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The self- Deicing Pavement System presents a sustainable approach to mitigating ice and snow accumulation on highway bridge decks - structures especially prone to freezing due to their exposure and the poor insulating properties of concrete. Traditional methods such as chemical deicing and salting not only degrade concrete over time but also harms surrounding ecosystems. Electrically heated pavements, while effective, are energy intensive and impractical for large scale deployment due to their reliance on grid power. This project proposes an embedded, self-powered system that addresses these limitations by using piezoelectric vibration energy harvesters (PVEHs) to convert ambient traffic induced vibration into electrical energy. The harvested energy powers resistive heating element embedded within the concrete surface, creating a completely autonomous deicing solution. The research encompassed a comprehensive review of current deicing methods and piezoelectric energy harvesting technologies - particularly two degree of freedom vibration-based system- followed by a comparative analysis of heating materials such as</td></tr>
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nichrome wire, carbon fiber sheets and recycled rubber pads. Experimental testing was conducted to tune resonate frequencies for optimal power output and evaluate the thermal performance of various heating elements. The design process employed a Pugh decision matrix incorporating key product design specifications, including performance, durability, cost, and safety. Based on these criteria, the final prototype integrated a three- sensor vibration energy harvester with a nichrome wire-based resistive heating system. Under simulated bridge vibration conditions, the prototype demonstrated successful energy conversion (0.77 J/day) and heat generation (45°C surface temperature), proving feasibility for ice prevention. This self-contained system offers a scalable environmentally responsible alternative for enhancing winter roadway safety without external energy demand.

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Transportation Infrastructure Precast Innovation Center (TRANS-IPIC)

University Transportation Center (UTC)

Combining Specific Heat of Concrete and Actuator Placement Optimization for Self-Powered Ice-Melting Precast Concrete Bridge Panels
#UI-24-EP-01

FINAL REPORT

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Executive Summary:

The Self-Deicing Pavement System aims to develop a prototype of an embedded energy harvesting system used to melt ice and snow on highway bridge decks when ambient air temperatures are below freezing. Ice and snow-covered pavements prove to be a significant hazard for motorists and these dangers are amplified to an even larger extent when driving on bridge decks. A lack of insulation from the ground coupled with the fact that concrete, a commonly used material to build bridge decks, is itself a poor insulator allows for these road surfaces to freeze easily.

A variety of methods have been used to tackle the problem of snow and ice accumulation on pavement such as chemical deicing, chemical anti-icing, and salting. However, each of these individually bring forth their own list of damaging effects to the structural integrity and life span of pavement on top of having adverse effects to the surrounding environment they are used in. More recently, heated pavement systems have grown in popularity but require substantial amounts of energy and a connection to the power grid, making its widespread implementation difficult and expensive.

The Self-Deicing Pavement System will avoid these issues by utilizing piezoelectric vibration energy harvesters (PVEH) to harness the vibrations of bridge decks and convert them into electrical energy (i.e., current). The current generated from the vibrations will power a heating system attached to the underside 12" x 12" x 6" concrete testing slab provided by the civil engineering concrete team.

The project began with research into current energy generation and harvesting systems and heat generation methods. Based on the research found by the team, various design concepts were made using the different energy systems and heating methods. A Pugh decision matrix was then used to determine which concept, energy systems, and heating methods will be pursued for the final design. Building and testing of the fully operational energy harvesting system and deicing mat were completed and demonstrated at the Mechanical Engineering Capstone symposium, <u>winning top demonstrator of the year.</u>

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1. Problem description:

Pavement deicing represents a substantial cost to every municipality and a danger to motorists. These dangers are more significant on bridge decks due to the lack of ground insulation and the fact that concrete, commonly used on bridge decks, readily freezes from exposure and requires a substantial amount of heating energy to prevent freezing. These factors are the main contributors to why heated concrete pavements have not been feasible in the past.

Figure 1. Motivation for the proposed work, (WSB Radio, 2024)

2. Background:

The Self-Deicing Pavement is not unique in its attempt to create a way of melting ice and snow from highway bridge decks. It is vital for the success of the project to first understand what the current state of deicing methods looks like and why alternatives are being pursued. Furthermore, research into different energy harvesting systems and heat generation mechanisms is important before any critical design choices can be made. Current deicing methods such as deicing chemicals and salts can damage the concrete pavements they are applied to. Common chemical deicing agents such as calcium chloride, sodium chloride, and magnesium dichloride induce the deterioration of concrete through primary through scaling. Scaling is when the surface of the concrete flakes or peels due to exposure to chemical deicing agents [2].

Scaling is particularly damaging when ice and snow are present because water can accumulate in the pores of the concrete and freeze into ice. Once the ice is formed it will exert hydrostatic pressure on the surrounding concrete and cause further scaling. See Figure 1 below for a visualization of this process.

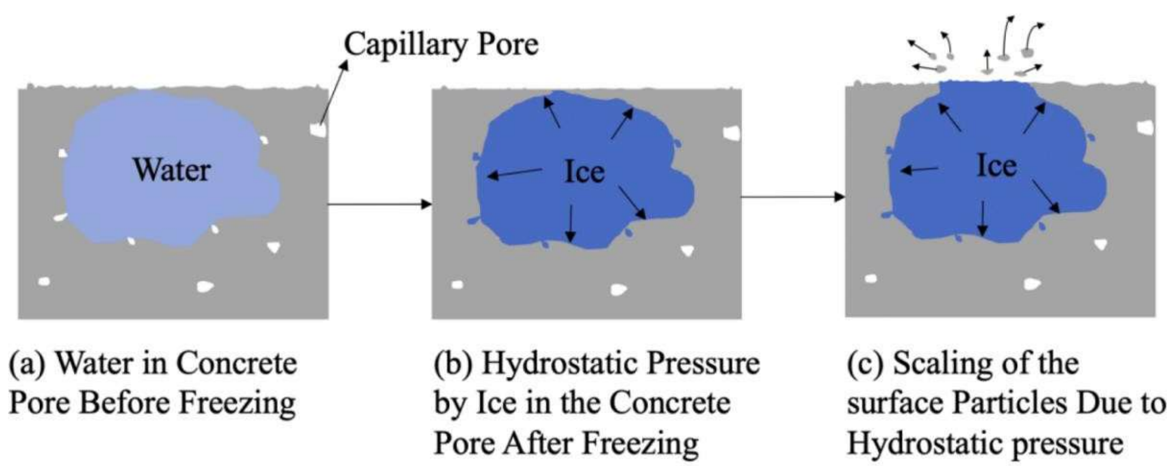

Figure 1. Mechanism of scaling due to hydrostatic pressure. (a) water in the concrete pore before freezing; (b) hydrostatic pressure by ice in the concrete pores after freezing where the capillary pores leave space to the increased ice volume (c) scaling of the surface particle due to hydrostatic pressure [2]

Furthermore, deicing salt used on highways can pollute water runoffs. A study done by Minnesota Department of Transportation noted that chloride from deicing salts readily dissolve in water and can find its way into lakes, ponds and wetlands, and even groundwater. In 2013 the Minnesota Pollution Control Agency (MPCA) found elevated chloride concentrations in roughly 22% of the 340 lakes, streams, and wetlands surveyed during the study [3].

