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Performance Analysis of Piezoelectric Energy Harvesting in Pavement: Laboratory Testing and Field Simulation

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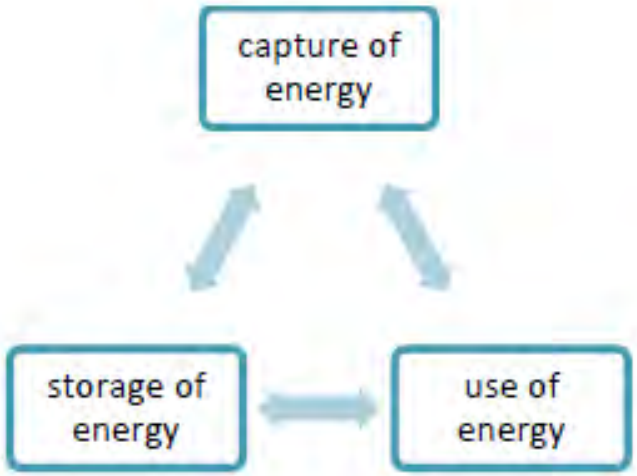
Outline

- Energy Harvesting from Roadway
- Novel Bridge Transducer Design
- Laboratory Testing of Energy Harvester
- Field Performance Simulation and Analysis
- Summary and Findings

Energy Harvesting

- More than 80% of energy production came from fossil fuels (IEA)
- Major renewable energy sources (hydro, solar, wind, waves)
- Energy harvesting is the process of capturing waste energy from natural occurring energy sources and storing it for later use

- Road surfaces are continuously exposed to two phenomena: solar radiation and vehicle loads
  - ✓ Considerable source of energy ready to be harvested and converted into useful forms of energy

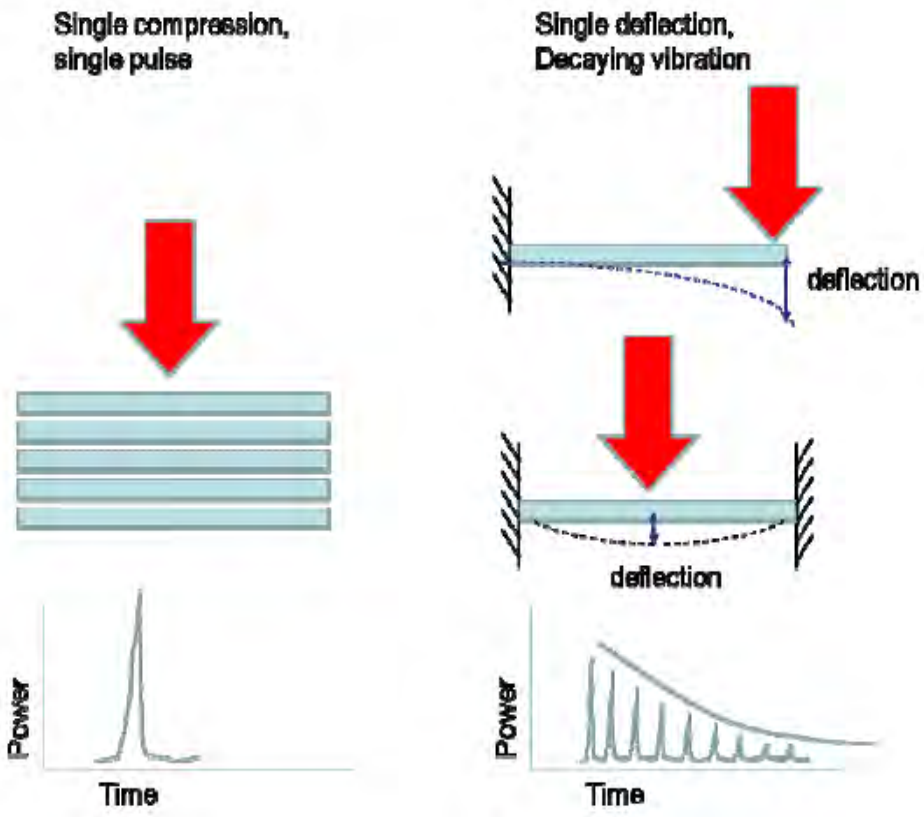


Advantages and Disadvantages

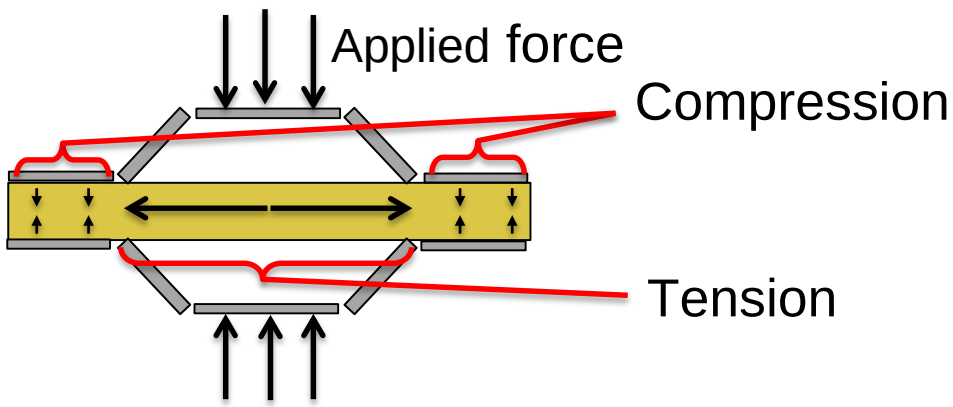
Technology	Energy Output	Advantages /Limitations	Technology Ready Level
Photovoltaic pavement	High	- High Cost - Fragility to resist traffic loading	Low
Asphalt solar collector	Medium	- Enhance pavement durability - Cannot be constructed in roads with high traffic	High
Geothermal Energy	Medium	- High cost - Depend on geology condition	High
Thermoelectric generator	Low	- Low energy transfer efficiency	Low
Piezoelectric generator	Low/Medium	- Need installation in pavements	Median

Piezoelectric Materials

- **Definition:**
  - Piezoelectric materials generate electric charges subjected to mechanical stresses; or change geometric dimensions when electric field is applied, which cause direct and inverse piezoelectric effect
  - Common piezo materials include lead zirconate titanate (PZT) and Polyvinylidene fluoride (PVDF)



Piezoelectric Bridge Transducer



Polarization direction

↑ $$Q = A_{Inner}\sigma_X d_{31} + A_{Outer}\sigma_Z d_{33}$$

➔ $$Q = A_{Inner}\sigma_X d_{33} + A_{Outer}\sigma_Z d_{31}$$

$$V_{gen} = \frac{Q_{gen}}{C_f}$$

$$U = \frac{1}{2} Q \cdot V_{gen}$$

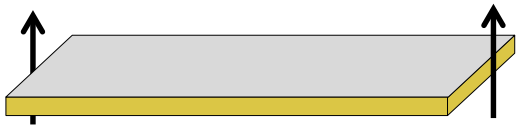
- Piezoelectric coefficient $d_{33} \geq 2 \times d_{31}$
- Tensile stress σ_x is larger than compressive stress σ_z
- Vertical poling and horizontally poling

