greenhouse gas emissions. With 1 percent market penetration, the benefits include:

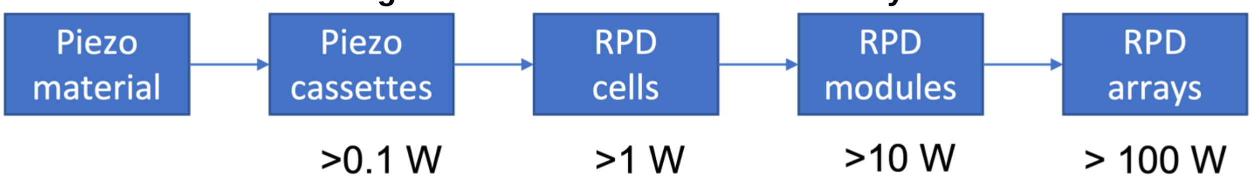
- Scalable energy solutions with a projected electricity cost of 2 cents/kWh.
- 5,000 homes serviceable by a 4-lane, 1-km highway during peak traffic hours (average demand = 1.60 kW).
- Up to $300 million in annual energy cost saving to California ratepayers.

# CHAPTER 2: Project Approach

The overall project approach included component, device, and system-level prototyping, iterative optimization, and the performance evaluations of power, efficiency, and reliability. The strategy for performance improvement, for example, analyzed various cross-sectional geometries that would minimize material strain and increase fatigue life. A finite element analysis (FEA) tool was validated using simple geometry (Appendix C). The FEA and analytical tools helped design geometries that were later validated through laboratory testing, an initial pilot, and a demonstrator pilot.

For the different tests conducted on the RPD, the terminology can vary depending on the power output and overall architecture of the device. Figure 3 shows the hierarchy of the piezoelectric materials that are configured into RPDs ranging from simple piezo-electric cassettes on the order of 0.1 W to larger arrays on the order of 100W.

**Figure 3: RPD architecture hierarchy**




**Terminology for RPD architecture.**

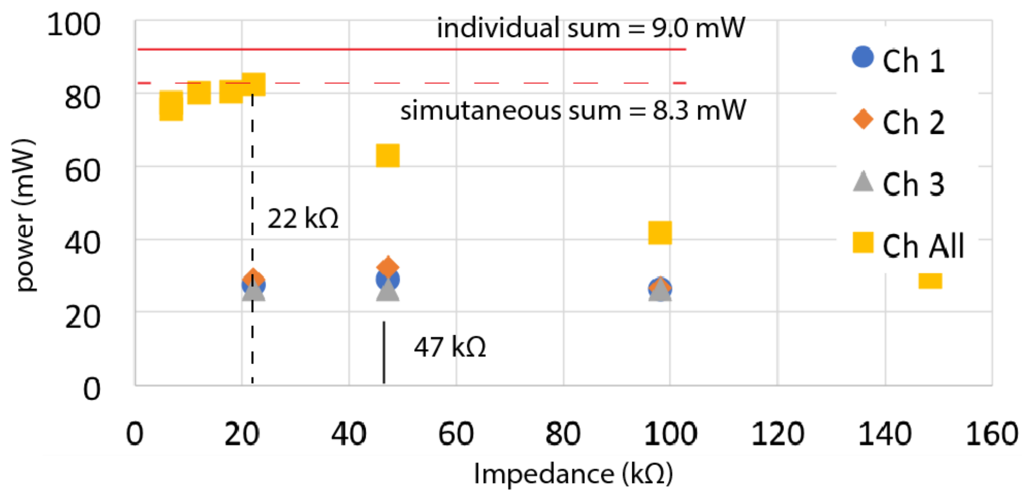
Source Pyro-E

## Rolling Impact Testing

The experimental methodology for testing the RPDs was chosen to replicate the real-world conditions of vehicle traffic by considering the contact force conditions to model tire-pavement interaction. A pneumatic cylinder was used to provide vertical forces directly to the energy harvesting cells of the RPDs. This would represent a static condition for a standing vehicle. In subsequent iterations a pneumatic slider was added to apply a horizontal force from both directions. During operation, the vertical force can stay stationary or actuate with the slider.

The resulting data demonstrated both power performance and consistency (Figure 4). The output matched the expected value from simulation and manufacturer's data and the consistency found between the multiple channels suggested repeatable mechanical tolerances in the construction of the RPD cells.

**Figure 4: Force Impact Testing Data**




**Individual and combined channel measurement of power vs. load at 25 ⁰C. It is observed that 10 percent loss of power is associated with parallel piezoelectric arrangement due to back-charging.**

Source Pyro-E

## Highly Accelerated Life Testing (HALT)

The methodology for determining device reliability was to conduct highly accelerated life testing (HALT). In addition to cyclic impact, the HALT methodology includes temperature cycling during testing. The temperature range chosen, -20 ⁰C to 35 ⁰C, is typical of ambient conditions in the US. The process provided cyclic stresses associated with mismatched thermal expansion and accelerated normal material wear and fatigue to enable performance projections. This is possible as temperature and environmental effects cause irreversible performance degradation over time. The monotonic changes allow strong predictability of future performance.

The HALT results indicate the potential failure modes for RPDs, as summarized in Table 3. HALT exacerbates the effect of extreme weatherization caused by the range of ambient conditions. The failure modes include corrosion, mechanical fatigue, electrical shorts, and battery degradation. Future design iterations of RPDs will take account of these findings to improve performance and lifetime.

**Table 3: Potential Failure Modes of RPD Components**

| Component | Failure mode | Potential Cause | Local/System Effect | (1) | (2) | (3) |
|---|---|---|---|---|---|---|
| **Piezoelectric elements** | Mechanical damage | Large shear stress creating excessive internal stress | Electrical shorting; damaged electrical leads; weakened compliance | L | I | L-I |
| | Corrosion degradation | Poor encapsulation; poor water seal | Loss of power; cracked multi-layer piezoelectric | H | II | H-II |

| Component | Failure mode | Potential Cause | Local/System Effect | (1) | (2) | (3) |
|---|---|---|---|---|---|---|
| | | | capacitors (MLPC); excessive strain; | | | |
| **Flexor** | Hinge breakage | Non-uniform structure stress; cycle fatigue; overheating | Performance degradation; no power; mechanical malfunction; weak forcing; loss of battery charging capability | L | II | L-II |
| | Plastic deformation | Poor strain-limiter design; cycle stress and thermal fatigue | | M | I | M-I |
| **Enclosure** | Corrosion | Water intrusion through seal; damaged seal; moisture damage | Lifetime degradation; debris/moisture found internally; loss of battery charging capability | H | I | H-I |
| | Water leakage | Poor material selection; poor quality control on assembly | | L | II | L-II |
| **Power electronics** | Battery fault | Component fault; over voltage | Loss of power; low operating voltage; poor efficiency | L | I | L-I |
| | Overvoltage | Excessive stress; hot weather | | | | |

**Root-cause analysis. Columns: (1) Failure probability (low-L, medium-M, high-H); (2) Effect severity (I-low, II-medium, III-high); (3) Risk index = (1)+(2). High-risk component (underlined) were tested under HALT.**

Source Pyro-E

## Power Management Circuit (PMC)

For power takeoff, the project team designed and prototyped a first iteration PMC. Its design objective was to rectify the alternating current produced by the piezoelectric elements under stress cycles. The most direct manner is to use a rectifying bridge circuit to minimize parasitic losses and increase output power. At low frequencies, the stressed piezo-stacks generate low currents because of high internal impedance. Overall, the two challenges facing the design of PMC are:

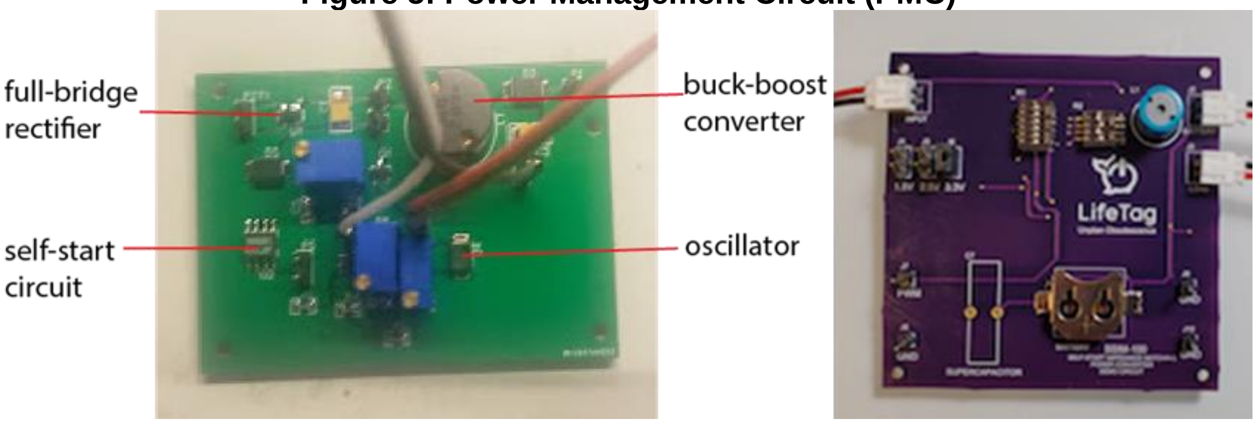
- Piezoelectric energy harvesters having high output voltage but low current level, requiring AC-DC invertors tolerant to voltage spikes.
- The high output impedance of piezoelectric devices makes it difficult to couple the devices with downstream electronics efficiently.

The PMC overcame the design challenges to maximize power and efficiency through the following methods (Figure 5):

- Incorporate variable input impedance (the load capacitance) to provide frequency tuning at resonance.
- Accommodate a generator array of piezoelectric elements to increase current output and battery charging.

Please refer to the Power Electronics section for more information in Appendix D.

**Figure 5: Power Management Circuit (PMC)**




**(Left) Breadboard AC-DC rectification, impedance-matching, and data communication.**
**(Right) PMC evaluation board for commercial sale.**

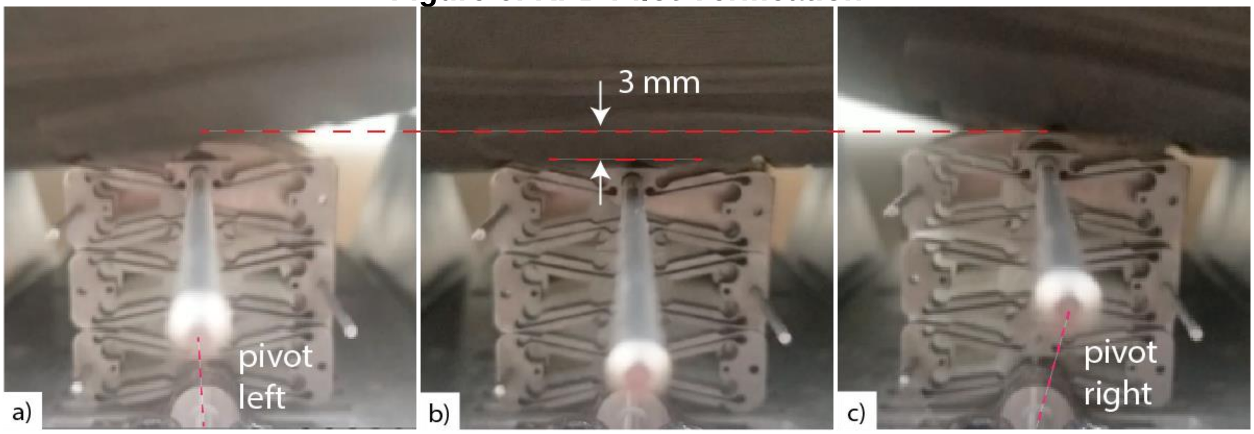
Source Pyro-E

## Initial Field Demonstration

Beyond the laboratory verification, the first road test was conducted for the full-scale RPD prototype. A test vehicle (Ford Mustang) was driven atop of an RPD placed between ramps. The objective of the initial demonstration was to verify the structural integrity of the RPD under the loading force of a car. If successful, the test would proceed onto the next step of placing the RPD below ground.

The test was a success as the results met the feasibility targets. One notable highlight was the smooth transition between the ramps across the RPD. The driver did not notice the ~3 mm deflection of the RPD during testing, as shown in Figure 6. Also, without bolting to the ground, the test RPD remained stable between the ramps. In the next testing phase, an in-ground RPD will accommodate for higher vehicle speeds for verification. Achieving those objectives will better demonstrate the strength of the RPD under real-world driving conditions.

**Figure 6: RPD Pilot Verification**

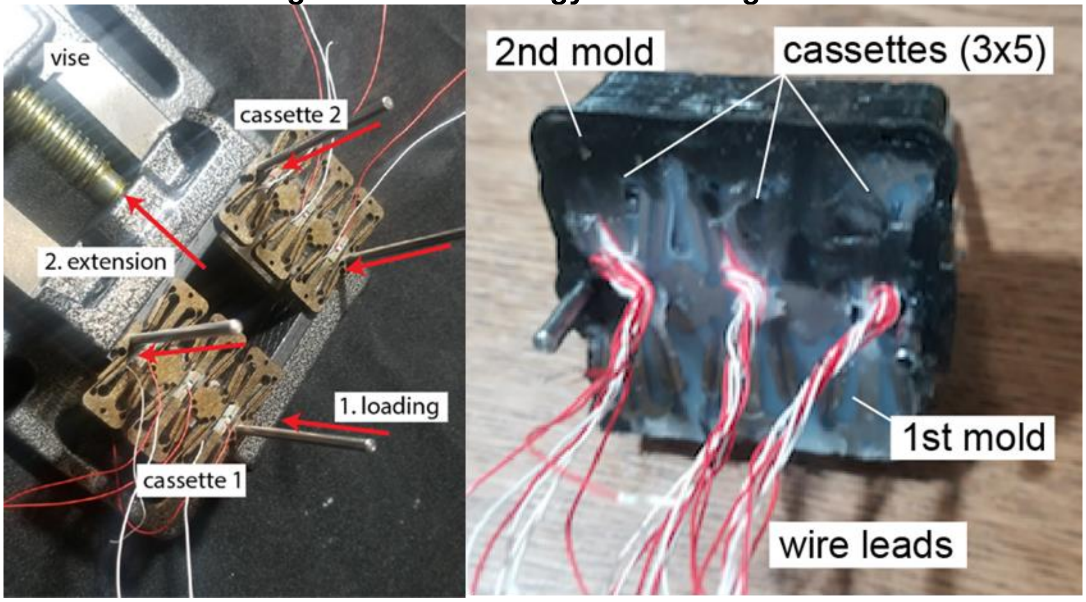



**Picture (a) shows the moment before the wheel contacted the RP– -- the RPD was at rest. Picture (b) shows the moment when the wheel contacted the R– -- the RPD deformed vertically. Picture (c) shows the moment after contact– -- the RPD was back to rest shape.**

Source Pyro-E

The process of building an RPD array began with building multiple cassettes (which are comprised of 3 piezoelectric stacks) by combining laser-cut flexor frames with piezoelectric stacks. In Figure 7, two cassettes are stretched by a vice in a manner that fits the piezoelectric stack in the mid-plane (six total). Multiple cassettes are then combined to form a single RPD cell where power will be harvested from parallel piezoelectric stacks. Cassettes can hold three piezoelectric stacks to form a single RPD cell. Next, the RPD cells are encased in an environment barrier so that dirt and debris do not impede normal operation. The barrier also increases protection against corrosion caused by moisture. The method used a soft silicone material that molds to the internal geometry of the cassettes. For external protection of an RPD cell, a tougher urethane sealant was used (Figure 7 clear white – silicone, black – urethane).