Thus, it becomes clear that current deicing methods are unsustainable not only for the concrete pavements themselves but also for the environment. Research was then conducted on possible ways to generate electrical energy to power a heating system that would be self-sufficient. Of primary interest was piezoelectric technology, specifically PVEH sensors.

One insightful paper that we looked at focused on creating and optimizing a two-degree-of-freedom PVEH device. The paper addresses a fundamental challenge with piezoelectric vibration harnessing —nuancing both the operating bandwidth and output power in low-frequency environments. By combining three separate cantilevers with two magnets, the experimental setup shows that the resonant frequency of the different sensors can be tuned to a lower frequency by adding additional mass to the tips of the cantilever beams. When the magnets are added to the system, the repulsive force allowed for more deflection in the beam tuned for lower frequencies, further improving the output power. In Hu et. al [4], results initiate a substantial improvement in output power, producing 2.80 mW and 1.4 mW, a 23.55% and 38.10% improvement in first and second order operating frequencies, respectively, compared to non-magnetic structures. See Figure 2 and 3 below to visualize the effects of different masses and magnetic configurations on output voltage.

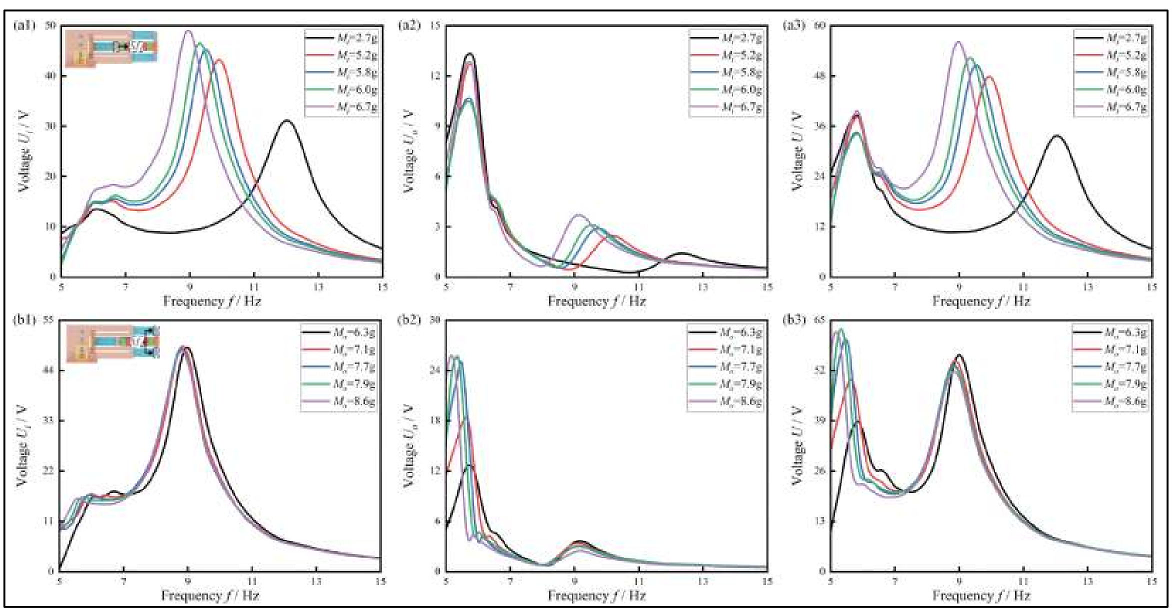

Figure 2. The open-circuit output voltage under changing the tip mass of beams: (a1) The output voltage of the inner beam under changing the tip mass of the inner beam; (a2) The output voltage of the outer beam under changing the tip mass of the inner beam; (a3) The total output voltage of the inner beam and outer beams under changing the tip mass of the inner beam; (b1) The output voltage of the inner beam under changing the tip mass of the outer beam; (b2) The output voltage of the outer beam under changing the tip mass of the outer beam; (b3) The total output voltage of the inner beam and outer beams under changing the tip mass of the outer beam [4]

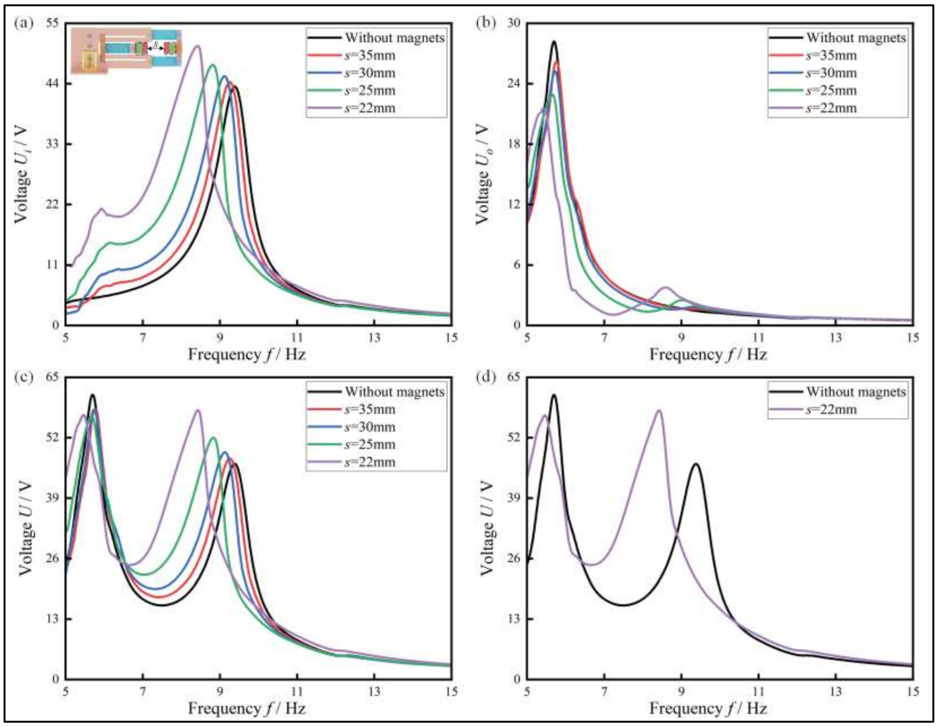

Figure 3. The open-circuit output voltage under changing the magnetic spacing: (a)The output voltage of the inner beam; (b) The output voltage of outer beams;(c) The total output voltage of the inner and outer beams; (d) The comparison between the proposed PVEH under the magnetic spacing is 22 mm and the PVEH without magnets. [4]