New Cymbal Transducer Design

32x32x2mm PZT-5X (Sinocera, State College PA). d_{33}=750pC/N

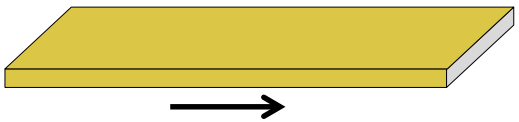
Conventional

700pC/N



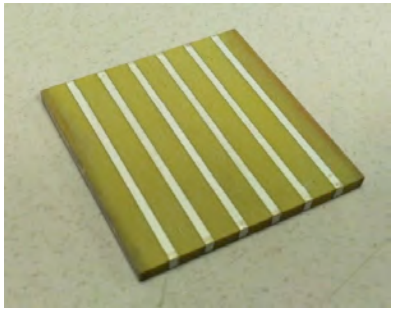
- Standard poling

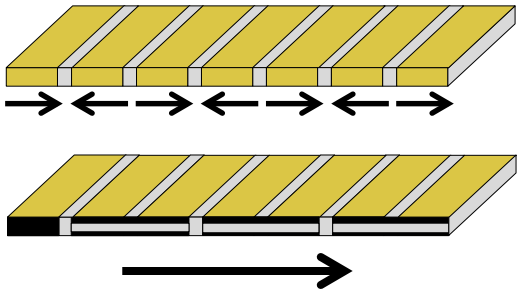
Horizontal poling



700pC/N

- Difficult to pole; Low capacitance

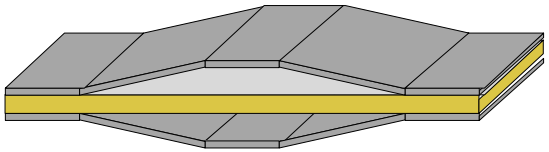




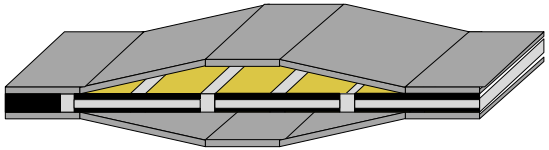
600pC/N x 7 segments

4200pC/N

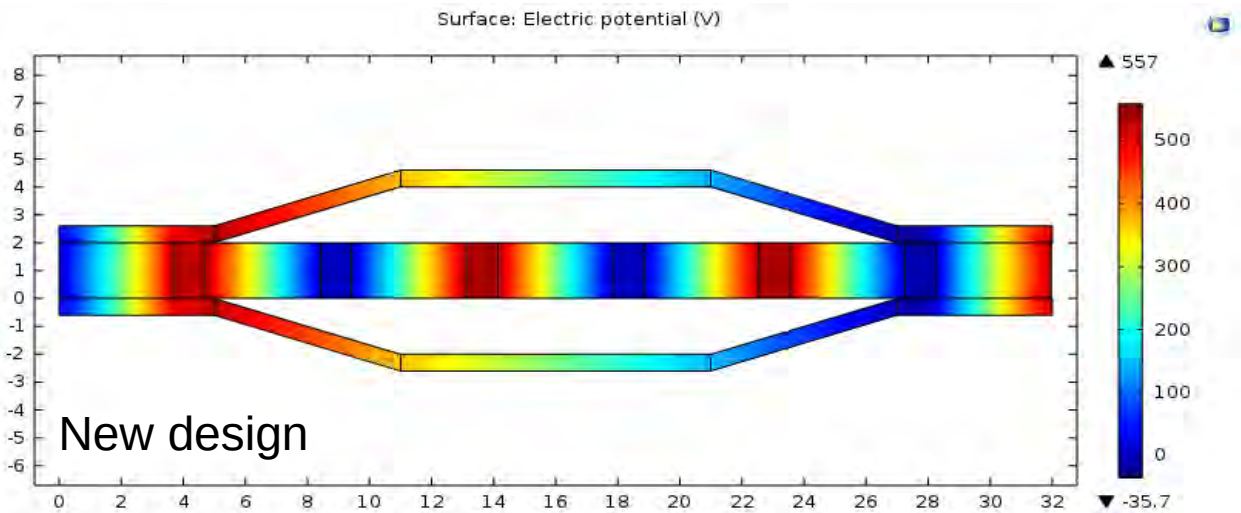
Conventional transducer

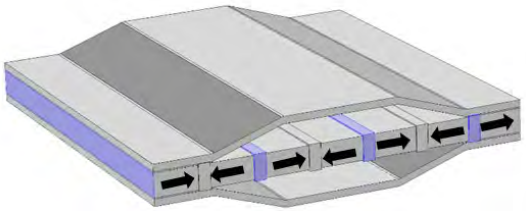


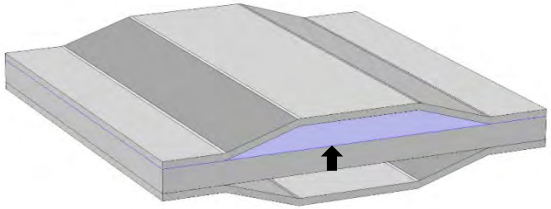
Novel transducer

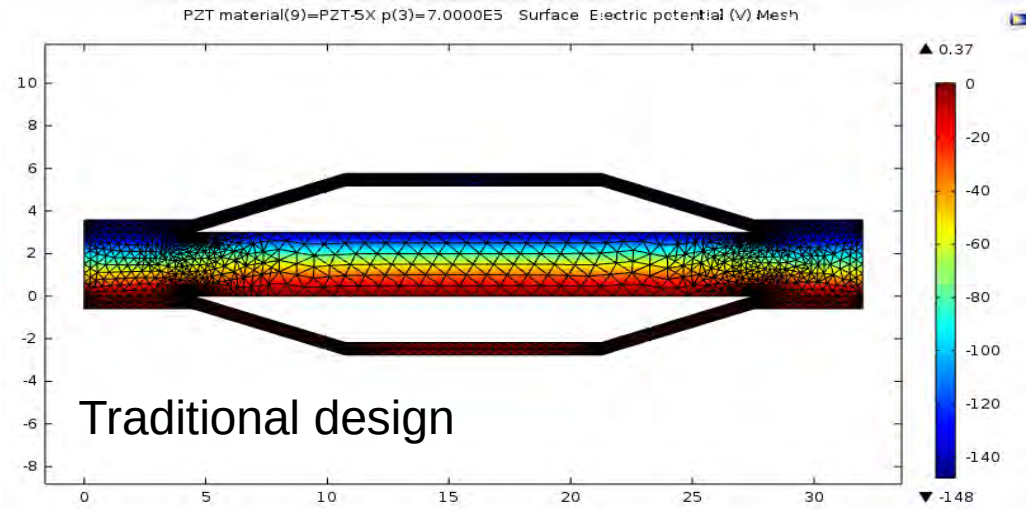


Simulation of Individual Transducer

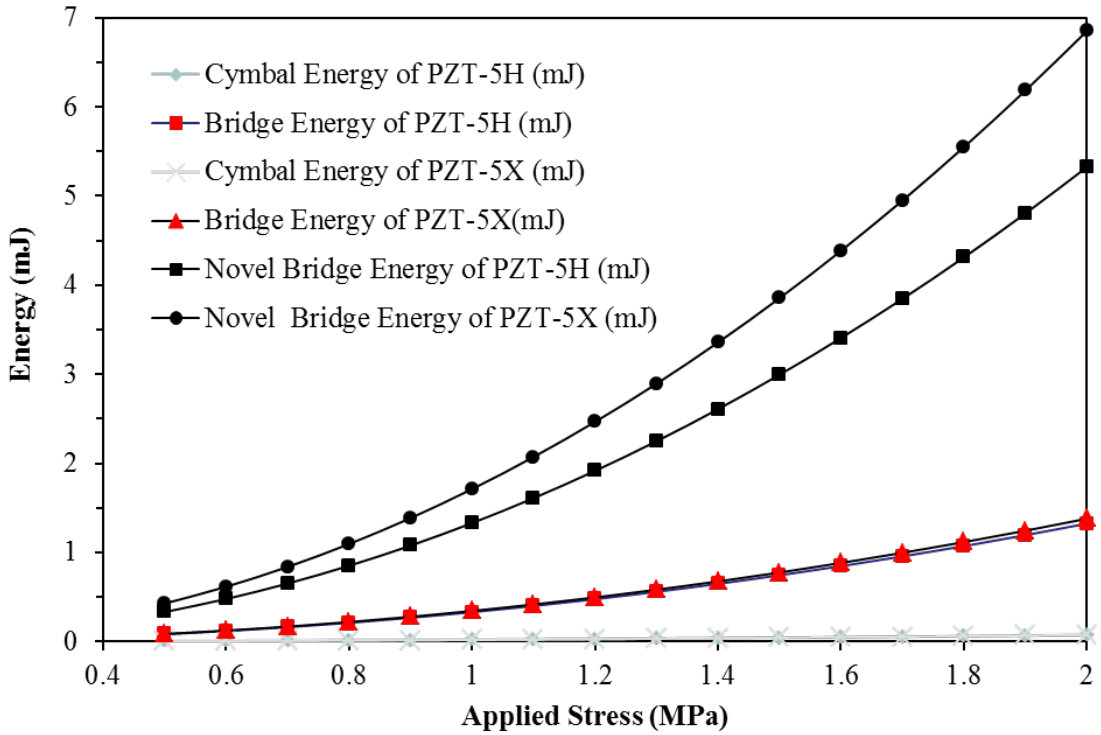


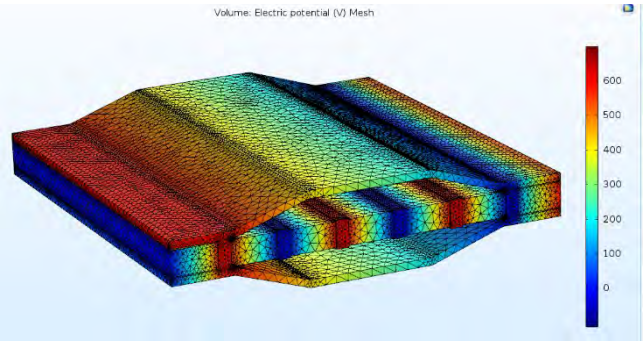