**Figure 7: RPD Energy Harvesting Cell**

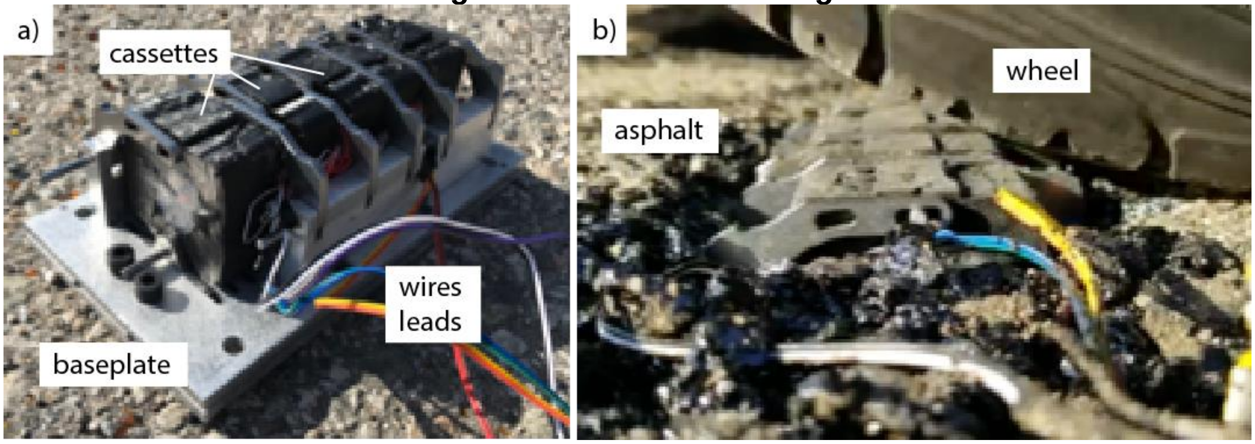



**Photograph of manual cassette loading jig and de-molded RPD cells.**

Source Pyro-E

Next, field testing was conducted (Figure 8). An initial build for a full-scale RPD array consisting of five RPD modules was installed into the pavement. A concrete base provides the mechanical support needed for compression. The RPD cells are electrically connected in parallel. The initial test used a compact passenger vehicle at relatively low speeds (approximately 25 mph).

**Figure 8: RPD Pilot Testing**




**Full-scale RPD testing using one three 3-cassette and two 5-cassette RPD cells (a) installed into pavement leveled with the road surface (b). The RPD cells are kept open to observe vertical deflections.**

Source Pyro-E

A summary of the recovered energy from wheel impact is shown in Table 4. The data are separated by vehicle type and production batch and show a large variation between runs. One contributing factor may be the speed of the vehicle, as indicated by the shortest peak separation (last column). As speed increases, inertial effects play a role, as well as the bounce back for the dual peak waveform seen in Figure 9. In addition, the piezoelectric effect may become saturated when excited at relatively long durations (that is, milliseconds).

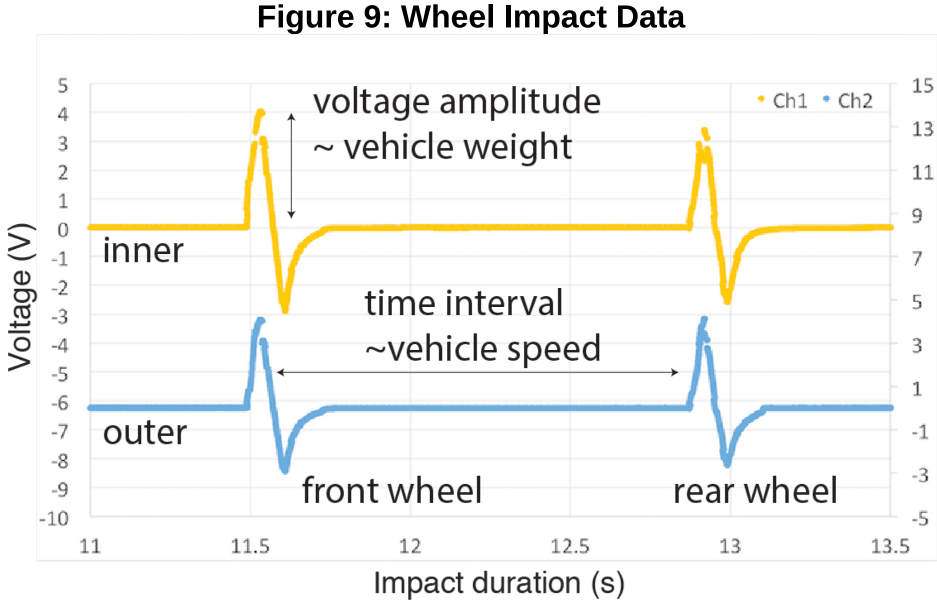
**Table 4: RPD Roadway Testing Result**

| | Power. Front (mW) | Peak Width (s) | Power Rear (mW) | Peak Width (s) | Peak Separation (s) |
|---|---|---|---|---|---|
| Ford 1, Batch 3 | 0.1 | 0.031 | 9.9 | 0.016 | 3.1255 |
| Ford 1, Batch 4 | 10.6 | 0.065 | 4.5 | 0.0385 | 3.174 |
| Mazda 1, Batch 3 | 32.2 | 0.0225 | 33.6 | 0.067 | 1.879 |
| Mazda 1, Batch 4 | 6.2 | 0.008 | 60.3 | 0.067 | 1.82 |
| Mazda 2, Batch 3 | 92.3 | 0.0846 | 63.3 | 0.079 | 1.3836 |
| Mazda 2, Batch 4 | 90.2 | 0.0846 | 94.3 | 0.079 | 1.3836 |

**Power output of RPD during field testing for batches 3 and 4 that used different design parameters to verify performance.**

Source Pyro-E

**Figure 9: Wheel Impact Data**




**Representative impact voltage data vs impact duration for the inner and outer tracks of an overpassing vehicle.**

Source Pyro-E

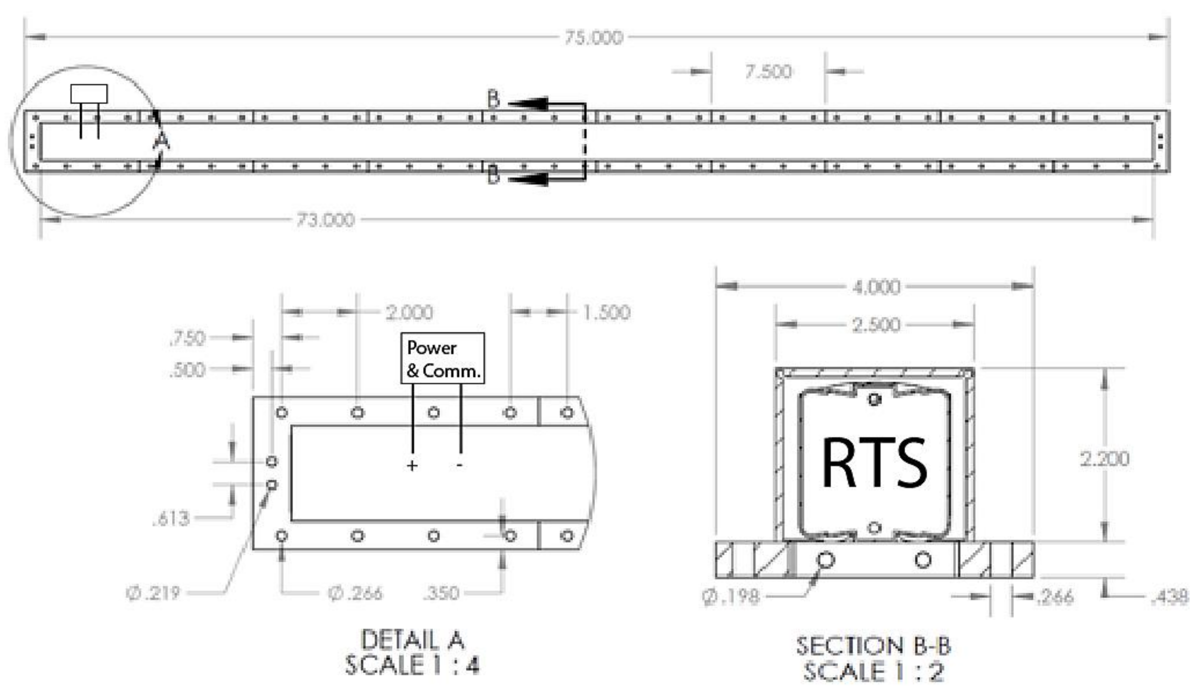
## Demonstrator Specifications

The illustration in Figure 10 covers the dimensions of the RPD module, consisting of three to five piezoelectric-cells. The interface specifications are provided in

Table 5. The mechanical, thermal, and electrical specifications and data interoperability meets the requirement given by customers. A summary of the specific capabilities and features of the RPD include:

- Real-time measurement for vehicle direction, axles, speed, and weigh-in-motion.
- Uninterrupted self-power for data collection and transmission.
- Minimalist two-part construction to mitigate failure-modes and improve reliability.
- Temperature compensation for environmental variabilities.
- Drop-in replacement for mechanical or fiber optic treadles.

**Figure 10: RPD Array Product Specifications**




**Dimensions and bolt patterns for RPD installation.**

Source Pyro-E

Driver speed was also influenced by the protrusion of the RPD installation. An early demonstration found that a 5-mm (0.20 inches) protrusion of the RPDs from the roadway caused noticeable surface disruptions to limit vehicle speeds to 35 mph. For a 3 mm (0.12 inches) protrusion, drivers maintained speeds between 40-50 mph. These results showed the RPD could be effective at limiting vehicle speeds where desired. Other features that were either demonstrated or supported include:

- ‘Intelligent’ operation able to adapt form and function to real-time traffic – in coordination with roadway sensors powered by RPDs.
- Direct visual and haptic feedback to motorists to reduce speeds if desired by existing road conditions.
- Effective safety countermeasure for reducing vehicle speeds.
- Intelligent data analyzer for lane-specific information on vehicle type and speed – in coordination with roadway sensors.
- Weatherized package against moisture/debris for maintenance-free operation.

**Table 5: RPD Product Specifications**

| **MECHANICAL** | | **THERMAL** | |
|---|---|---|---|
| **Configuration** | Sub-surface asphalt | **Ambient temperature** | -40 to 25 °C |
| **Overlay thickness** | < 1.5″ | | |
| **Dimension (LxWxH)** | 75″x6″x2.6″ | **Electrical** | |
| | (Customizable) | **Power supply** | No need |
| **Maximum force** | 6500 lb per tire | **Output voltage** | 4.5 VDC to storage |
| **Maximum speed** | 65 mph | **Operating life** | > 10 years |
| **Minimum load cycles** | 500 million | **Connectivity** | RS-232/485 |

**Mechanical and electrical interfacing specifications for field installation.**

Source Pyro-E

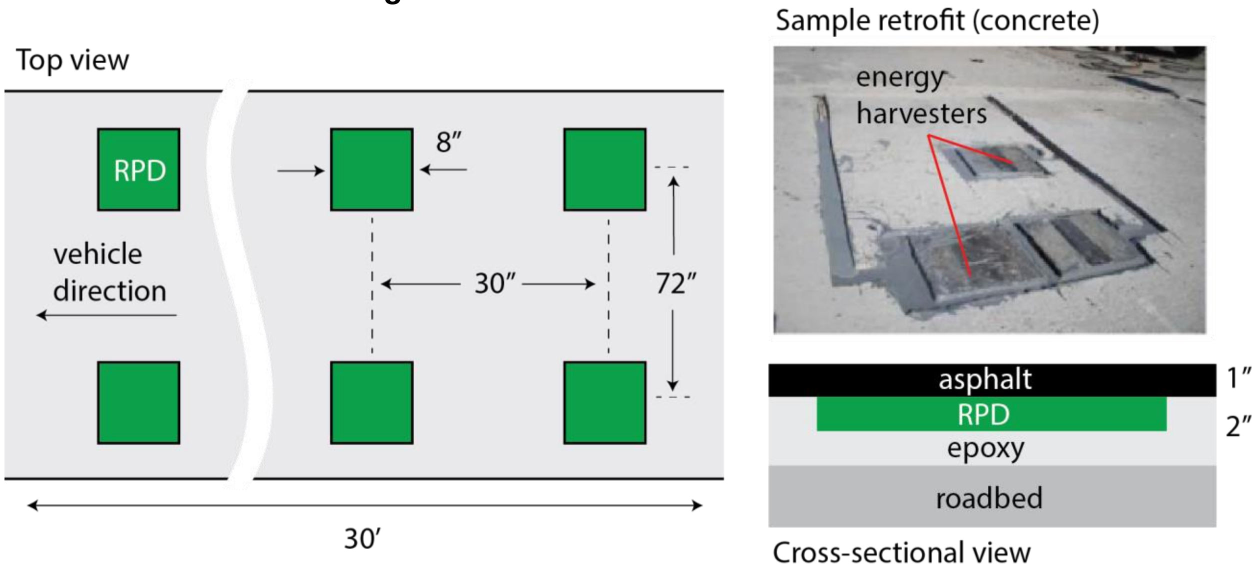
## Demonstrator Installation

The initial pilot provided a blueprint for installing the RPD below grade. As depicted in Figure 11, the RPD installation steps are to:

1. Mill and remove road top asphalt surface to dig trenches.
2. Arrange the individual cells onto the roadbed to form an array.
3. Place liners to form a 0.5″ gap around the cells.
4. Pave with base coat and asphalt, followed by rollers for surface leveling.
5. Remove liners and fill the gap between the RPDs and the asphalt with polyurethane epoxy.