The next stage of research was investigating possible heat generation methods. Mohammed et. al [5] overviews various carbon fiber resistance heating options with deicing purposes. In this experiment, the heat transfer properties were compared for carbon filament, woven carbon fabric, and unidirectional carbon fabric heat panels. Each method was embedded under a thin slab of concrete and supplied with a voltage of 6 V and power of 30 W. The concrete slab was subjected to evaluation under various initial temperatures (-5 C, -10 C, -20C) then heated up using the carbon fiber resistance methods. Through experimentation, the carbon filament performed the best with the unidirectional carbon fabric close behind. The woven fabric performed the worst out of the three due to difficulty in getting a uniform resistance across the fabric leading to uneven heating on the surface of the concrete. Another paper — Radwan and AbdelRaheem [6] — explores the practicality of a more cost- effective and sustainable option in waste rubber tires (WRTs). Rubber tires are embedded with around 10-20 % steel wire. This experiment utilized steel and copper wires connected to a power source to heat up rubber pads cut from the tires. Two methods of preparing the tire, exposed steel wire and a grooved rubber sample, were subjected to heating a concrete slab from freezing over an extended period. Based on the collected data, it was determined that the rubber pads made from WRTs effectively transferred heat to deice the concrete surface, albeit at lower temperatures compared to the carbon fiber alternatives.

A common barrier to embedded pavement heating systems is the relatively high specific heat of concrete. This results in high energy costs and often causes the system to be infeasible to install. Some research has found that increasing density, adding metallic aggregates or fibers, or adding silane all contributed to lowering the specific heat of the concrete [7-9]. These studies have largely considered the independent effects of these modifications and have not considered the interaction of the variables.

3. Research scope and objectives:

The objectives of this proposed work are to (1) interrogate the specific heat of concrete formulations incorporating alternative embedded elements (2) model the thermal transfer properties of the various materials, and (3) compare the experimental and modeled thermal properties to determine the optimum combination of constituents. Through the course of the research there was an opportunity to engage with an undergraduate senior design team that would expedite the development of the energy generation system so objectives (2) and (3) were changed to develop an inexpensive and readily deployable energy harvesting system and to develop a prototype concrete slab that would incorporate energy harvesting, heat generation, and low-specific heat concrete.

The goals of this project fall into 3 subcategories: concrete formulation, energy harvesting and heat generation. The concrete formulation considered the role of w/c and the additions of silica fume and steel fibers since these are readily available materials. The mixtures were tested in a semiadiabatic calorimeter to determine the role these modifications made in the thermal properties.

For energy harvesting, the goal is to create a system that reliably works in a wide range of operating temperatures to harvest the energy of vibrations of a highway bridge. The solution will harvest energy from vibrations within the concrete slab over a range of frequencies and convert the mechanical energy to electrical energy to be stored until an icing event occurs and the heat needs to be turned on to melt the sheet of ice.

The proposed experimental setup should be configurable to different frequency ranges and be able to efficiently combine the generated power from all 3 PVEHs to charge up a battery in the future. The frequency range should fall between 5 and 55 Hz. Bridges typically vibrate at 5 to 20 Hz but with our sponsors recommendation up to 55 Hz is acceptable, assuming high traffic density with trucks. The generated power should be between 3 mW at 5hz and 19 mW at 20 hz. Additionally, the solution should be easily serviceable in the future to ensure optimal performance. For the heat generation aspect, the goal is to find a heating element that efficiently and evenly heats up a concrete slab test specimen.

Along with this, a concrete compound with a higher specific heat than the standard compound will be tested to prevent future ice buildup. The heating solution needs to reliably melt the ice with the limited power captured from the vibrations of the slab and needs to withstand the various stresses associated with cars driving on the surface of the concrete. Finally, testing will be done to ensure that the heating cycle does not compromise the structural integrity of the bridge and will not cause the concrete to deteriorate faster than a standard bridge would. The heating solution should fit within the 12” x 12” x 6” concrete slab test specimen.

4. Research description:

Four concrete mixtures were developed and tested in the semi-adiabatic calorimeter. The formulations used a constant paste volume and coarse to fine aggregate ratio. Silica fume was added at a 15% replacement of cement and the fibers were 1.5” crimped metal fibers. The matrix of the formulations is found below. Cylinders for each mixture were cast and tested in a semi-adiabatic calorimeter after continuous moist curing for 14 days. For the calorimetry, specimens were heated to 122^{o}F and the rate of heat dissipated was measured.

Table 1. Concrete formulation descriptions

Mixture	W/C	Silica Fume	Fiber
1	0.67	No	No
2	0.50	Yes	Yes
3	0.50	Yes	No
4	0.36	Yes	No

Choosing the correct product design specifications (PDS) for a project of this caliber is essential in ensuring the project can find success. Each specification plays a role in helping guide the timeline of this project, so the final prototype is a success. As a group, the PDS we found to be most relevant were testing, maintenance, performance, environment, life in service, materials, safety, and cost. These PDS will help aid in the decision making of the right PVEH and heat generation combination.

Testing is a crucial aspect of the design process, and where most of our work will be. It ensures that the piezoelectric components are creating energy and converting it into sufficient electrical power to generate the heat necessary to melt the ice. Through testing, the performance of the system can be validated under different conditions, such as different vibration levels. It ensures that the system will operate the correct way when installed into the field.

Maintenance is another specification that needs to be carefully considered. Since the system will be embedded in concrete and exposed to different environmental conditions, the design must allow for easy maintenance and minimal intervention over time. Creating a maintenance process that is reliable will ensure that the system remains functional during the life in service. It will also reduce the need for costly repairs and establish consistent performance.

Performance directly impacts the effectiveness of the system. When evaluating the Pugh Matrix, it will have a section for performance of the PVEH and the performance of the heat generation. For the energy harvesting and heat generation system to fulfill its purpose, they each need to do their respective duty to melt the ice effectively. The performance of the system must meet the defined thresholds of creating enough energy and then using said energy to power the heat generation to function as required. The energy harvested per PVEH assembly needs to be at least 90.06 Watt Hours per year for the system to generate enough heat to melt ice. If the system fails to perform adequately, it will not meet the objectives of this project. The environment of the bridge will play a significant role in the design of the system. The real-life application will be exposed to various external factors such as different temperature, wet conditions, and vibrations. The design must be robust enough to withstand these different factors without degrading.