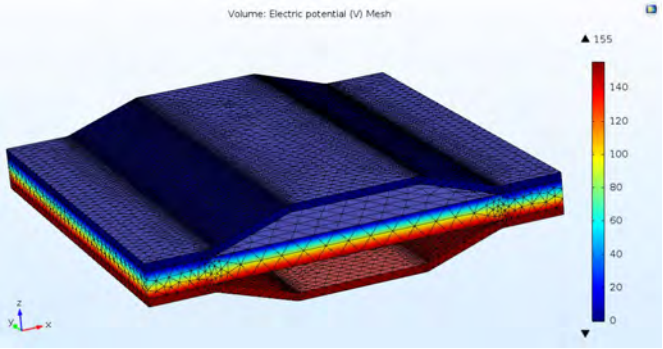


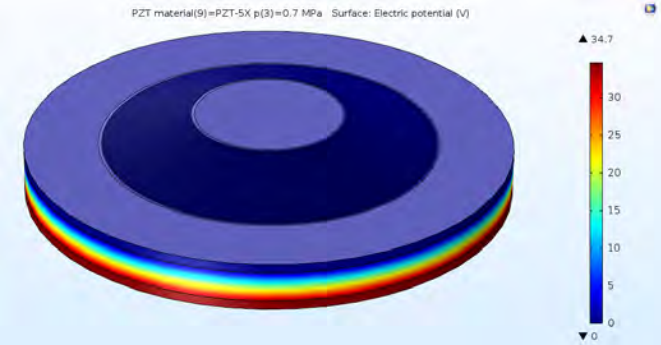


Effects of Transducer Type and Load



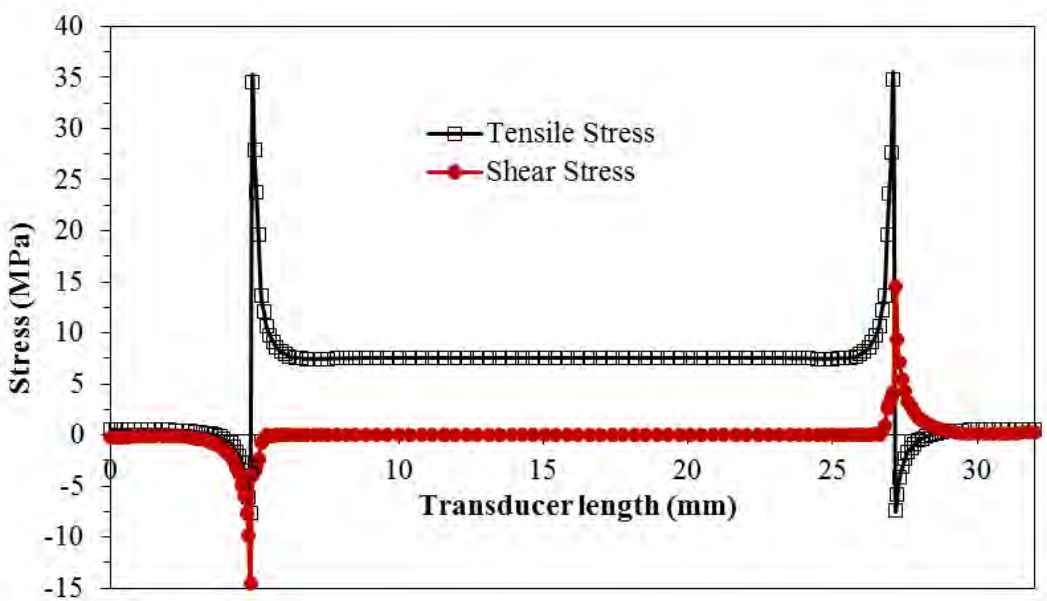


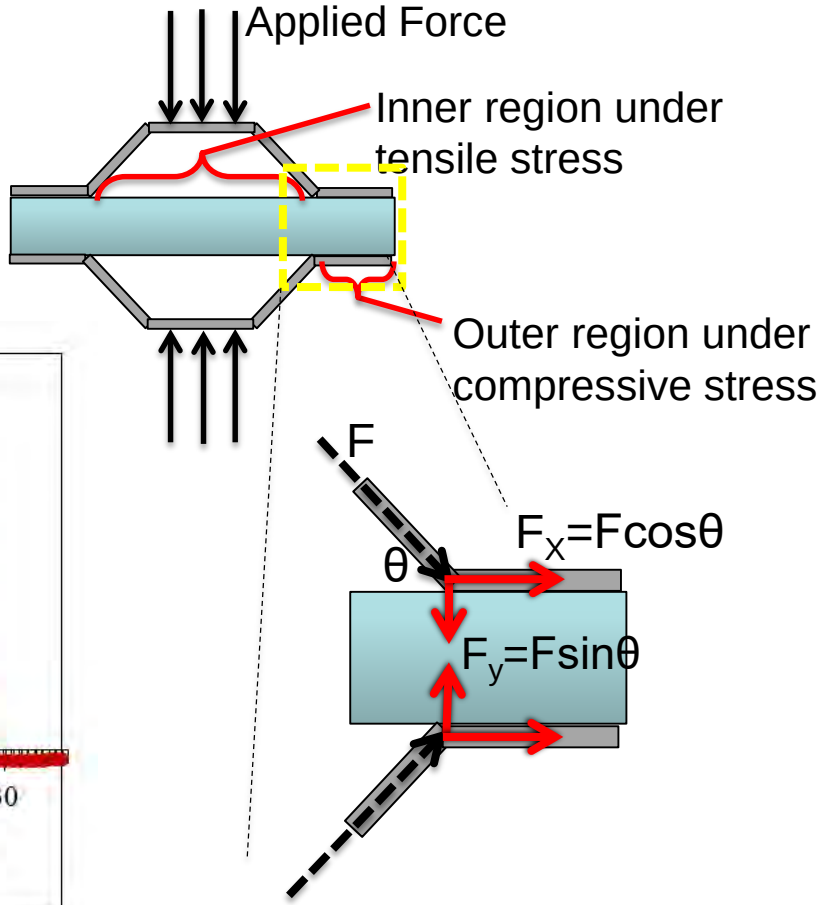




Stress Analysis of Bridge Transducer

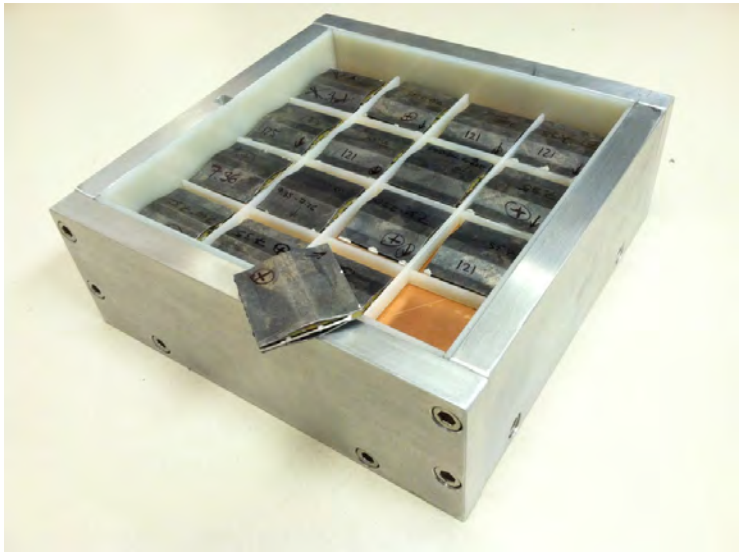
- The deflection and resulted stresses of piezo transducer is dependent on the geometry of transducer and material modulus

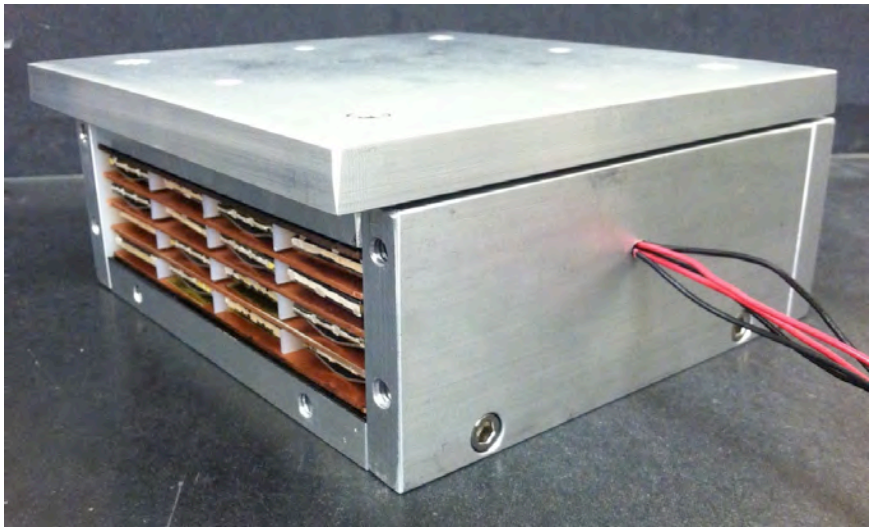




Energy Harvester Module

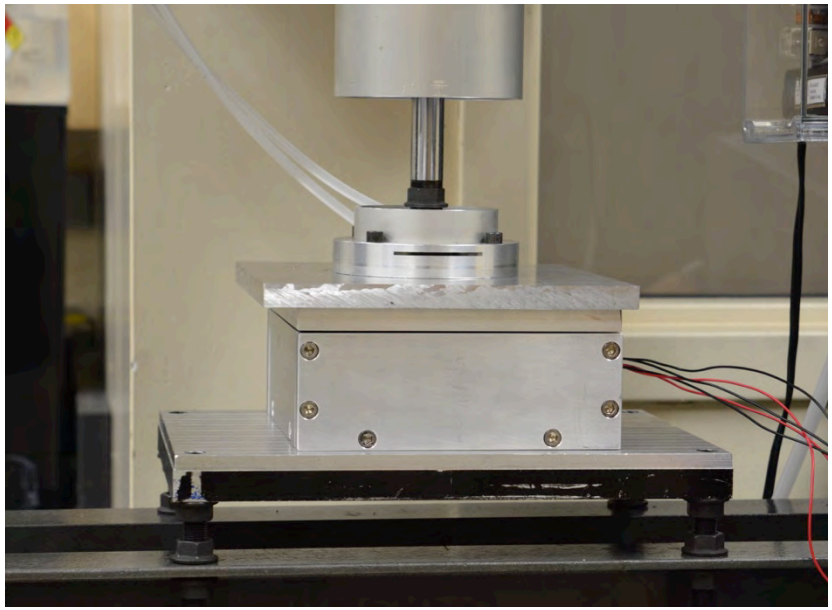
- 64 transducers
  - 4x4x4
- 1.25 cm aluminum case
- Top and bottom coated with insulating epoxy, side walls lined with nylon
- Copper plates between each layer acts as current collector
  - Wires connected to each plate in parallel
- 17.8×17.8×7.6 cm