Once complete, the RPD array resembles a square frame that provides two main functions: 1) the gap filled with a flexible epoxy material allows device movement , prevents water intrusion, and is replaceable at predetermined intervals; 2) it prevents the heavy rollers from crushing the RPDs. The asphalt layer on the top of the RPD array can be either prefabricated during manufacturing or laid during paving. This method of installation is consistent with standard roadway resurfacing and does not create conditions that impede safe driving.

**Figure 11: RPD Field Demonstration**




**Field demonstration of RPD array at DC Stages parking lot, Los Angeles, CA. Note: The RPDs are labeled as energy harvesters in this figure.**

Source Pyro-E

# CHAPTER 3: Project Results

The results include the component level performance and efficiency analysis. The mechanical and electrical aspects were resolved through laboratory testing and demonstrated in a field pilot. Previously, field testing was conducted on a subscale RPD. Performance data were collected for power and energy during an actual road vehicle impact test. The test was successful and yielded the following recommended improvements which were incorporated in the final RPD product:

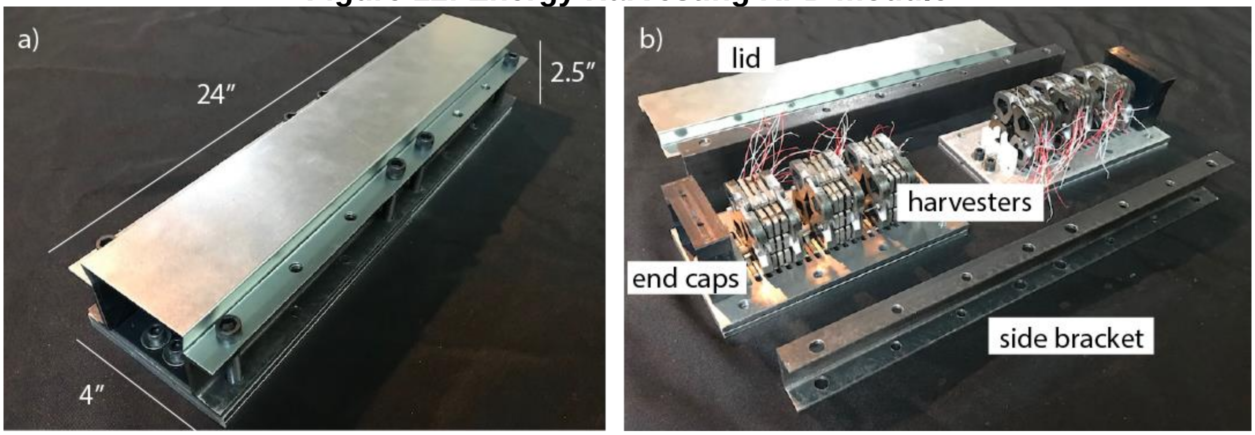
- Cassettes consisting of either three or five harvester RPD cells connected in parallel demonstrated that five RPD cells performed at a greater power and efficiency than a configuration of three RPD cells.
- The strain-limiter was not robust enough during testing. The support structure had to be improved to prevent swaying motion. A new strain limiter was designed and simulated to withstand high loads.
- A lid was required to keep out debris and reduce the shear stresses caused by wheel contact. A galvanized steel lid was design and fabricated to cover the RPD array from above.
- The RPD cells need to be released from the baseplate for servicing. A locking mechanism was designed and tested for ejecting the cells from the top of the RPD array.

## Demonstrator Pilot and Verification

The RPD cell design was updated given the recommendations from initial testing. Figure 12 shows an example of two RPD cells that were combined using steel side brackets and a steel lid to form a single RPD module. A total of 12 modules were built for installation and trial at DC Stages, Los Angeles. The in-situ field testing and evaluation provided preliminary product specifications to reach further commercial readiness. This task implemented the RPD modules at the test site and assessed performance under the relevant roadway conditions. The key tasks included:

- Determine key RPD features and user benefits.
- Deliver prototypes for in-pavement installation.
- Design experiment for vehicle type, speed, and acceleration/braking profile.
- Calibrate data acquisition and characterize transducer performance.
- Troubleshoot and diagnose device failure with traceable root causes.

**Figure 12: Energy Harvesting RPD module**



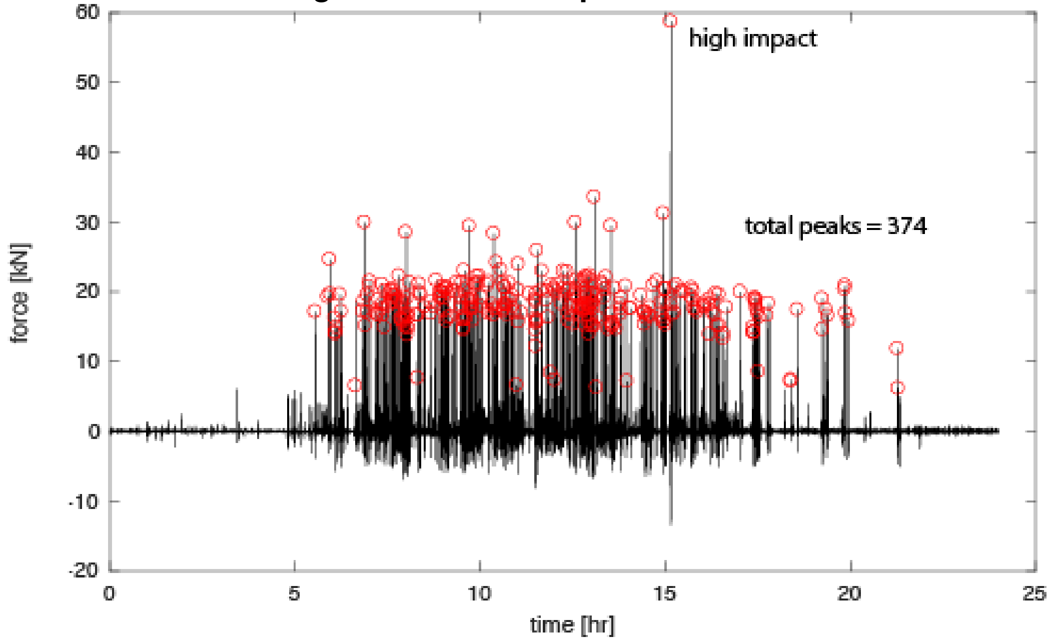

**Photos for a single completed RPD module consisting of 6 RPD cells and 18 cassettes for field installation at DC Stages in Los Angeles, CA.**

## Performance Validation

Preliminary data from the field tests included time-series force deflections from multiple vehicles throughout the day (Figure 13). The vehicles included passenger cars and trucks and delivery vehicles that had staggered wheels per axle.

In addition to the energy generated, wavelet analysis was used in examining the data. The reasoning for using the wavelet analysis is that real world data, or signals, frequently exhibit slowly changing trends or oscillations punctuated with transients. These abrupt changes are often the most interesting parts of the data, both perceptually and in terms of the information they provide. Alternatively, the Fourier transform could also be used as it is a powerful tool for data analysis, however, it does not efficiently represent abrupt changes. This is because the Fourier transform represents data as a sum of sine waves, which are not localized in time or space. These sine waves oscillate and propagate indefinitely in time. Therefore, to accurately analyze signals that have abrupt changes, a class of functions were used, called wavelets, that are well localized in time and frequency.

**Figure 13: Force Impact Measurement**

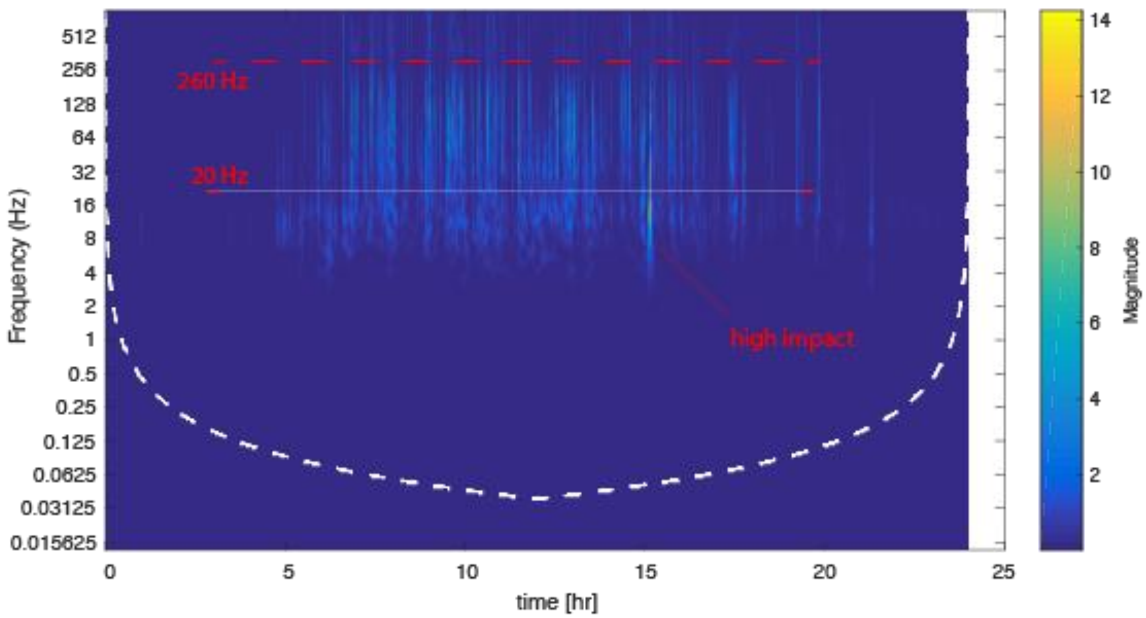



**Representative data on the impact force vs. time of overpassing vehicles over a RPD module.**

Source Pyro-E

More specifically, a wavelet is a rapidly decaying, wave-like oscillation that has zero mean. Wavelets come in different sizes and shapes to find hidden spectral features. There are two important wavelet transform concepts: scaling and shifting. Scaling refers to the process of stretching or shrinking the signal in time. The scaling factor, a positive value, corresponds to how much a signal is scaled in time. The scale factor is inversely proportional to frequency. For example, scaling a sine wave by two results in reducing its original frequency by half. For a wavelet, there is a reciprocal relationship between scale and frequency with a constant of proportionality. This constant of proportionality is called the "center frequency" of the wavelet. Shifting a wavelet simply means delaying or advancing the onset of the wavelet along the length of the signal. During operation, shifting the wavelet enables it to align with the features that exist in a signal. The result of the wavelet analysis using the continuous wavelet transform (CWT) is shown in Figure 14.

**Figure 14: Wheel Impact Feature Identification**

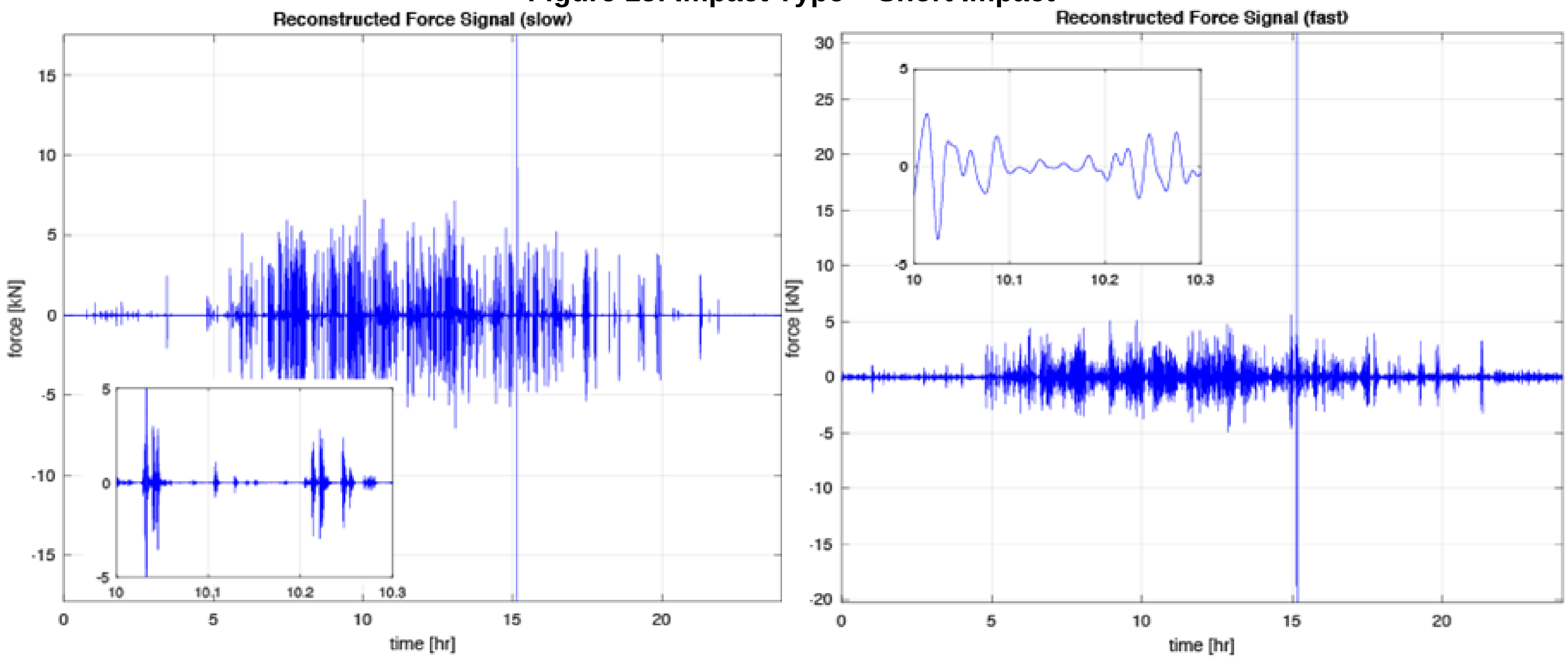



**Spectral frequency data in the time domain via continuous wavelet transform.**

Source Pyro-E

The objective for the wavelet analysis is to distinguish the predominant frequency modes of excitation. These show up as bright horizontal bands in the time-frequency space in Figure 14. The white dash line forms a "cone of influence" beyond which the accuracy is limited by having a smaller sets of frequency data. These predominant modes give a physical interpretation of the impact signal shown in Figure 13, which has no discernable frequency modes. Therefore, to understand the impact , one can observe in three bands of frequencies for which force peaks occur: <20 Hz, 20-260Hz, and >260 Hz. Applying CWT using these ranges, the result for the slow (<20 Hz) and fast (>260 Hz) frequency bands are shown in Figure 15. The calculated mean is zero for both signals, thereby attributing both to the dynamic response of the RPD cell and not from external forcing. In detail, the fast signal would correspond with the elastic behavior of the RPD cell whereas the slow signal to that of the pavement. From the Figure 15 inset plots, one can observe sharp but repeatable peaks for the fast signal. These peak frequencies match that of the RPD cell's resonance. For the slow signal, the inset plot shows slow-varying, irregular peaks that could have originated from a complex dynamic behavior of road pavement. The slow varying peaks also may be attributed to the massive pavement substrate in contact below the RPDs.