Life in service refers to the expected operation lifespan of the system. Since the system will be embedded in concrete, it must be designed to last for as long as the infrastructure itself to minimize the need for replacements and repairs. To ensure the longevity of the system, the cost can be reduced. The system can then provide consistent performance throughout the service of life. A design that focuses on life in service would reduce the downtime and maintenance costs. Material selection is vital to the durability and efficiency of the system. The materials used for the PVEH components, heat generation elements, and other components need to be chosen for their ability to withstand outside factors. The materials also need to offer high energy conversion efficiency and to integrate with the concrete infrastructure for optimal performance.

Safety is a critical specification to take into consideration to prevent risks to both the public and infrastructure. The system must be designed with safety in mind. Dangers to consider could be electrical hazards, overheating issues, and failures that could damage surrounding structures or pose safety risks to those near the installation. Figuring out the dangers before assembly and prototype will guide the decision-making process. Safety features need to be incorporated into the design to minimize these risks. Cost is a PDS that we need to consider given the project budget. The design must be cost-effective to ensure that it can be implemented at a scale while still meeting technical, performance, and safety requirements. Each bridge that this technology will be installed on will require a 100-200 PVEH assemblies per side to harvest enough energy, so a PVEH unit that has a low cost at volume must be chosen. Additionally, a balance must be found between high performance and reasonable costs to ensure that our prototype can be deployed on a real-life scale. Together, these product design specifications guide the development of a reliable, efficient, and safe design.

Through research and our literature review, it was determined that the design and prototyping of this project should be split up into two main subsystems — energy harvesting and heat generation. The main goal of the energy harvesting subsystem is to convert the mechanical energy created by the bridge into power that can be output through the heat generation subsystem to deice the surface of the concrete. For energy harvesting, we chose PVEH over other methods because of its ability to efficiently convert small mechanical deformations into usable energy. Since highway bridges are constantly vibrating, whether it be from traffic, wind, or some other source, harnessing the energy from those vibrations is essentially a continuous input of energy. Another advantage of piezoelectric technology is the small size especially on platforms like bridges where space is a constraint. Other forms of energy harvesting such as wind or solar energy are intermittent depending on the surroundings. These forms of energy harvesting take up a larger area of space which may not be available near bridges.

Within piezoelectric energy harvesting, there are two main categories: vibration based and strain-based harvesters. The strain-based harvesters take deflections from stresses placed on the harvester and convert that strain into electrical energy. This technology could be used to take the deformations caused by the force of cars driving over the sensor. From our literature reviews, this was a common technology, but it was typically custom made to maximize energy and the sensors on the market were expensive. The vibration-based sensors would take the vibrations from traffic on the bridge and wind hitting the bridge and converting that to electrical energy. These sensors would be tuned for a specific resonant frequency that is generally in the range of 5-20 Hz experienced by highway bridges with a maximum of 40-55 Hz assuming heavy truck traffic [10]. Additionally, maintenance on this type of harvester would be much simpler, and it is a less expensive form of energy generation compared to the strain. Once the strain-based sensors are embedded in the concrete, it would be difficult to diagnose or fix any problem. From this information and after researching available harvesters on the market, we decided to opt for the vibration energy harvester. When using this harvester, a tip mass may be added to decrease the resonant frequency. We are planning to have a set up that has 3 harvesters attached to a 3-D printed fixture with masses and magnets at the ends that will allow us to decrease the resonant frequency and increase the width of the peaks as needed [4]. This would help us generate the maximum energy possible while following the vibration frequency ranges needed.

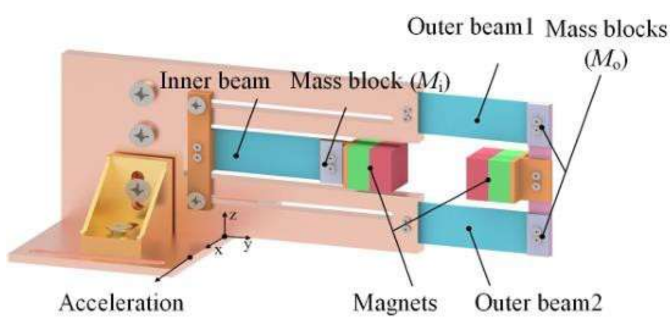

Figure 4. Mass and magnet set up of a 2 DOF PVEH system [4]

In Figure 4, there we can see an example of a similar design that we are pursuing. Three harvester beams with mass blocks and magnets that would allow us to adjust the resonant frequencies. The magnet attached to the outer PVEHs is mounted on a pinned slider, allowing the spacing of the magnets to be changed without printing a new mount each time.

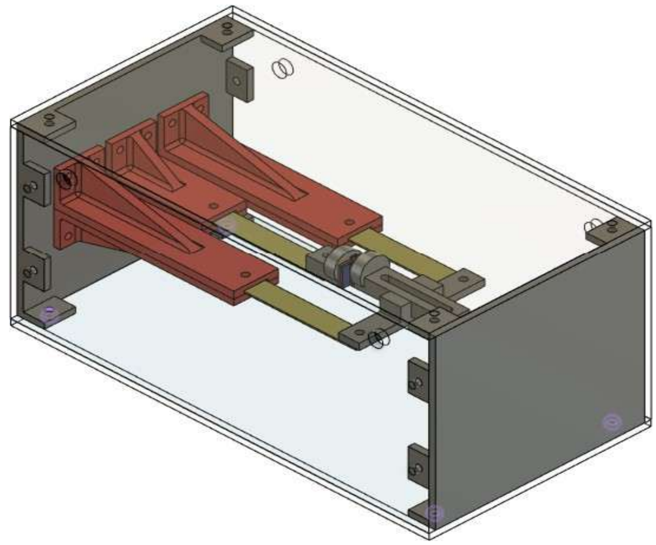

Figure 5. CAD set up of PVEH system

For heat generation, a unidirectional carbon fiber sheet was selected due to its high compressive strength, energy efficiency, and effective heat transfer properties. The high compressive strength that carbon fiber yields is important for handling the everyday forces of traffic. Considering the difficulty of substantial power generation, the energy efficiency that this solution provides is critical. The carbon fiber sheet has fibers aligned in a single direction allowing for consistent heat flow across the fibers. In addition, copper strips — chosen for their great conductive properties — will be attached at either end of the plate perpendicular to the grain of the fibers. This property allows for heat to be emitted uniformly to the concrete. Finally, a calcium silicate plate will be attached to the underside of the carbon fiber sheet, ensuring maximum heat flow being directed upwards into the concrete slab. A CAD render of the chosen design is shown below in Figure 5. In addition to the actual mat, three sensors will be added to the system: PID controller, Solid-State Relay, and a thermocouple. The thermocouple will be used to measure the temperature, while the other two components will regulate the temperature of the system to prevent overheating and damage. The regulation of temperature will also prevent excessive energy usage.