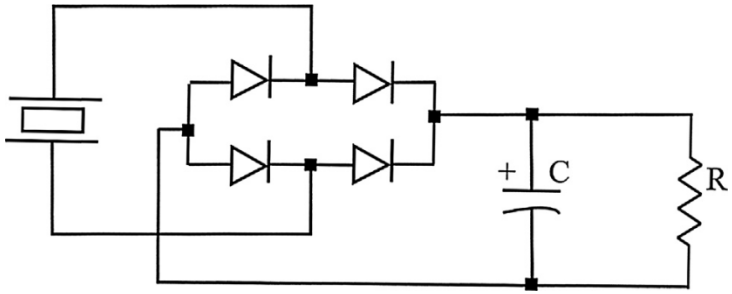




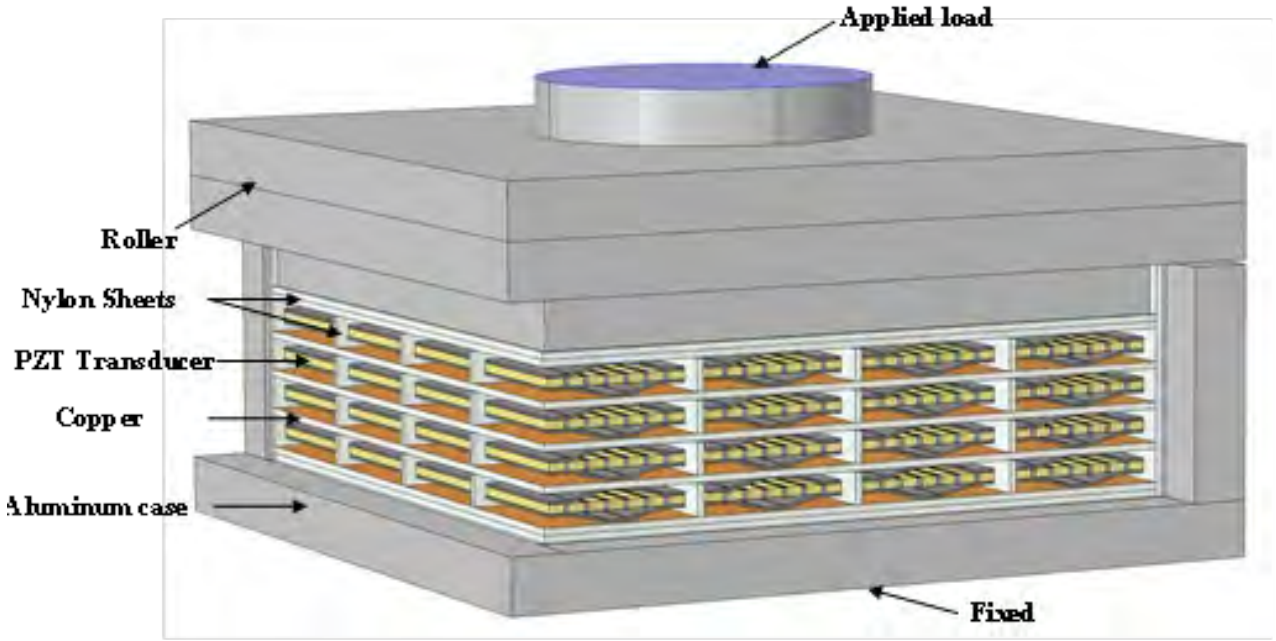
Laboratory Testing of Energy Harvester

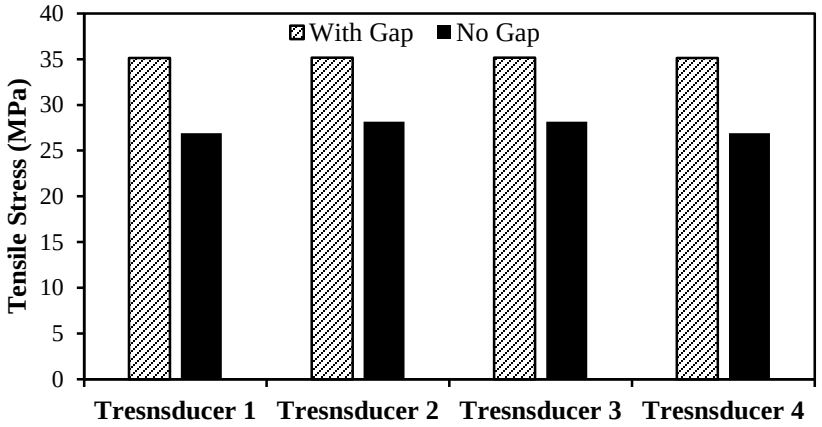
- Pneumatic loading system
  - Maximum impact loading: 1000lb
  - Loading frequencies: 0.5-5 Hz
- Voltage was measured across the capacitor in an open circuit
- The power generated from cyclic loading depends on resistance, or impedance of electric load
- The maximum power occurred at an intermediate resistive load was determined using different resistive loads from 50 kOhm to 1 MOhm