## Figure 15: Impact Type – Short Impact

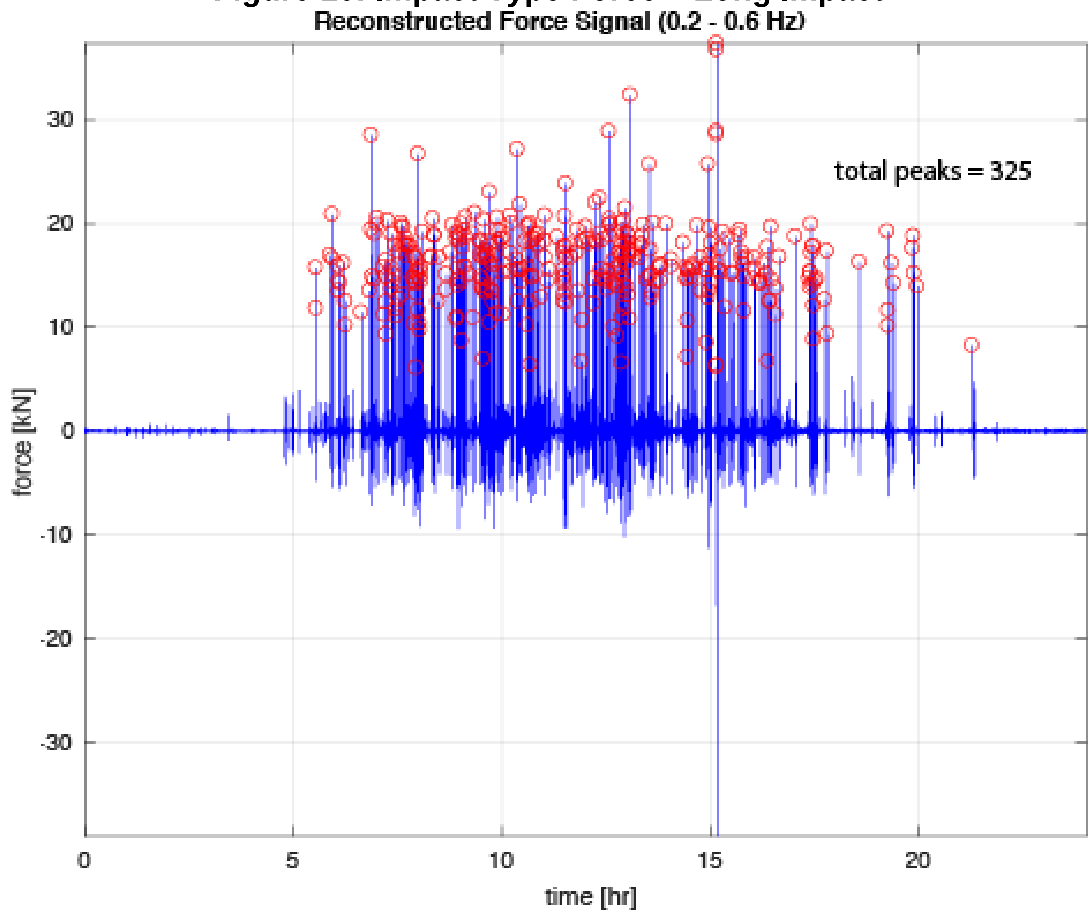



**Reconstructed force vs. time signal using wavelets with predetermined frequency range (left, slow; right, fast). Note the symmetry around force equaling zero, thereby indicating peaks are from the damping effects of the RPD rather than the actual impact. The inset plots represent data occurring at the same time.**

Source Pyro-E

Finally, the signal is reconstructed using the middle frequency band, 20-260 Hz, as shown in Figure 16. the non-symmetric data indicates external forcing. The frequency would correspond to the speed of the overpassing vehicles. Assuming a front-to-rear wheel separation of 1.2 m, the equivalent speeds would range from 10 to 136 mph. Moreover, the total number of peaks would correspond to the number of vehicles passing, where each vehicle would cause two pea–s - one from the front wheels and one from the rear. The signal showed a count of 325 peaks, or 13.1 percent lower than the 374 peaks found in the original data. This matches with the size of the parking lot that holds around 150-170 cars on a daily basis.

**Figure 16: Impact Type Force – Long Impact**

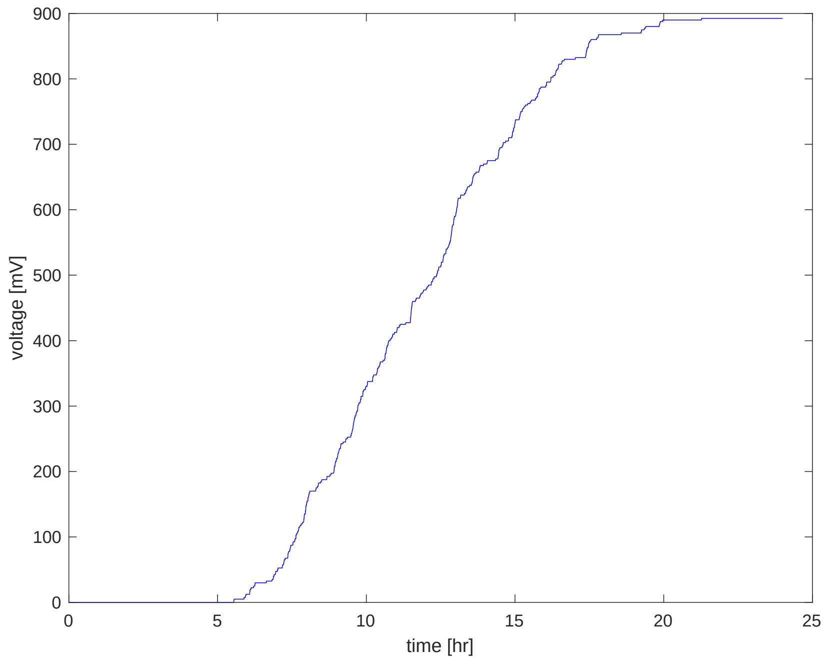



**Reconstructed force signal from the medium frequency range (middle band).**

Source Pyro-E

The calculated battery storage resulting from the force data is shown in Figure 17. The storage element is a 100 Farad supercapacitor. The stored energy is 40.5 J, or 11.3 mWh. This was calculated by measuring the initial and final voltages and multiplying each by half the capacitance of the supercapacitor to get the initial and final energies. The energy stored is then the difference between the initial and final energies.

**Figure 17: Demonstrator Battery Charging**




**Daily electrical energy stored into a supercapacitor for a single RPD module. The energy stored is 40.5 J. The full system with 300 RPD module would product 12.2 kJ.**

Source Pyro-E

# Performance and Cost Summary

## Power Projection

To meet the power density target of greater than 300 W/ft$^2$, laboratory testing of the subscale device can be used for extrapolating actual performance. As shown in Table 6, a two-stage prototype is shown to generate ~1 mW/cm$^2$, or about 100-times greater output than the predictions made by using material properties alone. The experimental data and the laboratory test performance of the prototype are extrapolated by scaling up the compressive force and the device width (not the device length since it does not enter the specific power calculation). The extrapolation meets the power density target specified by the solicitation.

**Table 6: Projected Power From RPD**

| Property | Cells | Prototype | Car | Truck |
|---|---|---|---|---|
| **Length** | cm | 4 | 4 | 4 |
| **Width** | cm | 4 | 30 | 30 |
| **Frequency** | Hz | 5 | 5 | 5 |

| | | | | |
|---|---|---|---|---|
| **Force** | - | 15 N | 5 kN | 15 kN |
| **Power** | - | 10 mW | 191 W | 571 W |
| **Power density** | $mW/cm^2$ | 0.625 | 1594 | 4766 |
| **Power density** | $W/ft^2$ | 0.581 | 1483 | 4433 |

**Experimental data on the flex-tensional prototype performance.**

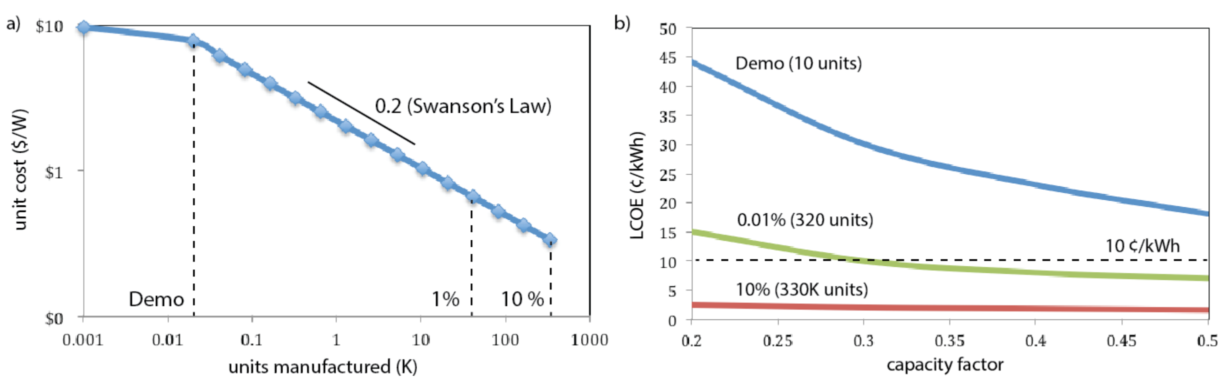
Source Pyro-E

## Cost Projection

Obtaining grid-parity requires moderate economies of scale to drive down the levelized cost of electricity (LCOE), a metric typically used to compare various generation technologies (Figure 18). The cost target, 10¢/kWh, can be met with a modest level of manufacturing scale and capacity factor. For the target projection assumes 320 RPD cells produced, and the capacity factor is associated with traffic volume, speed and the type of vehicles. Also, device lifetime and maintenance cost are expected to be 25 years and $0.02/kWh, respectively, at maturity with 330 thousand RPD cells produced. The maintenance cost is associated with replacing above-ground electronic components every eight years rather than the embedded device itself.

To meet the RPD equipment cost target of approximate CAPEX $10/Watt, the approach must reduce material cost by using a low-cost material chemistry and volume roll-to-roll manufacturing. The approach would take advantage economies of scale, akin to other solid-state devices such as photovoltaic cells. The latter follows Swanson's Law (Wikipedia, n.d.), which is an observation that the price of manufactured products tends to drop 20 percent for every doubling of cumulative shipped volume (Figure 18). The pronounced effect of roll-to-roll manufacturing for extruding piezoelectric films would allow the precipitous drop in equipment cost. The demonstration unit is expected to cost $9.68/W per device, excluding installation.

**Figure 18: Projected Economies of Scale**




**a) Log-log plot of unit cost projection using Swanson's law, including levels of cost reduction obtainable at 1% and 10% market penetration levels. b) LCOE vs. capacity factor anticipated for**

**the roadway harvesting technology and application. The equivalent length of roadway to demonstrate 10 ¢/kWh is 130 meters using 320 devices.**

Source Pyro-E

# CHAPTER 4: Technology/Knowledge/Market Transfer Activities

Potential clients representing demonstration sites across multiple US states were interviewed by the project team for feedback on technology, product, and commercial feasibility. These clients consisted of major toll roads and public works agencies who sought to lower the variable cost of maintenance and the environmental footprint of its operation. These discussions are leading to a project proposal that summarized the requirement for deploying the RPD technology on public highways. The specific client needs for implementing the RPD include the following added capabilities:

- Real-time measurement for vehicle direction, axle-count, speed, and weigh-in-motion.
- Interoperability in detection and identification data.
- Uninterrupted service during electrical blackouts.
- Temperature monitoring and compensation for environmental variabilities.
- Drop-in replacement for mechanical or fiber optic treadles.
- Reusability of hardware components during roadway resurfacing.
- CapEx/OpEx reduction and new revenue streams enabled by the new technology
- Backup power supply for toll plaza equipment.

RPDs combine the functionalities of data integration, analytics, and decision management into a self-powered sensor solution. The data network is designed to integrate with most IT environments such as supervisory control and data acquisition (SCADA), a leading industrial automation system. Once installed, the plug-and-play devices are fully autonomous and require low-maintenance. RPD data can integrate with those from other data streams as no proprietary software is used to meet client interoperability standards.

## Go-to-Market Activities

Pyro-E is preparing a go-to-market approach to RPDs that includes an explanation of how the knowledge gained from the project will be made available to the public, including the targeted market sector and potential outreach to end users, utilities, regulatory agencies, and others. The disclosed information will focus on the intended uses for and users of the project results, including published documents and patents. The primary approach for providing the pertinent project information is through the

Pyro-E website.

The intended purpose of the technology is to improve economics and reduce the environmental impact of toll road operation. With RPDs, backup power could reduce the burden of intermittent blackouts and the reliance on diesel backup generators. Other ancillary services such as vehicle counting, and pavement monitoring would also improve traffic flow and motorist safety. The latter represents a critical aspect of a pilot project beyond the operational, financial, and environmental benefits of RPD. All of the key benefits of the regenerative roadway are summarized in the pilot project description below.