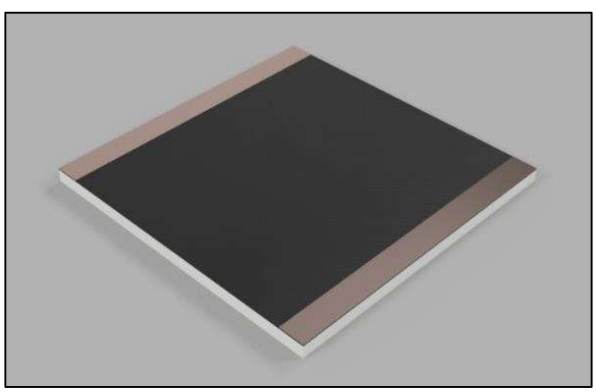

Figure 6. Heat Generation Subsystem

Other explored heat emission options were carbon fiber filaments, woven carbon fiber fabric, waste rubber tires, and impregnated concrete. Based on testing, the carbon fiber filament performed similarly to the unidirectional carbon fiber sheet. However, the filament would need to be bent back-and-forth across the face of the sheet allowing for variability in spacing between the strands of filament. The woven fabric was found to give inconsistent resistances across due to variability in fiber distribution and spacing of the weaves [5].

The waste rubber tires solution— although more cost effective than the carbon fiber plates — has a lower thermal conductivity, less durability, and less predictable conduction patterns [6]. Through research, it was found that impregnating the carbon fiber within the concrete provided the best heat transfer rates [11]. However, this method was not selected due to the extensive lead times for curing the carbon fiber within the concrete, which would make design iterations difficult. Also, mass implementation of this solution would require large-scale bridge surface modifications.

From the Pugh matrix, there is not much variation between the 10 design options. There are two clear that stood out with the most positives, which are design 7 and 8. Design 7 correlates to the combination of the PVEH and the unidirectional carbon fiber. Design 8 correlates to the combination of the PVEH and the woven fabric carbon filament. Since these two are a tie, we need to investigate the differences between the two. They both have a "-" in the performance section of heat generation. This is now a category that can prove a difference between the two designs. In this section the discussion on why unidirectional carbon fiber is better than woven fabric carbon fiber is explained, so as of right now design 7 is the better option. Both designs had a "+" under life in service. Again, there is a difference between the two. The unidirectional carbon fiber is predicted to have a longer lasting longevity effect on a real-life scale when compared to woven fabric. Still, unidirectional carbon fiber remains the better option. Since there is only one more PDS left to observe, the best option for our final design and prototype will be the PVEH system and the unidirectional carbon fiber.

Table 2. Pugh matrix for assessing project variable alternatives

Criteria	1	2	3	4	5	6	7	8	9	10
Testing		+	+	S	-	S	+	+	S	-
Maintenance		S	S	S	-	+	+	+	+	-
Performance (Energy Harvesting)	D	S	S	S	S	+	+	+	+	+
Performance (Heat Generation)	A	-	-	-	+	S	-	-	-	+
Environment	T	S	S	S	S	S	S	S	S	S
Life in Service	U	+	+	-	+	S	+	+	-	+
Materials	M	S	S	S	S	S	S	S	S	S
Safety		S	S	S	S	S	S	S	S	S
Cost		-	-	+	-	S	-	-	+	-
Total (+)		2+	2+	1+	2+	2+	4+	4+	3+	3+
Total (-)		2-	2-	2-	3-	0-	2-	2-	2-	3-

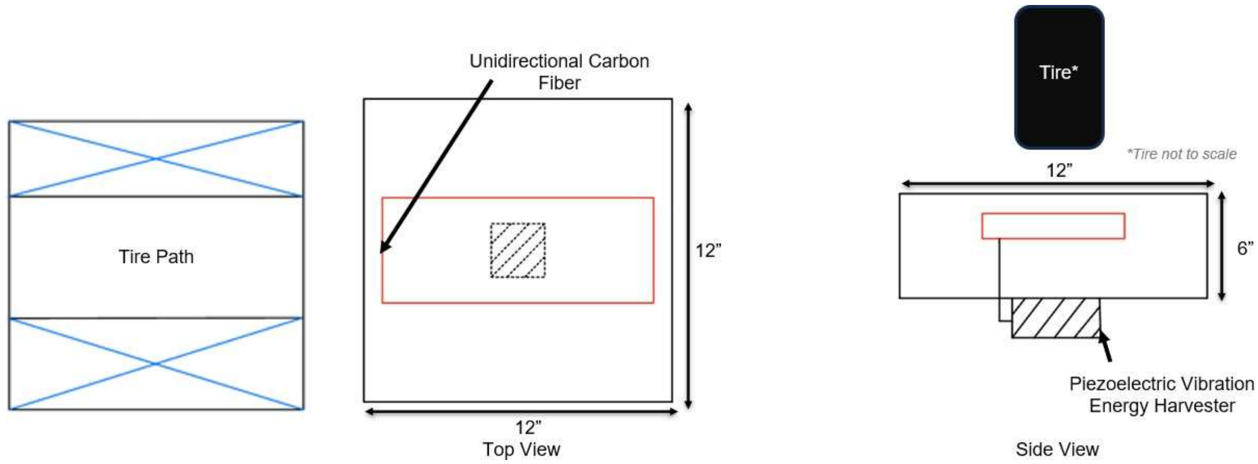

Figure 7. Final Design Concept

In Figure 7, the final design concept of our prototype is shown. It uses the PVEH system seen in Figure 4 and Figure 5. That energy harvester would be drilled on the underside of the cement block and encased in an acrylic home to give viewers visibility to the part. This will then be directly connected to the unidirectional carbon fiber heating pad, seen in Figure 6, that is embedded in cement. To the left of the Top View, and above the Side View in Figure 7, there is a tire path and tire. This is due to the translational research application, we would be targeting specific spots in the roads to heat up, which would be a little larger than the width of the average tire.

5. Project results:

Concrete Testing
The results from the semi-adiabatic calorimetry are found in Figure 8. The highest heat transfer took place in Mixture 2 which was the one with silica fume and steel fibers which suggests that the effects of each addition are additive since the mixtures with one or the other did not see as large of a change. Comparing Mixture 3 and 4, there is an indication that w/c can also play a role, but the combined effect of silica fume and w/c is not as strong as silica fume and steel fibers. Since all 3 variables seemed to have positive effects on the rate of heat transfer, future testing should include interrogate the interaction of all three variables.