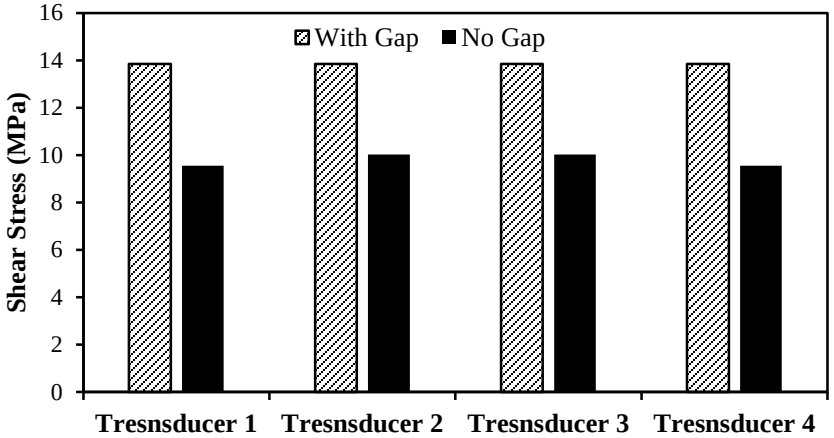




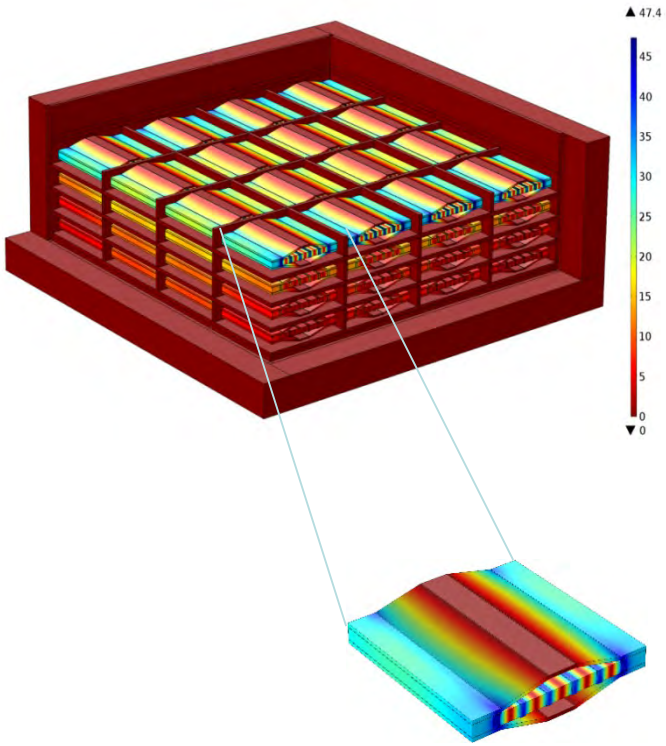
Simulation of Piezo Energy Harvester

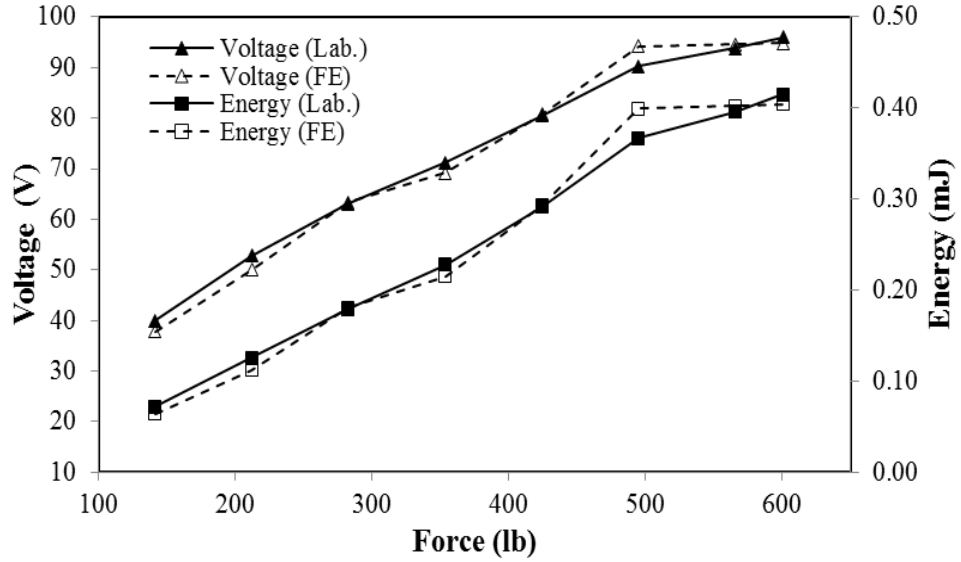


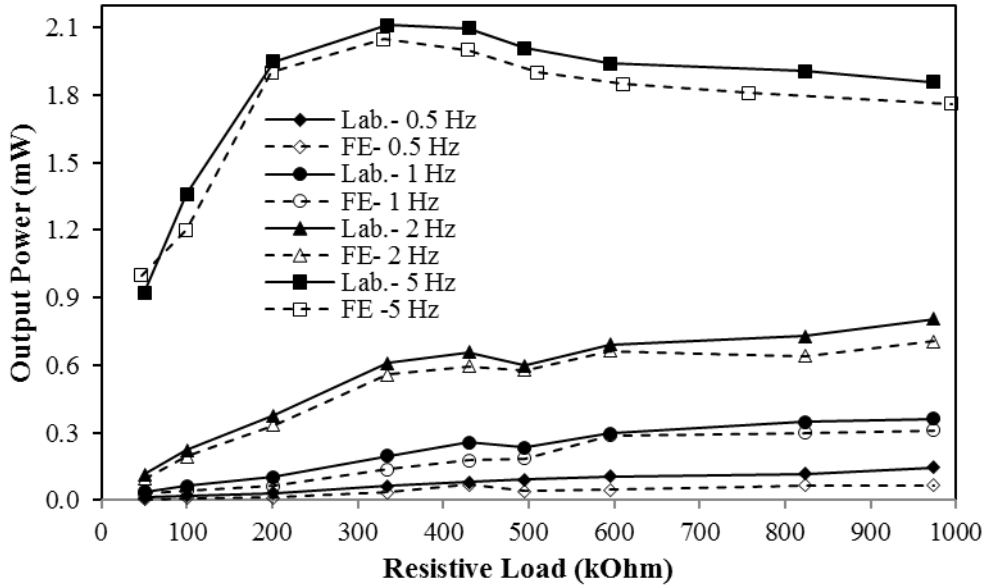




Laboratory and Simulation Results

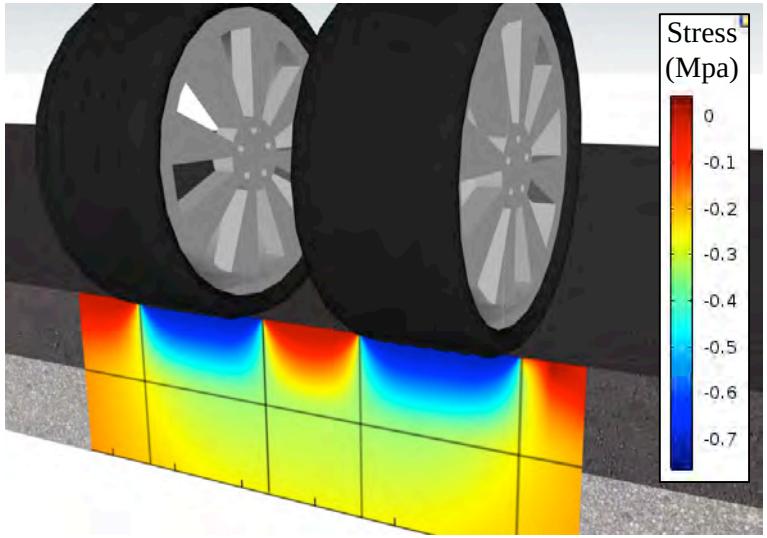


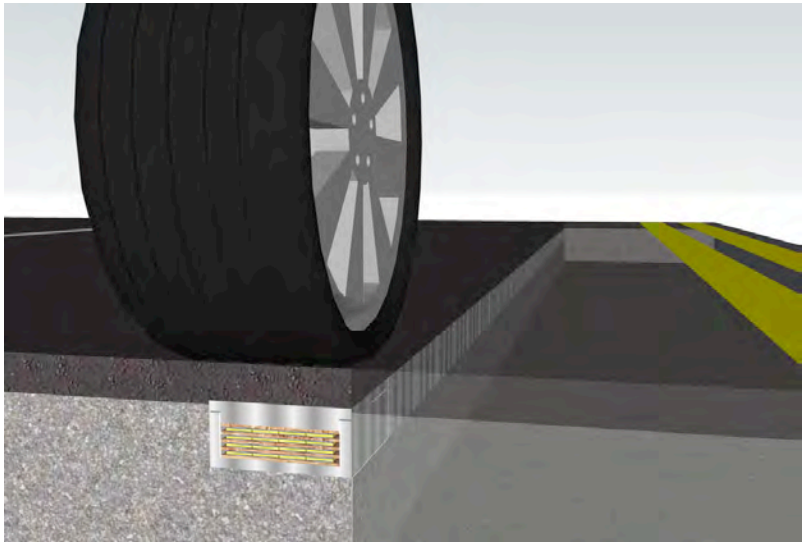




Piezo Energy Harvesting in Pavement

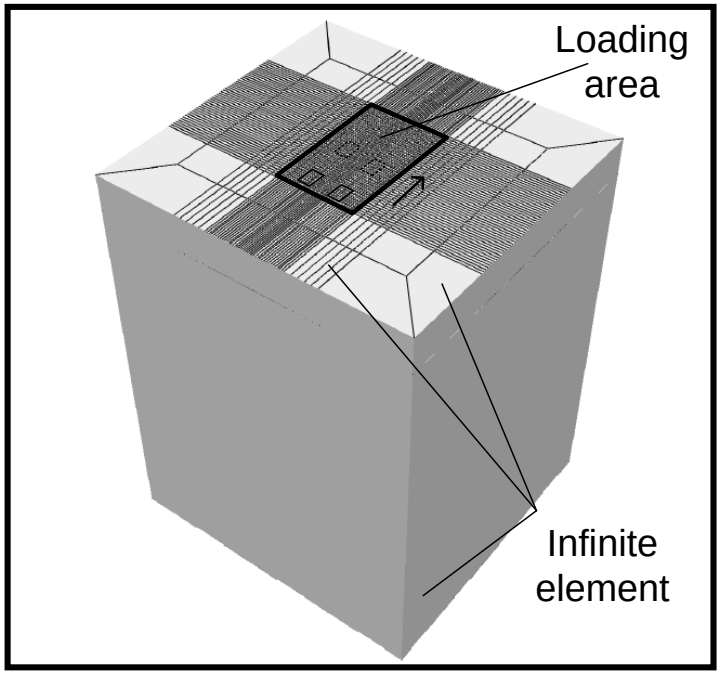
- Stress and strain from vehicle impact is transferred to piezoelectric transducers through pavement structure
- The elastic modulus of energy harvester may not match pavement stiffness and affect stress distribution
- PZT transducer should be protected from mechanical failure
- The embedment location affect energy output





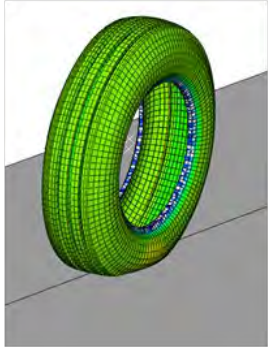
3D FE Pavement Modeling

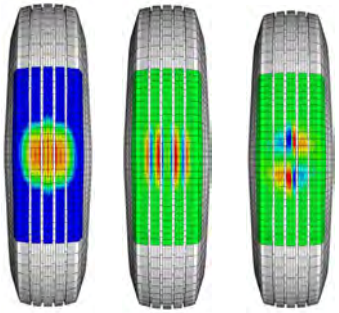
- Non-uniform tire contact stresses in three directions
- Moving loads
- Viscoelastic asphalt layer
- Nonlinear cross-anisotropic behavior of unbound material
- Interface condition
- Temperature gradient