## Client – Toll Road Concessions Company

Early commercial interest came from owners of private toll roads. The team began negotiations with an toll road concessions company to leverage the RPD technology as a self-powered road treadle – a subsurface device used to count the axles of overpassing vehicle for tolling – and provide a clean and scalable power source to tolling stations. As treadles, RPDs will collect traffic data to inform operational improvements. The high-fidelity traffic data acquired will measure vehicle speed, track width, and weigh-in-motion at 12-bit precision. The high-frequency data will be significantly more accurate than the current analog treadle through intelligent filtering algorithm. Field results will be verified against existing fiber-optic treadles to demonstrate greater accuracy, improved reliability, and remote diagnostic capabilities. To enhance safety, the chosen road section leads into a curving up ramp so that vehicles will be slowing down approaching the RPD array. Clearly label speed limits will be added to inform the road surface modification to limit safety hazards in all weather conditions.

The broader impact of this project is to improve the efficiency of US toll road infrastructure. In particular, the commercial impact to toll road clients is both measurable and verifiable. With a one-percent improvement in toll accuracy, the payback period on the capital expenditure would be less than 18 months at 46 percent internal rate of return. In recent years, the Federal Highway Administration has indicated a declining revenue from fuel tax due to more fuel-efficient vehicles. The Congressional Budget Office further projects that outlay from the Highway Trust Fund will exceed its reserves by a cumulative $119 billion (highway portion) by 2028. By improving tolling accuracy, the added revenue would help bridge the gap in the impending budget shortfall and mitigate additional excise taxes. By overcoming challenges in better vehicle identification, US roads and bridges would become more financially sustainable, operationally efficient, and economically competitive.

## Pilot Project Overview

A preliminary plan for an 18-month RPD pilot project is to complete a 30-ft test section at a toll plaza for test and evaluation (Figure 19). The project would be divided into two phases. The time to finish for the field deployment is 12 months and an additional six months will be needed for traffic data analytics and performance validation. To mitigate project and budget overrun, Pyro-E will provide at the beginning of the project the approach to identify, analyze, and respond to the perceived bottlenecks. This activity will include the initial identification of significant technical, resource and management issues that may impede progress, and, additionally, strategies to minimize impacts from those potential bottlenecks.

The budget proposal included provisions on fit, form, and function of the RPD array. Specifically, the pilot study will include:

1) Determining the performance baseline of existing tolling technology.
2) Developing and embedding low-fidelity supervised learning software for vehicle class identification.
3) Measuring and verifying accuracy against available tolling data in an operational environment.

**Figure 19: Regenerative Pavement Installation**


**Project overview for roadway recovery from toll plaza on-ramp with a toll concession company.**

This demonstration's deliverables included:

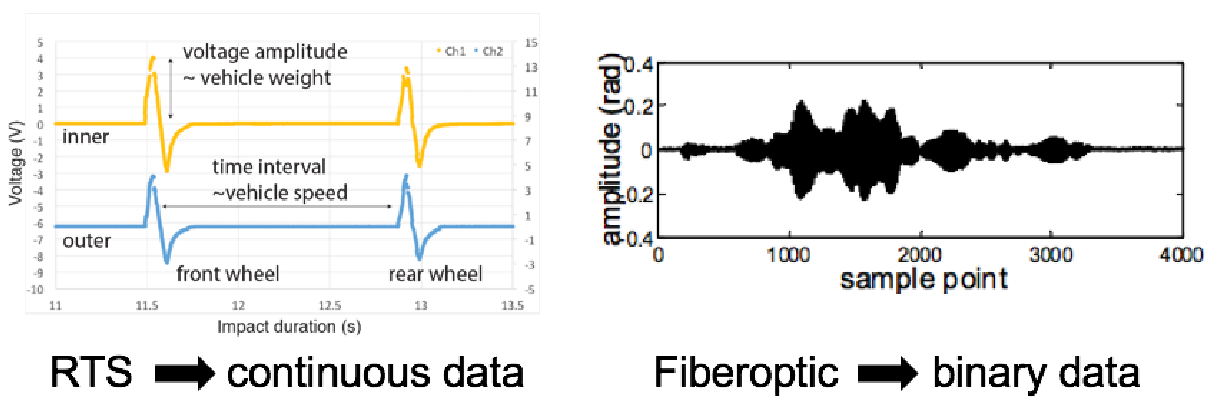
- Toll enforcement accuracy exceeding 90 Percent.
- Four times less maintenance than the existing treadle system.
- Two times longer service life based on the product having no moving parts and rated for billions of cycles.
- Reusability from road resurfacing.
- No traffic management system required.
- Self-powered through blackouts.

## Client Benefits

A self-contained, fully integrated in-ground sensor technology combining power, data-processing, and telemetry can greatly improve the visibility and operational efficiency for toll roads. By monitoring pavement vibration, in particular, RPD technology would provide data associated with pavement health, driving conditions, as well as vehicle identification. For treadle replacement, RPDs would immediately yield financial return on the mitigated cost and labor in maintaining legacy treadles while improving toll enforcement. The increased reliability, data fidelity, and life-cycle savings will be gauged throughout the pilot project in the following areas:

- Real-time measurement for vehicle direction, axle-count, speed, and weigh-in-motion (Figure 20).
- Interoperability in detection and identification data.
- Uninterrupted service during electrical blackouts.
- Temperature monitoring and compensation for environmental variabilities.
- Drop-in replacement for mechanical or fiber optic treadles.
- Reusability of hardware components during roadway resurfacing.
- CapEx/OpEx reduction and new revenue streams enabled by the new technology.
- Backup power supply for toll plaza equipment.

**Figure 20: Treadle Technology Comparison**




**Comparative advantages of RPD and fiber optic treadles for traffic counting and vehicle identification.**

Further, a set of performance metrics were developed as a memorandum of understanding for a future contract. Details are summarized in Table 7:

- Self-powered through blackouts through:
  - Reducing generator usage to yield a decreased carbon footprint.
  - Providing 10 hours of battery backup supply for the plaza.

- Toll enforcement accuracy exceeding 90 percent through:
    - Four times less maintenance than the existing treadle system.
    - Two times longer service life based on the product having no moving parts and rated for billions of cycles.
- Vendor provides full-service warranty up to six years.
- Reusability from road resurfacing.
- Operational without traffic management system oversight.

**Table 7: Summary of RPD Fit, Form, and Function for an Interstate Toll Lane**

| Product feature | Technical advantage | Economic benefits |
| --- | --- | --- |
| **Self-power** | Off-grid operation against blackouts | Cost, safety, and sustained operation against inclement weather |
| **Autonomous** | Low maintenance; no traffic management systems required | Low operation cost without management overhead |
| **Reusability** | Recoverable during roadway resurfacing | Return on investment, non-disruptive to operation |
| **Vehicle counting** | Improved accuracy over fiberoptic systems | Value-add services without adding cost or overhead |
| **Service warranty** | Product replacement during service contract | Risk of adoption |

**Return on Investment:**

The RPD is a more robust solution for toll enforcement than fiber optic in-road sensors. The offering is designed specifically for roadways to accommodate the impact and vibrations created by heavy vehicles. It installs below the surface in a manner that is protected from roadwork, service equipment, and ground snow/debris. The trial project aims to validate vendor claims on performance addressing speed, accuracy, and reliability. The potential benefits offered to private toll roads and the success metrics of the project include:

- Two times longer service life.
- Four times less frequent maintenance.
- 50 percent improved accuracy.
- Ease of installation as a drop-in replacement.
- Reusability from road resurfacing.

- A compact solution (no traffic management system required in toll plaza tunnels).

The system is self-powered through blackouts thus reducing the need and existing loads experienced on diesel-powered generators. By reducing generator use, associated fuel and maintenance costs are also reduced, and in turn its carbon footprint. Other advantages include:

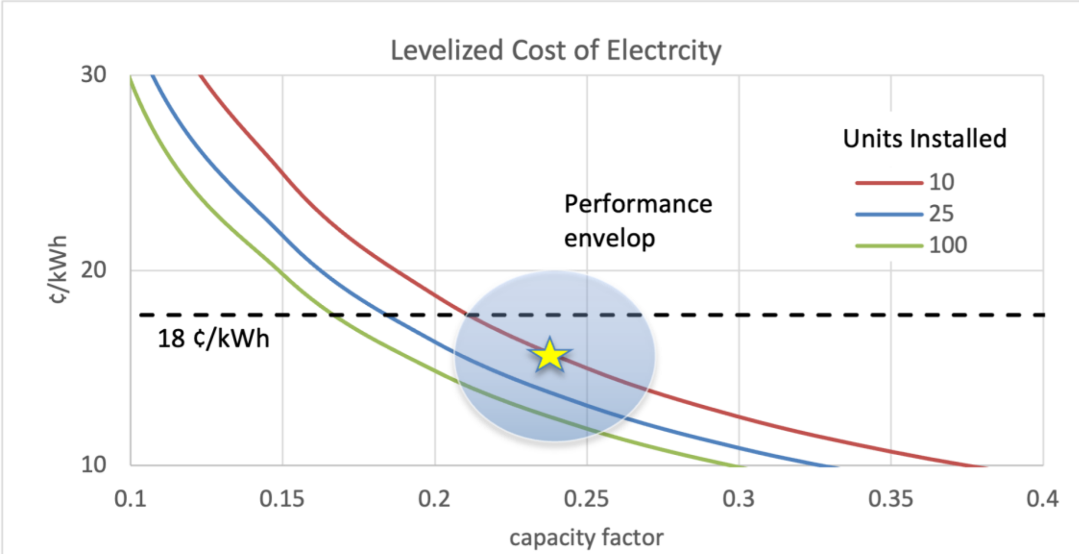
- 1-2 percent improvement in vehicle identification at toll.
- Zero operating cost with product and service warranty.
- Reusability from road resurfacing for life of product.
- Simple data interoperability to alleviate toll management fees.

Given the three sizes of generators used at toll plazas at this time, the toll road currently is spending $15,000, $21,600, and $30,000 per year for leasing for each plaza. For 12 years, given the life of the RPDs, that is $360,000 (based on 50KW) just for backup power supply.

An initial cost analysis for the RPD array is shown in Figure 21. The calculation produces levelized cost of electricity for the renewable generation. For grid feed-in, the cost must compete with grid electricity (local rate: 18¢/kWh, USD). Given the expected 2,400 truck-axles per day, the analysis shows that the anticipated cost of electricity provided by 10 RPD cells will be 16¢/kWh (yellow star in Figure 21). The calculation assumed a 28 percent capacity factor to peak traffic at 8,640 truck-axles per day. The financial analysis does not include non-recurring engineering costs.

To improve economics, the levelized cost of electricity (LCOE) may be reduced either through having additional truck/passenger vehicles or through economies of scale. The latter accounts for bulk savings on the purchase of key RPD components from material suppliers. At an estimated installed size of 100 RPD units, the anticipated LCOE would be 13 ¢/kWh. Further LCOE reduction is achievable at scale through streamlined manufacturing.

**Figure 21: RPD Levelized Cost of Electricity**




**Projected electricity cost of RPDs compared to grid power with different system installations. Assumptions include lifetime (20 years), discount rate (3%), and fixed O&M (100/kW/yr). Blue shading represents the achievable LCOE with 100 RPDs installed. Yellow star represents the performance target of the project. Dash line represents the average local electricity rate in USD.**

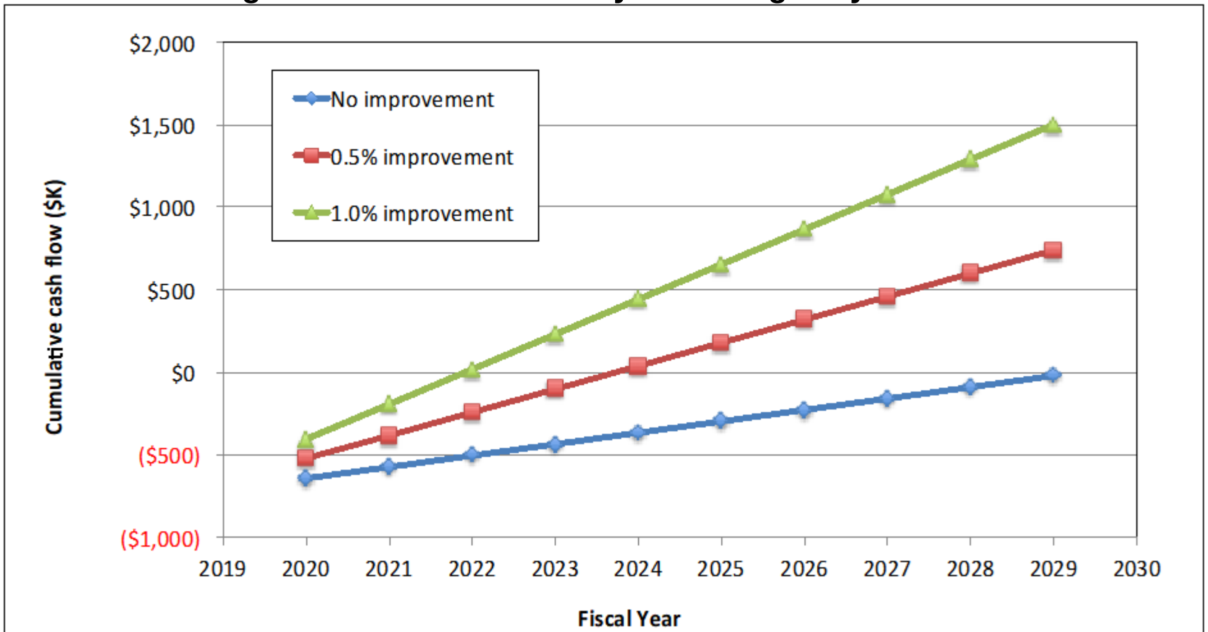
Source: https://www.globalpetrolprices.com/.

In addition to the LCOE, a cash flow analysis was done to determine the payback on the upfront capital investment (Table 8). The information allowed key decision makers to determine the risk-to-reward of adoption of a clean generation technology. First, the various cash flow tranches are determined based on the expected efficiency improvements, including savings generated from avoided fossil fuel use. Second, the cumulative cashflow underwent a sensitivity analysis given the variabilities of the expected improvement. Namely, variations of one-half and one-percent improvement in vehicle detection were added to the analysis to correlate with the changes in the payback period. The results found that the cashflow from power service alone is $68,000 for the installation and 10-year payback. With improved vehicle detection, the associated cash flow (power and sensing) the payback is three years. It suggests that the RPD technology could justify the capital expenditure without providing the added ancillary services (Figure 22).