Energy Harvesting
For energy harvesting, the final assembly can be seen in Figure 9. There are 3 PVEHs held in place at one end with 3-D printed mounts. The mounts have slots where wires exit that were soldered to the PVEH can connect to the bread board. The sensors are epoxied in the mounts to minimize any movement within the mounts. The outer two sensors are connected with a 3-D printed bar with a slot that has a magnet slider. The inner sensor has a 3-D printed magnet holder as well. The mounting system is enclosed by laser cut acrylic. The pieces are connected to the 3-D printed panels with 3 mm screws. For this project, the intention for the housing design was to prioritize testing. Therefore, the box was designed to be easily unconstructed. The two side panels have ¼” holes for a dowel to be inserted for testing.

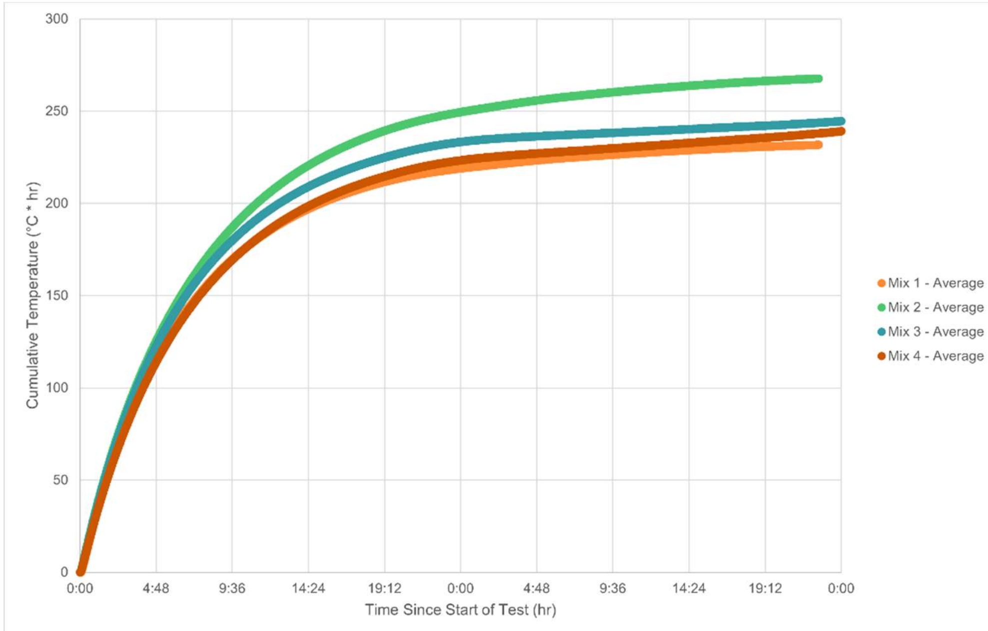

Figure 8: Semi-Adiabatic Calorimetry testing of the various concrete formulations

Figure 9: Final Piezoelectric Energy Harvesting Assembly within Housing

To determine how much mass to add to each sensor the equation (1) was used. This equation relates the original frequency, spring constant, acceleration, max deflection and mass. added to the new frequency. The system was configured to have two resonant frequencies, 23hz for the outer 2 PVEHS, and 29hz for the inner PVEH, with a spacing of 15 mm between the 2 magnets. To accomplish this, masses of 29.46g and 8.04g to the tips of the PVEHs, respectively. It is worth noting that the mass of 29.46g added to the outer PVEHs is split between 2 sensors, so the effective mass added to each tip is 14.73g. Lead fishing sinker weights were used to accomplish this as it was the easiest way to securely add a precise amount of mass. The total mass on each of the sensors includes the screws, nuts, 3-D printed pieces, magnets and lead fishing tape.

Testing then proved that the true resonant frequencies of the system were closer to 21hz and 33hz, respectively. The difference between theoretical and experimental can be attributed to the mass distribution and testing set up. At these resonant frequencies, the recorded peak-to-peak voltage of the output was measured to be 31.62 mV and 12.29 mV, respectively. These results are valid because 2 PVEHs were tuned to the lower frequency of 21hz, so it would follow that the output voltage was almost double at that frequency when compared to the output voltage at 33hz. These voltages, when passed across the Nichrome wire heating element with a resistance of 40Ω, dissipates 3.124 μW and .47 μW, respectively.
Assuming that a highway bridge vibrates at the 2 resonant frequencies for 6 hours a day at each frequency, 21hz for low density traffic and high density traffic at 33hz, the total energy harvested per day is .077 J, or 28 J per year.

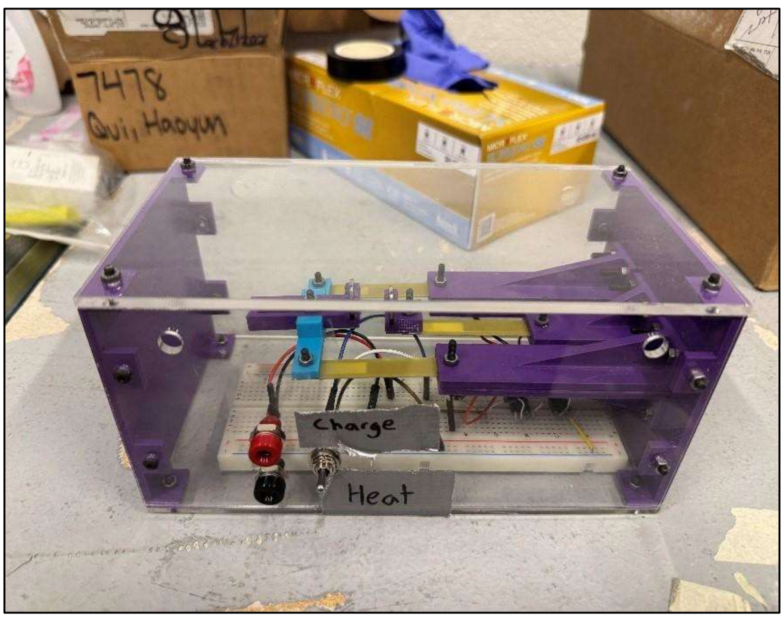

Figure 10. Housing with Breadboard

Circuit Design

The connecting point between the piezoelectric vibration energy harvester and the heat generation system is the circuit system. In Figure 10, one can see the circuitry of our system inside of the housing. There are a few reasons why the breadboard is necessary. First, the piezoelectric vibration energy harvester creates AC voltage which then needs to be converted into DC voltage. Second, there needs to be two separate modes in the breadboard. One to be storing said DC voltage, and a second to be releasing that voltage into the heat generation system. As seen in Figure X there are two labels, “Charge” and “Heat”. When the switch is flipped to the “Charge” side the circuit is in the mode of converting and storing the voltage. When the switch is flipped to the “Heat” side the circuit is in the mode of releasing the stored voltage to the heat generation system. The system itself contains 2 bridge rectifiers, 2 diodes, a 100µF capacitor, a 100Ω resistor, and an On-On Switch. The schematic diagram of the circuit is shown below in Figure 11.