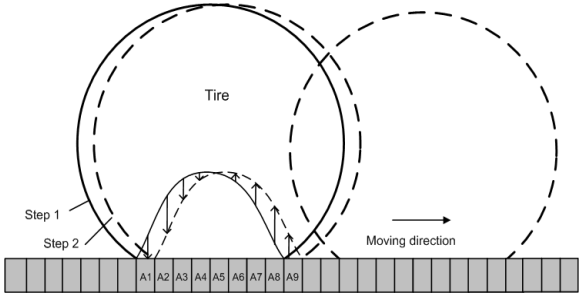


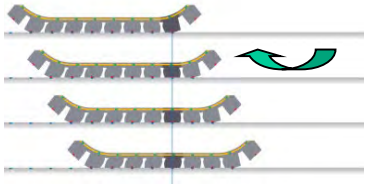
- Validated by field instrumentation measurements in previous studies

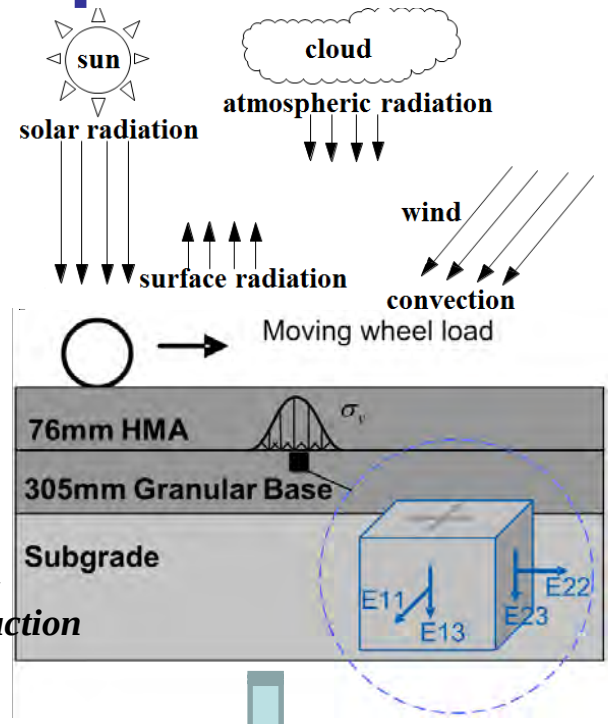
Prediction of Pavement Responses

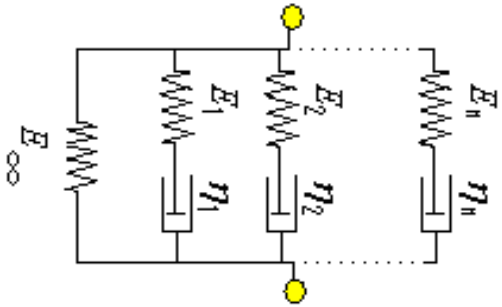




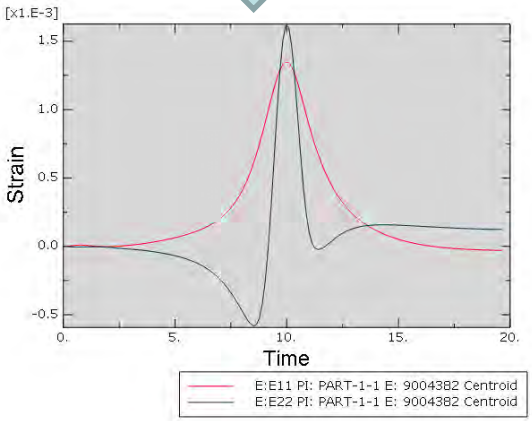




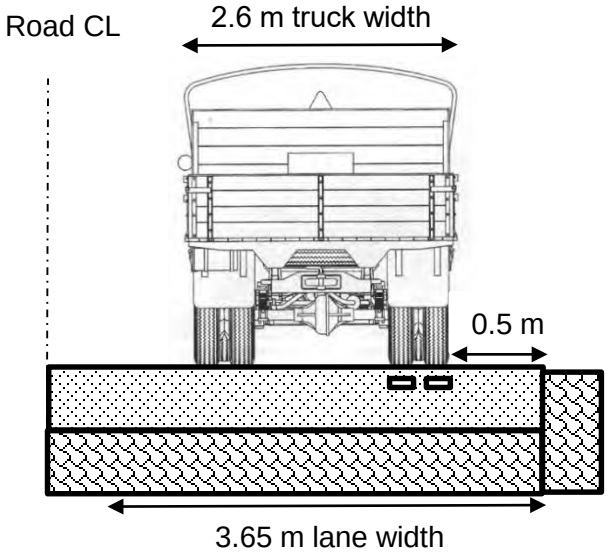


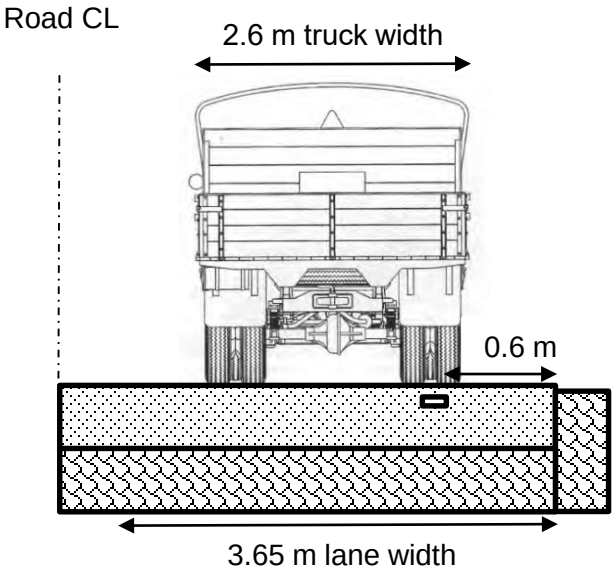


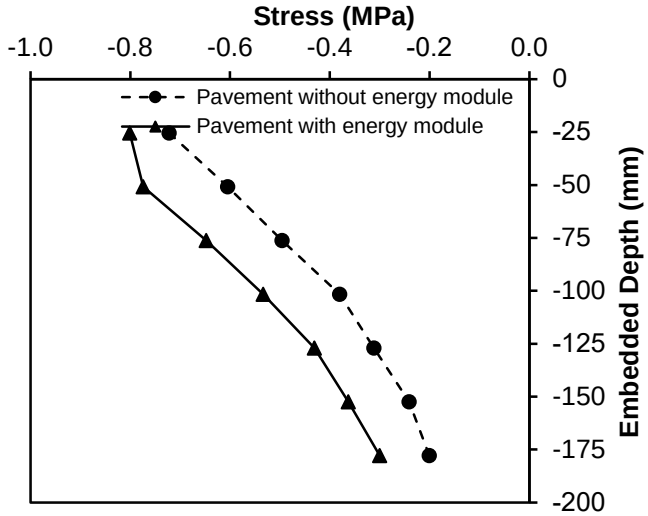
$$\begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{12} \\ \sigma_{13} \\ \sigma_{23} \end{Bmatrix} = \begin{bmatrix} D_{1111} & D_{1122} & D_{1133} & 0 & 0 & 0 \\ & D_{2222} & D_{2233} & 0 & 0 & 0 \\ & & D_{3333} & 0 & 0 & 0 \\ & & & D_{1212} & 0 & 0 \\ & sym & & & D_{1313} & 0 \\ & & & & & D_{2323} \end{bmatrix} \begin{Bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ \varepsilon_{12} \\ \varepsilon_{13} \\ \varepsilon_{23} \end{Bmatrix}$$