**Table 8: RPD Cash Flow Analysis**

| | | | |
|---|---|---|---|
| Savings generated (from avoided costs) | $/year | $ | 328,174 |
| Avoided treadle replacement | $/year | $ | 30,000 |
| Reduced toll management fee | $/year | $ | 30,000 |
| Mitigated generator fuel & maintenance | $/year | $ | 8,000 |
| Improved detection | $/year | $ | 238,174 |

## Figure 22: Cash Flow Analysis for Highway Toll Roads




| Overall vehicle detection | Cash flow | Payback | IRR (10-yr) |
|---|---|---|---|
| 0.0% improvement | $68,000 | 10 yrs | -5% |
| 0.5% improvement | $119,087 | 5 yrs | 17% |
| 1% improvement | $238,174 | 3 yrs | 41% |

**Cash flow analysis of RPD technology as a dual purpose backup generator and tolling technology.**

# CHAPTER 5: Conclusions/Recommendations

This project successfully demonstrated the use of piezoelectric technology for harvesting energy from roadway deflections and vibrations. The demonstrator pilot achieved a higher technology readiness level (TRL) for a commercial product. Initially, the developmental steps in concept formulation and proof-of-concept were established. Both indicated successful results for manufacturing a scalable design laying the foundation for an initial prototype. Likewise, the custom-developed power management chipset also provided the basis for fine-tuning parameters for dynamic impedance matching and maximum power tracking. With prototype validation, the objectives of this project were achieved in going from a TRL 3 to:

- TRL 4 – Component validation in a laboratory environment.
- TRL 5 – Component validation in a relevant environment.

The unique technical merits of the technology include:

2. High efficiency – the use of ultra-thin films allows for greater electrical energy conversion for a given material strain.
3. High power – the use of flex-tensional actuation as a force multiplier improves power output.
4. Off-resonant mode – low-frequency operation is optimized for improved load matching and peak conversion efficiency.
5. Uniform applied stress – the flex-tensional frame helps to distribute the overburden stress across hundreds of film layers and multiple stacks.

Future engineering work includes advancements from additional technology and business milestones. Both developments will focus on iterating through the development cycles of design, build, and test to reach commercialization. In the next 18 months, the engineering milestones are to:

- Optimize system architecture for harvesting, conditioning, and storing electrical power through iterative testing.
- Verify device lifetime via highly accelerated testing.
- Plan and implement low-volume manufacturing.
- Verify in-situ performance for peak shaving and load matching.

The business milestones aim to bridge the gap between technology and solution that can bring value to customers. In the next 18 months, the business milestones are to:

- Verify customer ROI with initial technology demonstration.

- Verify third-party performance using performance and cost metrics (per solicitation).
- Determine and demonstrate product specifications to meet customer needs.
- Determine and demonstrate scalable manufacturing and robust processes.

The market potential for RPDs is validated in go-to-market activities. Namely, the measured performance metrics would yield techno-economic metrics for RPD technology as a form of renewable energy. Specifically, the levelized cost of electricity (LCOE), which determines the life cycle cost of any power provisioning technology, considers the rated power, service lifetime, maintenance interval, performance degradation, and even the usage rate. Given the promising technology development, the next milestone is to secure commercial interest from the public and private sectors. For the next phase of work, the project team will seek partnerships with domestic toll road concession companies and public transportation agencies for example California State Department of Transportation Agency (Caltrans) and San Francisco Municipal Transportation Agency (SFMTA) for product installation and sales. The effort seeks to achieve the following business milestones:

- Demonstrate potential net savings to utility ratepayers and transportation authorities.
- Optimize performance and cost benchmarks with continued product iterations.
- Qualify technology as CEC renewable portfolio standard energy resource based on preliminary validation under laboratory and relevant environments.

Early discussions with vendors confer the need to resolve the adaption risk of new technology. In response, the key to overcoming end-user benefits includes:

- Provide RPD as a direct drop-in replacement without needing additional hours for installation such as for sealing and wiring.
- Use of off-the-shelf components rated for billions of stress fatigue cycles.
- The vendor contributes 20 percent cost share to the project budget.
- The vendor offers a replacement warranty and service contract at no cost for the life of the product.
- The service interval for an RPD array at every 48 months and is included in the warranty of the product.

## Future Developments

The next phase of the project phases will establish low-rate initial production (LRIP) of the RPD technology to reach manufacturing readiness level (MRL) 8. If successful, Pyro-E would establish the first U.S.-based advanced manufacturing of vibrational energy harvesting devices. Its benefits will deliver significant cost-reduction, improved quality, and at a greater capacity from the current prototype. Achieving LRIP capability will help meet the early market demand for RPD in smart highway projects, where a set of RPD arrays could harvest parasitic energy from pavement deflections and vibrations for electricity generation. At scale, the goal is to enable greater use of untapped energy sources for decarbonization, electric rate-reduction, and revitalization of transportation infrastructure. The specific 3-year objectives are to:

- Establish pilot-line capabilities for RPD components and assembly at LRIP.
- Improve yield for piezoelectric material manufacturing by 30 percent.
- Obtain a production rate of 2,000 RPD cells per annum.
- Obtain RPD cell cost-reduction by 600-percent compared to the current prototype.
- Provide RPD technology for deployment in an operational environment.

**Material Innovation**

Over the past decade, significant investments have been made in energy harvesting materials and devices for generating electricity from ambient vibrations. Compared to electromagnets, the advantage of solid-state generation is redundancy; electricity is produced via a plurality of individual power units. Also, the strain-amplification is material agnostic. The flexor accepts any family of piezo-electric and piezo-magnetic origin, including crystalline, polycrystalline, and composite types. In this project, the chosen piezo-magnetic material excels in charge density, ease of handling, and mechanical fatigue strength versus their counterparts (piezo-ceramics). The material development will focus on improving the manufacturing yield and creating a cost-effective method of material production.

The potential need for advanced US manufacturing of piezoelectric ceramics is immense. Similar to solar photovoltaics, where thin-film crystalline technologies prevailed in performance, crystalline piezoelectric materials also hold promise with up to 100-fold improvements in energy density. Such advancement would foster new markets such as powering personal electronics, wearables, and the internet-of-things. Positively, the electromechanical conversion efficiency is about 45 percent for piezoelectricity. Likewise, new material compositions will continue to drive cost reduction at scale. Some candidate materials and suppliers include:

- Barium zirconate titanate, BZT (1700), Hechi Industry, Inc.
- Barium titanate oxide, BTO (1420), Nexceris, Inc. (formerly Nextech Materials).
- Potassium sodium niobate, KNN (1570), FerroPerm, Inc.

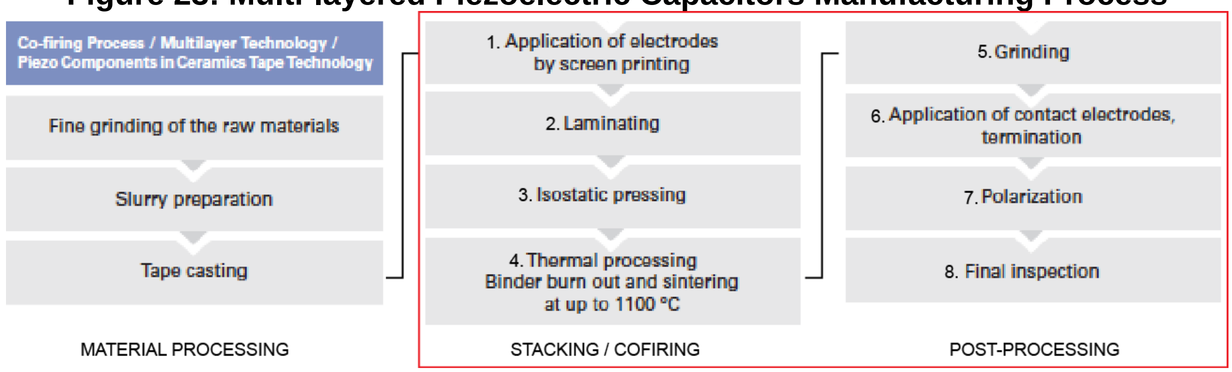
The IP strategy is to develop proprietary software that builds intelligence onto the backbone of the device network. It would enable devices to communicate and synchronize for collective action by sensing and adjusting to road conditions. This software would include these capabilities:

- Record power signal for data analysis, device control and traffic prediction.
- Analyze and transmit data for vehicle types, axle-count, weight, and speed.
- Toggle between transduction and actuation modes during free flow/congested traffic.
- Build interoperability and compliance that meets Intelligent Transportation Standards (Vehicle-to-Infrastructure Deployment Guidance, n.d.).

### Multi-layered Piezoelectric Capacitors (MLPCs) Manufacturing

Currently, no US industrial base exists for the MLPC stacks used in the RPD array. The closest analog is the production of millions of multilayer ceramic capacitors (MLCCs) each year with fully automated processes. MLCC contract manufacturers, however, typically work with a minimum ordered quantity greater than 10,000. To attain lower costs, the stop-gap strategy for MLPCs is therefore to use in-house manufacturing and leverage existing MLCC processes, equipment, and tooling. The fabrication steps for MLPCs are summarized and a detailed outline of the pilot line fabrication process flow is shown in Figure 23.

**Figure 23: Multi-layered Piezoelectric Capacitors Manufacturing Process**




**Standard industrial process for MLPC stack manufacturing via piezoelectric material stacking/cofiring/post-processing (red box).**

The key justifications for LRIP are to reduce lead time, improve customization, and tune the manufacturing process for performance and cost optimization. These will be enabled by having a vertically integrated manufacturing process from raw material to end product. Compared to the current prototype, LRIP will yield almost a six-fold, or 578 percent, cost savings in the cost of goods sold (COGS). By climbing the supply chain, it is possible to obtain further savings to accomplish grid-scale energy harvesting at parity. Namely, economies of scale, of which brought lithium-ion batteries to prominence, may foster a new energy industry through vibrational energy harvesting (through MLCC manufacturing methods).

# CHAPTER 6: Benefits to Ratepayers

## Projected Benefits

Given the proof-of-concept, the future promise is the benefit of having smart roadways that can offset the cost of electricity. In dense traffic (more than 500 vehicles/hour), RPD technology can provide cost-effective power without GHG emissions (GHG emissions would potentially be coming from the passing vehicles and not the RPD technology itself). The current design study calls for at least 2,000 RPDs to be installed per every lane-kilometer of the roadway for performance benchmark. At this scale, the equipment cost represents one-fifth the cost of road paving and less than 1 percent cost of highway expansion. The anticipated electricity and costs are shown in Table 9. Renewable energy benefits at 10 percent penetration can be quantified as:

- About $260 per household in annual energy savings.
- About 2.36 GWh/yr of peak load reduction.
- About $178K/km per-lane in capital cost (≈20% of road paving)
- 217 kWh/hr of electricity produced per km-lane of traffic (About 1500 homes per km-lane).

The stated energy generation rate is verified by prior feasibility studies (Edery - Azulay) that showed 200-300 kWh/hr per km-lane. At 10 percent penetration of California highways, the potential socio-economic benefits include:

- Electric rate-reduction of approximately 80 percent from the central grid (≈0.02¢/kWh).
- About 4.2M average homes serviceable with renewable electricity.
- About 1.2 kton/yr $CO_2$ emissions displaced from thermal plants.
- About 16.8 Mgal/yr of fresh water savings alleviated from thermal plants.
- About $1 billion/yr in savings through improved mobility, motorist safety and traffic decongestion.

**Table 9: Ratepayer Benefits at Scale**

| | Initial production | 1% penetration | 10% penetration |
|---|---|---|---|
| **Cost** | | | |
| Equipment: | $3.37/W | $0.15/W | $0.06/W |
| Levelized electricity: | $0.133/kWh | $0.033/kWh | $0.021/kWh |
| **Benefits** | | | |

| | | | |
|---|---|---|---|
| Displaced capacity:<br>Displaced electricity:<br>Displaced $CO_2$:<br>Displaced water: | -<br>-<br>-<br>- | 86 MW<br>0.236 GWh/yr<br>0.35 Mton/yr<br>5.9 Mgal/yr | 862 MW<br>2.36 GWh/yr<br>3.5 Mton/yr<br>59 Mgal/yr |
| **Total Savings:**<br>Per CA household | - | ~$1B/yr<br>$103/yr | ~$2B/yr<br>$260/yr |

**Cost-benefit summary of the roadway device. Benefits include savings obtained through avoided traffic accidents and motorist deaths.**

The state's energy goals will be met within the following framework: 1) Assembly Bill 32 (Nunez, Chapter 488, Statutes of 2006) mandates a statewide reduction in $CO_2$ emissions of 6.7 MMTon/yr from combined heat and power resources (The Electric Program Investment Charge: Triennial Investment Plan 2015-2017, 2017); 2) Renewable Portfolio Standards (Senate Bill 100 [De Leon, Chapter 312, Statutes of 2018]), which set a target for all electricity retail sellers to serve at least 50% of electricity from renewable sources by 2026 and 60% by 2030; and 3) Governor's Clean Energy Jobs Plan, which calls for 12,000 MW of localized energy generation. In response, the potential for roadway energy recovery accounts for:

- About 862 MW of localized capacity in urban areas (7 percent of the Governor's mandate);
- About 2.36 GWh/yr of renewable electricity (15 percent of California utility solar generation, 2015);
- About 0.65 MMTon of displaced $CO_2$ from electricity generation (10 percent of AB32 goal).

Furthermore, viable renewable energy technology requires other stakeholder benefits to incentivize broad adoption. When compared to other civil infrastructure projects, the pronounced benefits of RPDs include:

- *Public health improvement* from reduced $CO_2$ and $NO_x$ emissions by offsetting power generation from fossil fuels ($80B/yr (Federal Highway Cost Allocation Study., 2000).
- *Capital efficient solution* with 10X performance and 1 percent cost of roadway expansion (when comparing road resurfacing to lave expansion).
- *Accelerated timetable* with direct 'drop-in' retrofit into existing treadle well when retrofitting existing road stock during pavement resurfacing.
- *Lower operational cost* with self-powered, maintenance-free operation.

- *Energy sustainability* by capturing lost energy from road pavement without adversely impact normal driving (with which accounts less than 1 percent of rolling resistance).
- *Taxpayer appeal* for having an equitable solution to infrastructure upgrades.