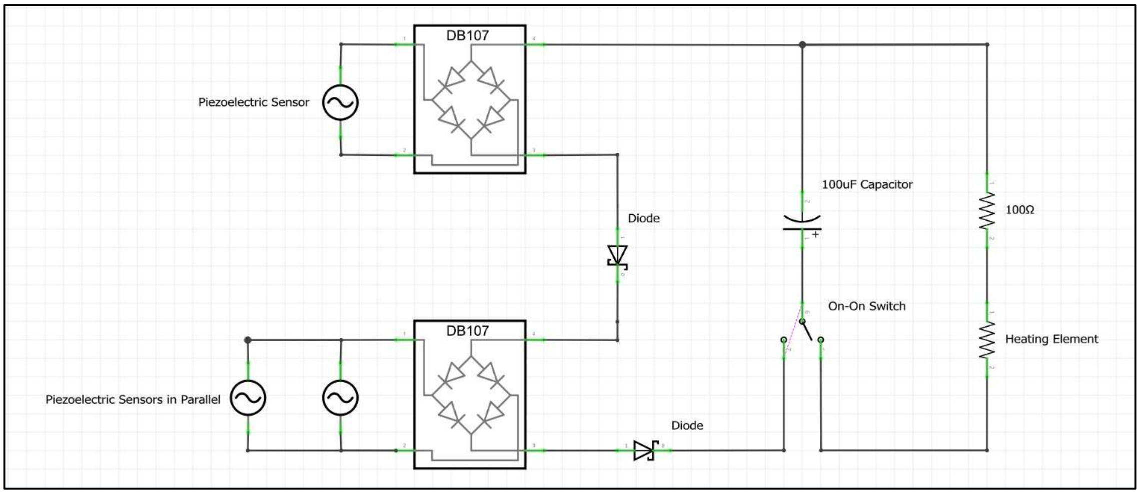

Figure 11. Schematic Diagram of Circuit

Heat Generation

For heat generation, nichrome wire, found in Figure 12 was selected due to its resistive heating capabilities, consistency, and durability. This varies from the final design concept discussed in the Ideation and Discussion section. The nichrome wire was snaked back and forth across a calcium silicate plate. This plate acts as an insulator that prevents heat loss downward and ensures that the heat is directed upward toward the surface of the concrete, allowing it to melt ice effectively. Nichrome was chosen for its high electrical resistance, which makes it ideal for generating heat through Joule heating. The wire layout consisted of six fully stretched loops placed three inches beneath the concrete surface. The spool of nichrome wire came tightly coiled, but the best heating performance was found to be when the wire was slightly stretched out in Figure 12.

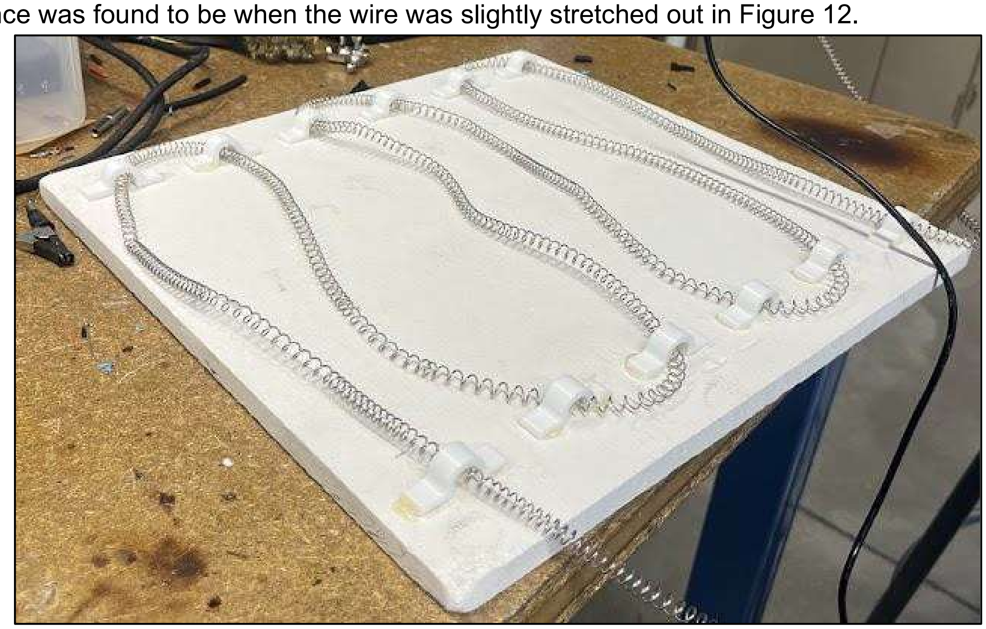

Figure 12. Nichrome wire for heating the concrete.

Other explored heat generation options were a unidirectional carbon fiber plate and woven carbon fiber fabric. The unidirectional carbon fiber plate was initially considered due to its high strength and heat transfer characteristics. However, testing revealed that the plate had virtually no resistance, so it did not heat up via Joule heating. Any heat present was due only to conduction from the copper slabs where current was applied, making it unsuitable for active heating.

Next, woven carbon fiber fabric was tested. On a small scale, this system provided promise. For a 2×6-inch sheet powered at 90 watts, the carbon fiber fabric reached temperatures of 120°C within two minutes. However, for larger applications, the added paths from the weave caused exponentially more regions of heat loss. Due to this fact, and degradation concerns when casting the concrete, other alternatives were explored.

Nichrome wire was explored due to its resistive heat control, uncomplicated structure, and flexibility to be mixed with concrete in the lab or in nature. Open environment testing of the nichrome wire solution yielded encouraging results. With an input of 1.58 A and 17.0 V, the temperature of the wire rose from 24°C to 50.4°C in 5 minutes. This provided enough confidence to proceed with embedding this subsystem within concrete.

The heat generation system is intended to sit 2 inches below the surface of the concrete. However, the mold used was made slightly too tall in the current iteration, causing the heat generation system to be approximately 3 inches below the surface of the concrete. The two ends of the nichrome wire are routed through the mold for connection to power after the concrete fully sets. A midpoint of the concrete casting process can be seen below in Figure 13.

Figure 13. Concrete Casting Process

Since concrete does not typically have good heat transfer properties, the project sponsors are testing various ways to lower its specific heat. The current mixture involves a low water to cement ratio, and infused steel fibers and silica fumes. As research into improving the heat transfer properties of the mixture continues, this system will become more energy efficient.