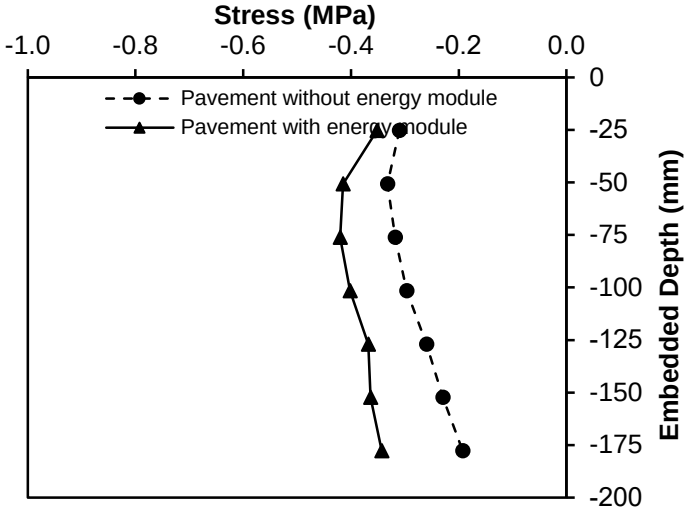


Compressive Stress on Energy Harvester

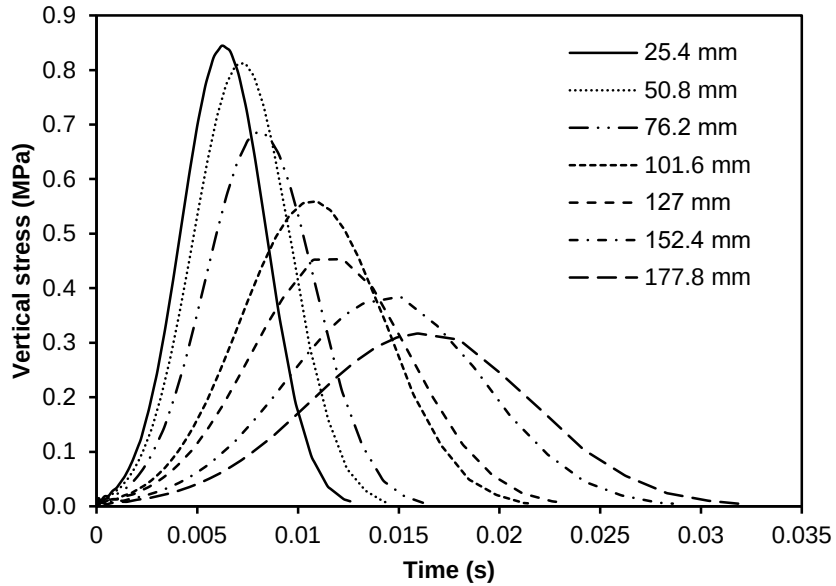


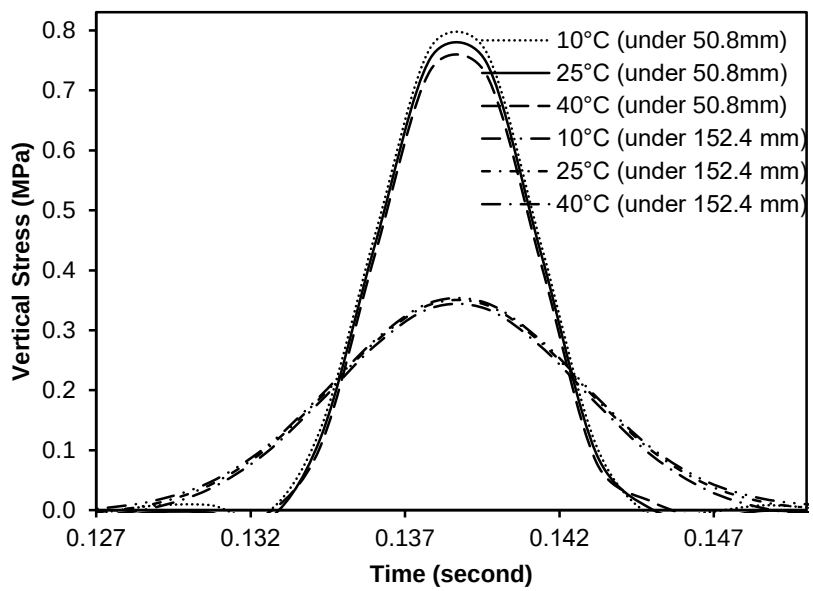


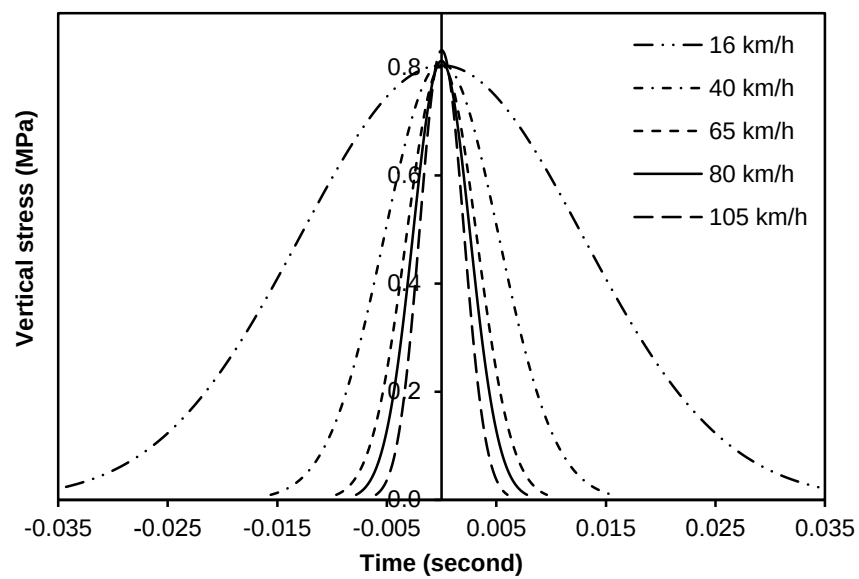




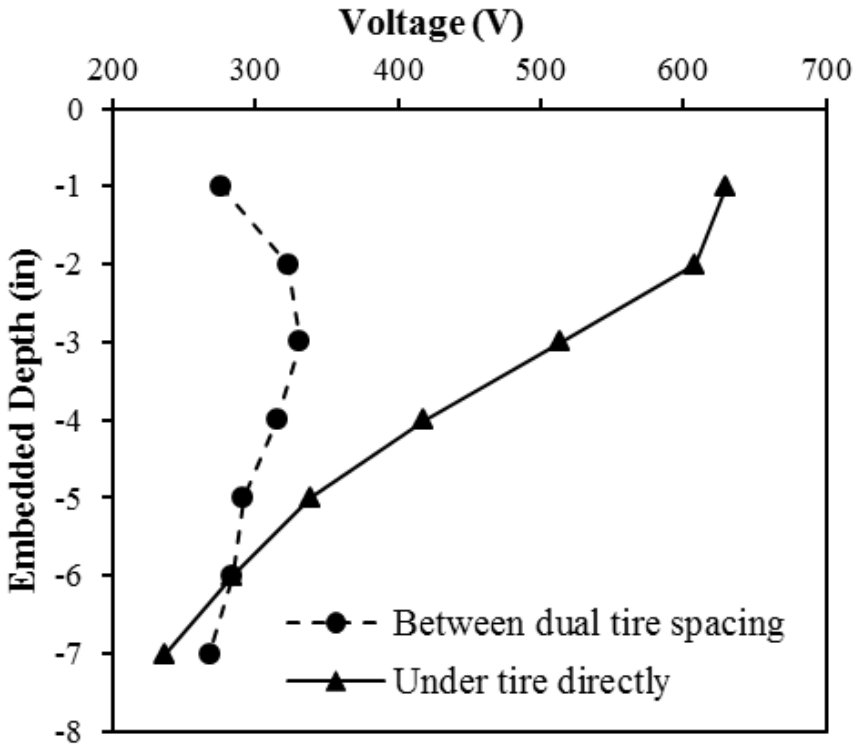
Effect of Embedment Location, Temperature, and Speed