The total market size for roadway energy in California assumes 10 percent of the US total when state information is not available – which is the ratio of California to US drivers. For the addressable market, 10 percent of California roads (km-lanes) are assumed to have, on average, over 50 percent of peak traffic flow. Other assumptions include:

- LCOE basis: 50 percent capacity factor, 15-year life, and $0.08/W/yr fixed O&M costs.
- Addressable California market: 53,000 million km-lanes of busy roads (10 percent California total) (Caltrans, 2020).
- California registered drivers: 24 million (12 percent US total).
- 277 gram/kWh of $CO_2$ from the *displaced* grid electricity, accounting for T&D loss.
- Annual highway congestion cost: Los Angeles ~$13M, San Francisco ~$3M.
- Annual California traffic fatalities ( Cost of Auto Crashes & Statistics, 2013): 3,200 (10 percent US total).
- US average cost of traffic fatalities: $3,104,738 per fatality (2014).
- US average cost of highway asphalt paving: $940K/km per lane.
- California’s average home electricity use (Household Energy Use in California, 2019): 583 kWh/month or 1.60 kWh/hr.
- Total California traffic delay and cost: 5 million hours and $16.79/hour.
- The Socio-economic cost of carbon (Estimated social cost of climate change not accurate, Stanford scientists say, 2015): $220/metric ton.

## Projected Cost

The improved performance and manufacturability will significantly reduce the per unit cost of RPDs. At $5.3/W, the projected cost is 10-times cheaper than current practice. The calculation assumes an excitation frequency of 32 Hz, which corresponds to highway traffic speeds of 65 miles per hour and normal vehicle spacing of 22 vehicles per mile. For the installation, the capital cost is approximately $400,000 per km-lane. This figure is on par with the raw material cost for paving (The New Paving Realities: The Impact of Asphalt Cost Escalator Clauses on State Finances , 2012).

For energy generation, the LCOE is calculated assuming a device life of 25 years. The average life of ancillary components (power electronics) is eight years and those can be installed above ground. Scheduled servicing would require an annual cost of $0.020/kW-yr (on-par with solar PV). The expected *initial* product LCOE is $0.13/kWh.

At scale, set at 10 percent of California roadways, that figure is expected to reach about $0.02/kWh. These cost estimates assume peak traffic of 2,000 vehicles per hour and a 50 percent capacity factor (half of the time at peak traffic). This cost reduction is realized through improved manufacturing automation, permitting standardization, and renewable portfolio standards. The raw material supply chain is robust without the need for precious or toxic metals.

## Economics and Buildability

The economics of retrofitting roadways with RPDs is favorable compared to adding new roadways (for example lane expansion) (Figure 24). It was found to be extremely cost-effective if the devices were installed during road paving. No procedural change or additional installation costs were assessed since a portion of asphalt materials was obviated by the device footprint. The simple installations were enabled by the 1-inch-thick RPD, which is less than the typical asphalt layer of 3 to 4-inches.

Moreover, the concept is highly scalable for cities where the predominant mode of travel is driving. No new land is needed for construction or risky mobility concepts to be adopted. Only existing roadways are needed for retrofit by adding interconnectivity and intelligence to the aging infrastructure. Compared to the road widening of the I-405, the difference in cost is staggering. The new 4-year, $1.7B construction project will take 10-times longer than retrofitting roads with RPDs. The latter can be done during asphalt resurfacing so that normally scheduled maintenance can be completed concurrently.

**Figure 24: Case study of Highway Projects**

| | New Lanes | Smart Lanes |
|---|---|---|
| Cost per mile: | $100M | $1M |
| Project duration: | 4 years | 3 months |
| Capacity: | 1000 cars/hr | 23,000 cars/hr |
| Commute time: | 2.5 hours | 18 minutes |

**Cost comparison between roadway expansion and RPD retrofit for improving a 13-mile stretch of Interstate 405 linking Costa Mesa and Long Beach**

## Other Benefits

Unlike standalone mobile apps, hardware solutions can make infrastructure “smart” by combining real-time data with signaling and enforcement. Data sharing on pedestrian and motor vehicle movements would create new opportunities to improve safety and mobility. New light projection technologies could enable holographic displays as dynamic signage. Real-time information can forewarn drivers of emergencies and enforce dynamic speed limits. Overall, the technology could create a new smart infrastructure based on:

- Unimpeded signaling for pedestrians and motorists at busy intersections.
- Greater coordination between vehicles to mitigate stop-and-go traffic.
- Broader Interconnectivity for data-sharing and data-as-a-service platforms.

To relieve congestion, RPDs would form a network of dynamic "speed bumps" that can provide haptic feedback to the drivers. The self-adjustment is made through the detection of lane-specific speed and volume information. During peak traffic, peak throughput can be maintained at the ideal speed of roughly 40 mph. Even with unexpected accidents, active road feedback could slow the approaching traffic *miles* ahead to prevent a choke point from occurring. These and other key advantages of the technology include:

- Dynamic pavement can diffuse congestion and adapt to real-time traffic conditions.
- Direct visual and haptic feedback to motorists for advance traffic warning.
- Effective safety countermeasures for reducing vehicle speeds en masse.
- Intelligent data analyzer for lane-specific information on vehicle type, weight, and speed.

Taxpayers would benefit from reducing traffic congestion, improving safety, and mitigating carbon pollution. With 10 percent market penetration to the busiest corridors, the economic benefits, instead of spending billions on roadway expansion (Gropman, 2015), would include:

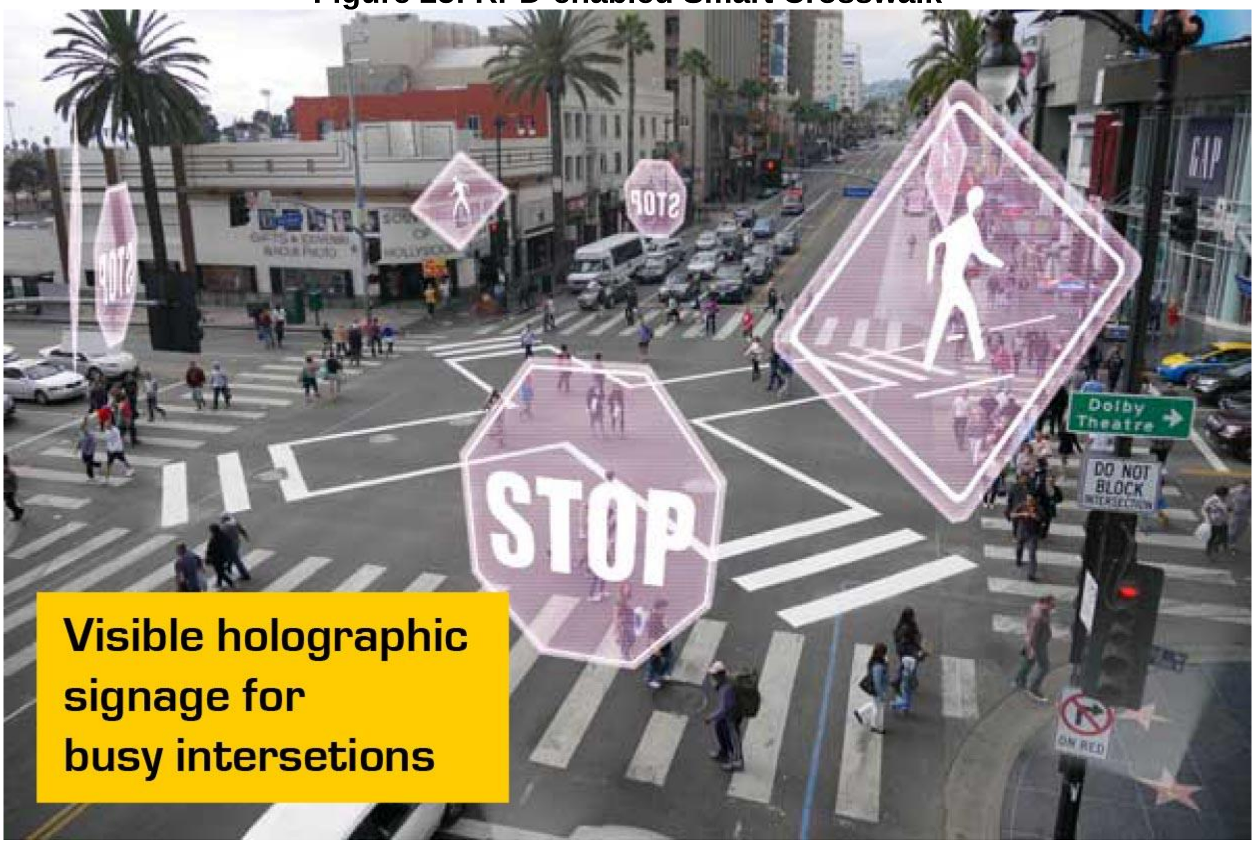
- ~$1,500/yr saving per driver through alleviated congestion in San Francisco and Los Angeles (California Commute: State's 5 worst bottlenecks are in L.A., Orange counties, 2015).
- ~$80 million savings in recovered economic productivity.
- ~$990 million savings in averted car crash fatalities (assuming 10 percent averted).
- ~$1 billion savings in averted collision damage and bodily injury claims (10 percent averted).

## Adaptability

Greater than 80 percent of traffic-related accidents occur during rush hour. This makes sense because roads and signage with outdated designs cannot cope with overcrowded intersections or heavy traffic. New research, for example, points to creating narrower lanes and tighter curb radii for improving driver attentiveness and reducing turning speeds. Despite the benefits of having permanent fixtures, further improvements can be made with dynamic countermeasures such as RPDs. These areas include:

- Pedestrian crossings without traffic lights (Figure 25).
- Highways that face high volume and high-speed traffic.
- Parking lots and shopping centers are predominated by irregular walkways and roads.

**Figure 25: RPD-enabled Smart Crosswalk**




**Dynamic signage powered by RPDs for pedestrian and vehicle coordination.**

All of these cases are absent traffic lights and, as a result, are the most dangerous. At pedestrian crossings, for instance, safety can be much improved with a pavement that can signal drivers to slow down. Beyond sensing, an RPD-powered Smart Crosswalk can dynamically alter the road surface to signal drivers as they approach an intersection. This would drastically reduce the chances of pedestrian injury when visibility is impaired by other vehicles or in bad weather.

## Pedestrian Safety

In city streets, passive traffic management techniques such as road dieting – narrowing lanes to deter speeding – have shown proven results at improving pedestrian safety. By far, the leading factors are *speeding* and *distracted driving*. If both can be mitigated, then the total number and severity of pedestrian injuries would fall dramatically. By 2050, cities could retrofit busy road intersections with RPDs that physically signal drivers to slow down when a pedestrian is detected at street crossing.

Also, an RPD deflecting by 5-mm when stepped on could produce up to 8 watts of energy (Figure 26). Enough RPDs and enough footsteps can create enough energy to be stored in batteries or to help power streetlights and other electrical items. Each RPD also could include a unique proprietary wireless communications technology that uses only 1 percent of its power to transmit data about the number of footfalls and energy generated. This means city officials could see how many people are passing through each area. At an intersection, the RPDs could signal upcoming traffic automatically for safe passing.

By averting only 10 percent of pedestrian deaths, a city such as Los Angeles could save $100M/yr (~330 deaths in 2014 at an average cost of ~$3 million each) (USA Today 2014; US DOT Bureau of Transportation Studies 2017). The total cost of retrofitting 817 of the most dangerous intersections that represent 35 percent of all incidents would be ~$100 million.

**Figure 26: RPD-enabled Smart Sidewalk**


**RPD use for pedestrian detection and warning system.**

Source: Pyro-E

## Advance Traffic Warning

Dynamic signage would provide advance traffic warning to drivers unaware of conditions ahead. Rather than relying on poor visibility, information can now travel upstream to the driver. This creates vehicle-to-vehicle coordination that improves reaction time and allows for early evasive maneuvers if needed. The urgency of the information can be reinforced by physical feedback provided by the pavement device.

The hovering display is possible with multi-angle projection from adjacent devices. Based on laser interferometry, the technology was developed recently and will be available commercially on television sets. The light rays focus on a single plane so as to be visible to the approaching driver. The so-called "holographic effect" creates an illusion of the physical signage, which can appear to move or rotate to gain the attention of the driver. The signage would appear semi-transparent so that it does not adversely affect visibility. Different information may be displayed depending on the vehicle speed and spacing, which can include the following information:

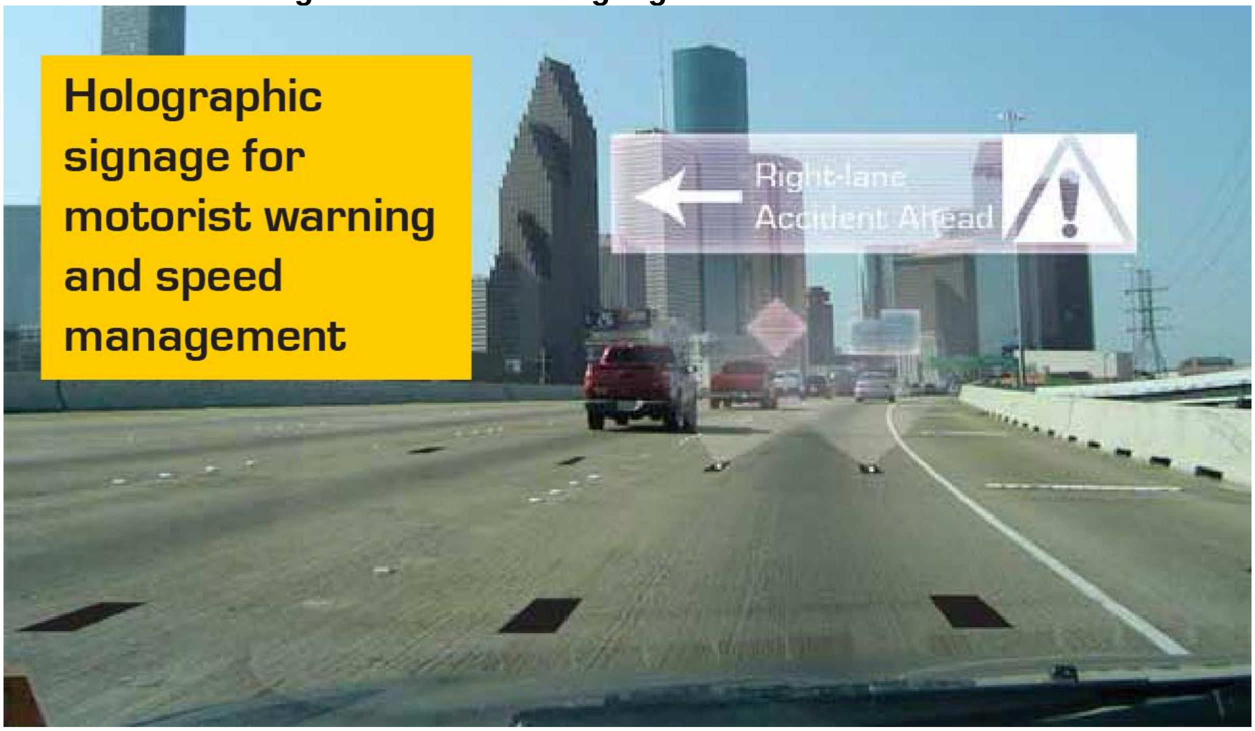
- Construction warning
- Lane closure warning
- Speed limit
- Alternate route
- Accident avoidance

By averting 10 percent of motorist fatalities, a city similar to Los Angeles can save $300M/yr from avoiding 10 percent of the ~1,100 traffic fatalities that occurred 2014. These estimates assume no cost distinction between pedestrian and traffic accidents, which could be grossly different

## Infrastructure-to-Vehicle (I2V) Communication

Beyond city streets, dynamic countermeasures are applicable to freeways during both peak and off-peak traffic (Figure 27). Take highway congestion, for example, RPDs would stay level to road surfaces when traffic volume is low. This accounts for most of the hours in a day when normal driving conditions are expected. During rush hour, in contrast, road surfaces could adapt to the increased volume and respond to deter speeding and alleviate traffic. As before, such direct road feedback would not be adversely impacted by other vehicles or bad weather.

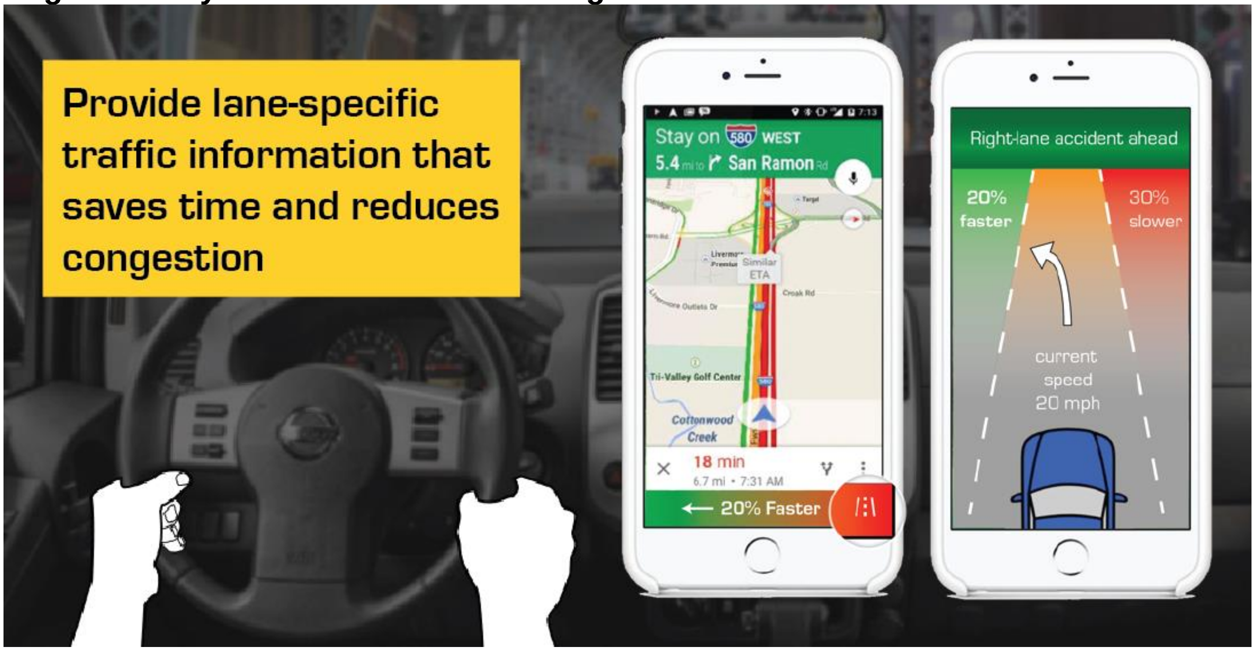
**Figure 27: On-road Signage for Real-time Alerts**




**Dynamic Light Display (DLD) for roadway signage and advance warning**

Cameras are inaccurate, maintenance-heavy, and expensive to install. GPS sensors that locate mobile devices are slow and inaccurate to the dimension of lane spacing. These shortcomings limit the applicability of mobile apps to provide low-latency, lane-specific information to drivers. If RPDs were available and integrated with traffic map and navigation apps, traffic speed for express and normal lanes could be provided (Figure 28). Commute times would be more accurately predicted. Emergencies of lane-closure and accidents could be made in advance to drivers. These improvements make better use of roads, increase traffic coordination for cars with and without drivers, and can uniquely identify vehicles for congestion tolling or other price-signal schemes.

**Figure 28: Dynamic Driver Alerts using Vehicle-To-Infrastructure communication**




**Integration with traffic map and navigation apps**

## Virtual Parking Assistance

Traffic experts estimate that 19 to 34 percent of cars in urban streets are looking for parking, causing driver distraction and creating roadway congestion. Luckily, new research points out that parking in US metro areas is, on average, over supplied by 65 percent. A study of mixed-use districts across US cities found "parking was universally oversupplied." Those studied included six cities in New England and California.

RPDs can detect and communicate empty city spaces to the cloud. Drivers can then use mobile devices to locate and reserve public spaces. With the rise of self-driving taxis, an empty parking spot can share its location to those vehicles not in service, such as when waiting for customers or having mechanical issues. Cutting time and frustration for drivers who are looking for parking can reduce volume, alleviate congestion, reducing emissions, and improve pedestrian safety.

# GLOSSARY AND LIST OF ACRONYMS

| Term | Definition |
|---|---|
| $k_s$ | Stiffness or spring constant of the applied spring load |
| $k_{pzt}$ | Stiffness or spring constant of the piezo-actuator |
| $d_0$ | Pre-load compressive deflection of the piezo-stack |
| $d_{pzt}$ | Displacement produced by the piezo-actuator under load and applied electric field |
| $d_{pzt,¥}$ | Maximum displacement produced by the piezo-stack under no load |
| $F_{pzt}$ | Force capacity produced by the piezo-actuator exerted against the frame |
| $F_{pzt,¥}$ | Maximum force capacity produced by the piezo-actuator |
| CAPEX | Capital expenditure |
| Caltrans | California Department of Transportation |
| COTS | Commercial off the shelf |
| LCOE | Levelized Cost of Electricity |
| LRIP | Low-rate initial production |
| MLPC | Multilayered piezoceramic |
| MHK | Marine hydrokinetic |
| RPD | Regenerative Pavement Device |
| PMC | Power management circuit |
| PWM | Pulse width modulation |
| SFMTA | San Francisco Municipal Transportation Agency |
| TRL | Technology Readiness Level |
| USD | United States dollar |

| Constant | Description | Units | Value |
|---|---|---|---|
| $Ln_{CA}$ | Total CA lane-miles, 2013 | lane-miles | 394,787 [1] |
| $E_{HOME}$ | Average home energy use, CA | kWh/month | 583.3 [1] |
| $N_{HH}$ | Total households, CA | M | 11.5 [2] |
| $CO2_{CC}$ | $CO_2$ emission rate of gas equipment | metric ton/MWh | 0.000382 [3] |
| $C_{CO2}$ | Cost of CO2 emission | $/ton | 220 [4] |
| $C_{RE}$ | Avoidable retail rate of grid electricity, CA | $/kWh | 0.1737 [5] |
| $L_{T\&D}$ | Grid transmission and distribution loss rate | % | 7.8% [5] |
| W | Freshwater alleviated at thermal plants (http://www.nrel.gov/docs/fy04osti/33905.pdf) | gal/kWh | 0.47 [6] |
| | Total CA automobile crash | - | 600,000 [7] |
| | Avg. cost of accident, property | $ | 3,231 [7] |
| | Avg. cost of accident, body | $ | 13,440 [7] |
| $C_{MED}$ | Total cost of accidents, CA | $M | 10,003 [7] |
| $C_{EXP}$ | Cost of construction, I-405 | $M/mile/lane | 50 [8] |

[1] https://www.eia.gov/consumption/residential/reports/2009/state_briefs/pdf/ca.pdf

[2] http://www.census-charts.com/HF/California.html

[3] "Fuel and Carbon Dioxide Emissions Savings Calculation Methodology for Combined Heat and Power Systems." US EPA, CCHP Partnership, Feb 2015 (Page 5).

[4] http://news.stanford.edu/2015/01/12/emissions-social-costs-011215/

[5] CEC suggested default

[6] http://www.nrel.gov/docs/fy04osti/33905.pdf

[7] http://www.rmiia.org/auto/traffic_safety/Cost_of_crashes.asp

[8] http://www.laweekly.com/news/11-billion-and-five-years-later-the-405-congestion-relief-project-is-a-fail-5415772

# REFERENCES


*Cost of Auto Crashes & Statistics*. (2013). (RMIIA) Retrieved from Rocky Mountain Insurance Information Association: http://www.rmiia.org/auto/traffic_safety/Cost_of_crashes.asp

Aleecia Gutierrez, V. L., Gutierrez, A., Lew, V., Ng, A., Spiegel, L., & Stokes, E. (2017, Apr 17). *The Electric Program Investment Charge: Triennial Investment Plan 2015-2017*. Retrieved from http://www.energy.ca.gov/2014publications/CEC-500-2014-038/CEC-500-2014-038-CMF.pdf

Baxandall, P. (2009, Spring). *Private Roads, Public Costs: The Facts About Toll Road Privatization and How to Protect the Public.* Frontier Group.

Brown, R. (n.d.). Power Generation Using Piezo Film.

*Build America Investment Summit*. (n.d.). Retrieved from https://www.transportation.gov/fastlane/build-america-investment-summit

*California Census Data: Households & Families*. (2000). (US Census Bureau) Retrieved from Census Charts: https://www.census-charts.com/HF/California.html

*California Commute: State's 5 worst bottlenecks are in L.A., Orange counties*. (2015, Feburary 10). Retrieved from Los Angeles Times: http://www.latimes.com/local/california/la-me-0210-california-commute-20150210-story.html

Caltrans. (2020, Dec). *Statistical Information Derived from the Highway Performance Monitoring System .* Retrieved from CA DOT: https://dot.ca.gov/-/media/dot-media/programs/research-innovation-system-information/documents/california-public-road-data/prd-2019v2-a11y.pdf

Commission, C. E. (2014). *Assessment of Piezoelectric materials for Roadway Energy Harvesting.*

Edery-Azulay, L. (n.d.). *Innowattech: Harvesting Energy and Data; A Standalone Technology.* Retrieved from https://www.yumpu.com/en/document/view/10271650/innowattechs-technology

*Estimated social cost of climate change not accurate, Stanford scientists say*. (2015, January 12). Retrieved from Stanford News: https://news.stanford.edu/2015/01/12/emissions-social-costs-011215/

FastCap Systems, Inc. (n.d.). Retrieved from https://www.energy.gov/sites/prod/files/2014/02/f7/fast_cap_sys_peer2013.pdf

(2000). *Federal Highway Cost Allocation Study.* Final Report, Federal Highway Administration.

*Free Vibration of a Cantilever Beam*. (n.d.). Retrieved from Amarita: https://vlab.amrita.edu/?sub=62&brch=175&sim=1080&cnt=1

Gropman, A. (2015, March 4). *$1.1 BILLION AND FIVE YEARS LATER, THE 405 CONGESTION RELIEF PROJECT IS A FAIL*. Retrieved from LA Weekly: https://www.laweekly.com/1-1-billion-and-five-years-later-the-405-congestion-relief-project-is-a-fail/

H. Weimerskirch, D. F. (2017). Use of radar detectors to track attendanceof albatrosses at fishing vessels. *Conservation Biology, Volume 32, No. 1, 240–245, 32*(1), 240-245.

*Household Energy Use in California.* (2019). Retrieved from https://www.eia.gov/consumption/residential/reports/2009/state_briefs/pdf/ca.pdf

*Mide Corporation.* (n.d.). Retrieved from http://www.mide.com/products/volture/volture_catalog.php

P Torcellini, N. L. (2003). *Consumptive Water Use for U.S. Power Production.* Golden : Nat Renewable Energy Laboratory. Retrieved from http://www.nrel.gov/docs/fy04osti/33905.pdf

Qabur, A., & Alshammari, K. (2008). A Systematic Review of Energy Harvesting from Roadways by using Piezoelectric Materials Technology. *7*(1).

*The Electric Program Investment Charge: Triennial Investment Plan 2015-2017.* (2017, April 17). Retrieved from https://docketpublic.energy.ca.gov/PublicDocuments/17-EPIC-01/TN217347_20170428T145448_The_Electric_Program_Investment_Charge_Proposed_20182020_Trienn.pdf

*The New Paving Realities: The Impact of Asphalt Cost Escalator Clauses on State Finances .* (2012, Februrary 27). Retrieved from Portland Cement Association: http://www2.cement.org/econ/pdf/escalator_report_2-27-12.pdf

(2007). *The Potential Benefits Of Distributed Generation And Rate-Related Issues That May Impede Their Expansion.* Dept. of Energy.

The White House. (2014, Sept 9). Retrieved from https://obamawhitehouse.archives.gov/the-press-office/2014/09/09/fact-sheet-build-america-infrastructure-investment-summit

*Total Accident Value*. (n.d.). Retrieved from http://bca.transportationeconomics.org/benefits/safety/total-accident-value

Ueda, J. (2010). Large Effective-Strain Piezoelectric Actuators Using Nested Cellular Architecture with Exponential Strain Amplification Mechanisms.

US DOT Bureau of Transportation Studies. (2017, April 14). *National Transportation Statistics*. Retrieved from: https://www.bts.gov/archive/publications/national_transportation_statistics/index

USA Today. (2014, May 29) Staggerring toll: *Car crashes cost $871 billion a year*. Retreived from: https://www.usatoday.com/story/news/nation/2014/05/29/steep-economic-toll-of-crashes/9715893/

US EPA. (2015, February ). *Fuel and Carbon Dioxide Emissions Savings Calculation Methodology for Combined Heat and Power Systems.* Retrieved from EPA: https://www.epa.gov/chp/fuel-and-carbon-dioxide-emissions-savings-calculation-methodology-combined-heat-and-power

*Vehicle-to-Infrastructure Deployment Guidance*. (n.d.). Retrieved from https://www.its.dot.gov/factsheets/v2i_guidance.htm