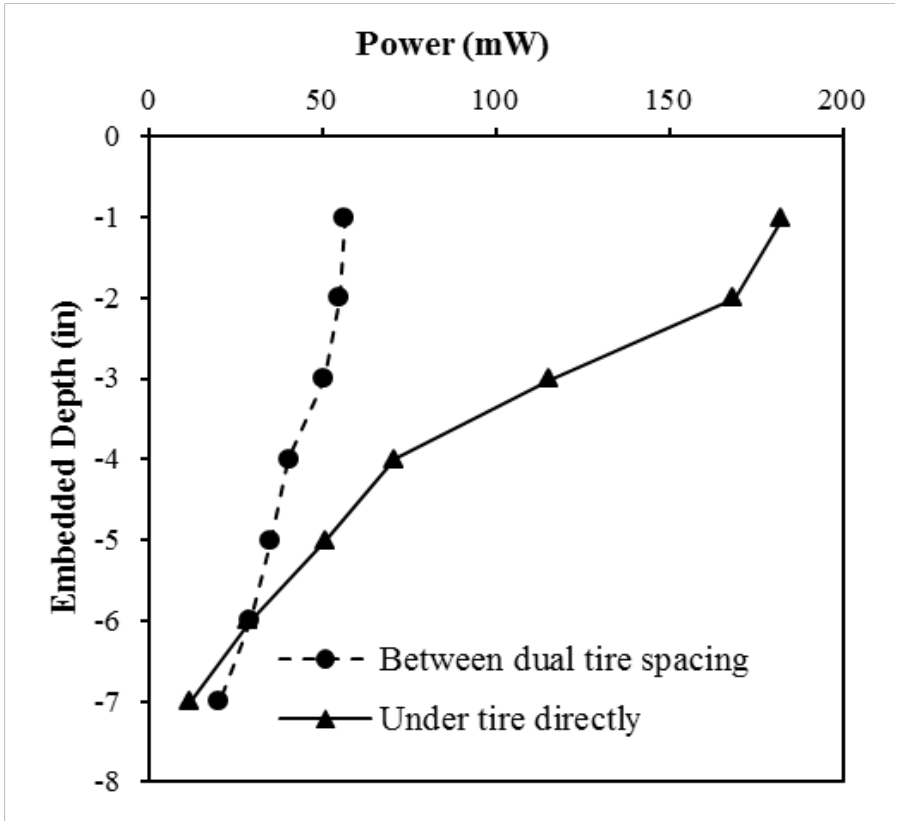




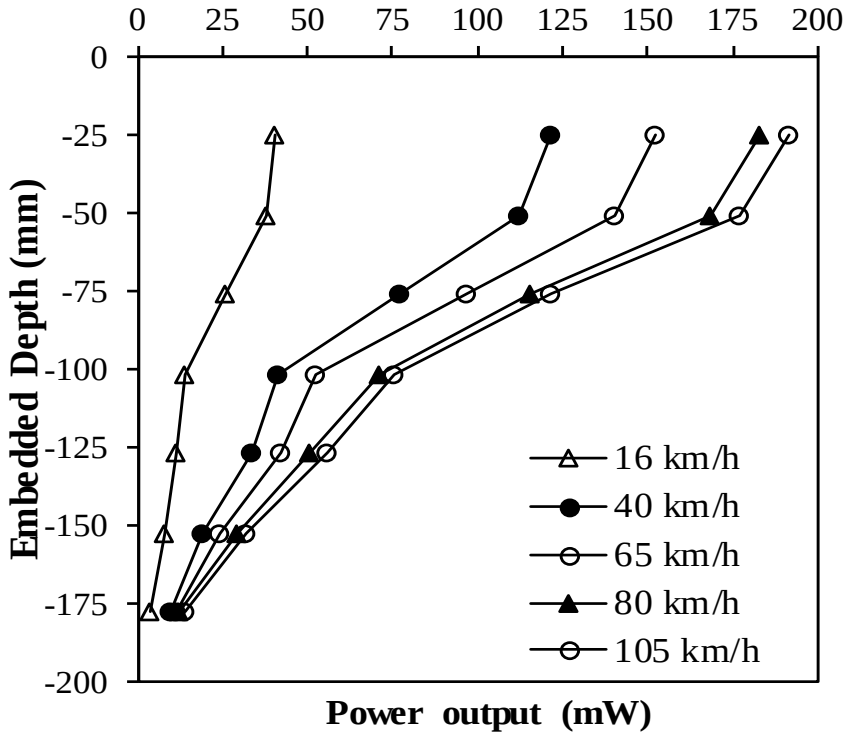


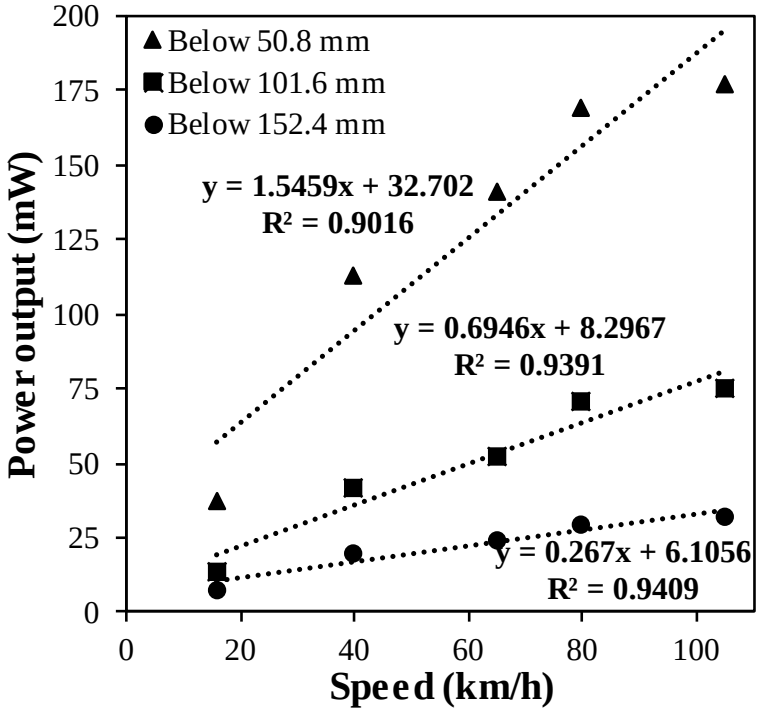
Voltage and Power Under Truck Loading



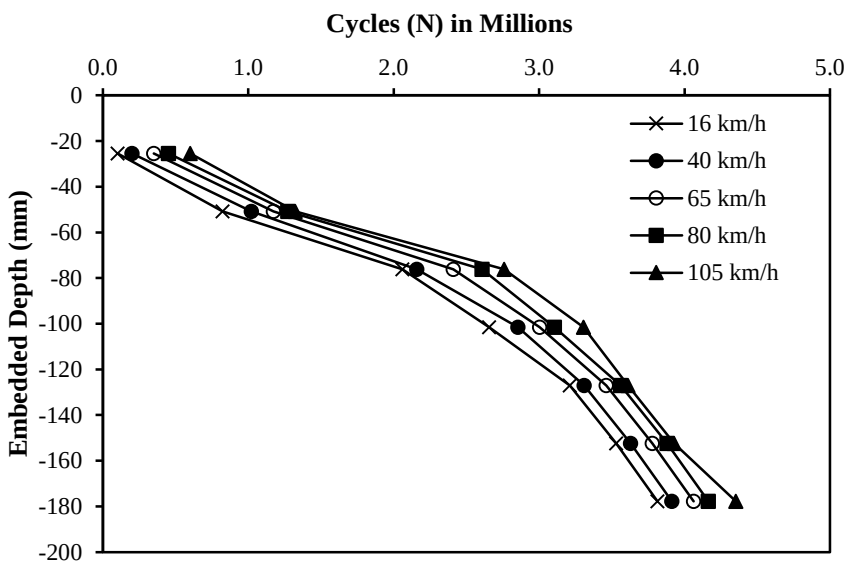


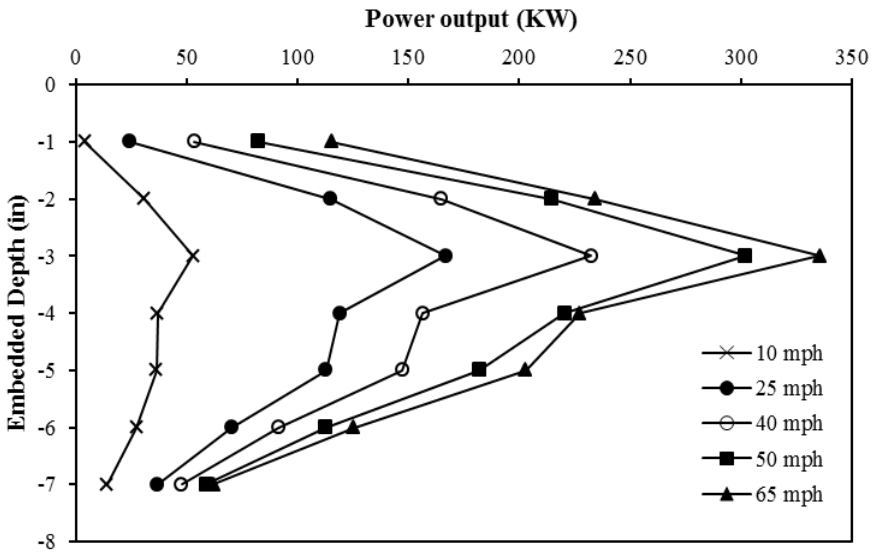
Power Outputs at Different Speeds





Power Output in Life-Cycle of Energy Harvester





The relationship between the cyclic stress amplitude (σ) and the number of cycles to fatigue failure (N):

$$\text{Log}(N) = 13 - 0.2\,\sigma$$ Tensile failure of PZT material

$$\text{Log}(N) = 11.65 - 0.422\,\tau$$ Shear failure of epoxy

Effect of Energy Module on Pavement Responses

- Due to high stiffness of energy harvester, the embedment of energy module in asphalt layer will cause smaller deformation in asphalt layer or on top of subgrade, which is also proved by the FE model results.
- The tensile strains were not significantly affected when energy module was placed in the upper parts of asphalt layers. As energy module was placed close to the bottom of asphalt layer, tensile strains were found smaller as compared the case of intact pavement.
- The effect of energy module on pavement surface displacement was found negligible. It is reasonable to assume that energy module will not affect pavement surface roughness.

Conclusions

- The innovative layered poling and electrode configuration of Bridge transducer increases piezoelectric coefficient and capacitance for higher energy outputs
- Two different material failure models need to be considered in relation to mechanical failure of Bridge transducer, namely tensile and shear failure
- Energy harvesting performance is affected by vehicle weights, speed, and embedment location. Therefore, optimum placement strategy in roadway is needed.
- The analysis of strain responses in the pavement suggest that the embedment of energy module will not cause adverse effect on pavement deterioration. Field study is recommended to verify these finding.

Thank You
Questions ?

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