Buried three inches in the concrete, the nichrome system initially drew 2.0 A at 30 V, and after four hours the current was 4.0 A with the temperature rising from 24°C to 45°C. These results confirmed the wire's ability to generate and store heat in the concrete mass effectively, even with the insulating character of the material. This temperature increase is similar to that of the experimentations in the

literature review.
With this testing, nichrome wire emerged as the optimal choice due to its resistive heat control, uncomplicated structure, and flexibility to be mixed with concrete in the lab or in nature.

Testing Setup
The 2 testing systems used for data collection and tuning of the PVEHs are shown in Figures 14 and 16. The initial testing system, shown in Figure 14, utilized a shaker table where the sensors were then fixed to using custom-made brackets, shown in Figure 15. This testing configuration verified that the circuitry was functioning properly, converting AC to DC, and that the 2 outer beams, when connected, were in phase with each other. However, this setup had major drawbacks. The maximum frequency that the shaker table could produce was around 15hz. Additionally, the amplitude of the oscillations was much larger than a bridge would reasonably flex under load. Finally, the orientation the PVEHs were mounted onto the shaker table was not representative of the true orientation of the system. This means that the effects of adding additional mass to the tips of the PVEHs couldn't be studied, as the added mass adds a small amount of deflection in the PVEHs in a static state, changing the amount of current generated. Therefore, a second testing setup was deemed necessary to test a higher range of frequencies with a smaller displacement, while allowing the system to be oriented properly and testing the effect of the magnets.

The second testing setup is shown in Figure 16. This setup was provided by Professor Blake Johnson, and it was created for a past senior design project. With some retrofitting, it proved to be much more informative than the shaker table.

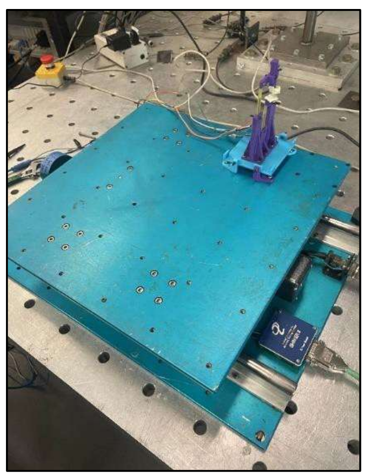

Figure 14. Initial Shaker Table Testing Setup using custom brackets

Figure 15. Custom Brackets for mounting PVEHs to shaker table

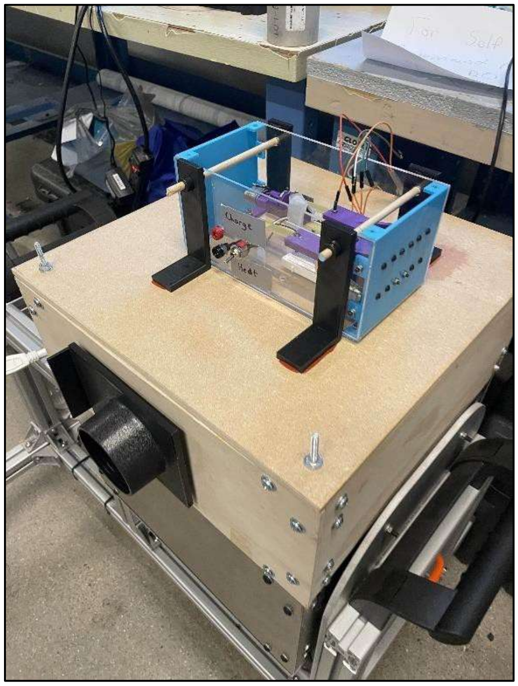

Figure 16. Second testing setup using subwoofer

This setup used a subwoofer, and a fully enclosed volume constructed with plywood. When connected to a computer, tone generation software can be used to play an isolated, constant frequency, which then vibrates the surface of the box where the PVEH enclosure is mounted to. This test allowed for data acquisition at frequencies closer to the targeted frequencies from the calculations. Additionally, it allowed the enclosure to be oriented in the same direction that it would be mounted to the underside of a highway overpass. One downside of this setup, however, was that the amplitude of the oscillations couldn't be quantified in terms of displacement, rather quantified by volume output level from the computer. Due to this, it is hard to verify that these results are representative of the performance of the system if it were mounted to the underside of a highway bridge. For our testing, we chose one volume of 28 and kept it constant throughout.

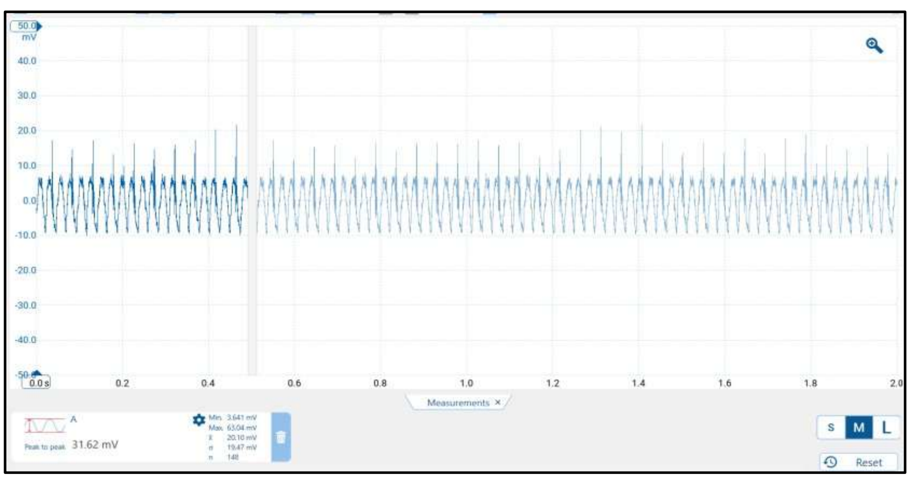

Figure 17. Image Capture of PicoScope 4444

For both testing set ups, an oscilloscope was used to collect the necessary voltage data from the piezoelectric sensors. The oscilloscope was borrowed from Professor Blake Johnson and the model was a PicoScope 4444. An image of the software can be seen in Figure 17**.** Three different scopes were used during testing, one to measure the AC voltage of one of the outer piezoelectric sensors, one to measure the AC voltage of the inner/middle piezoelectric sensor, and the third to measure the DC voltage across the 100Ω resistor.

With our data collection, we did some preliminary calculations on the amount of power generated. In these calculations a few assumptions were made: (1) 6 hours of high density and 6 hours of low- density traffic daily, (2) the average peak to peak voltage generated is 31.62 mV for low frequency and 12.29 mV for high frequency as per our testing, (3) power is perfectly dissipated through the heating element. Given that the highway dimensions are 100 ft x 36 ft and each unit is 8 in x 4 in. We could fit approximately 14,000 units. These units would generate ~1400 W of power per year. The total cost assuming $162 per unit would be $2,268,000. This is a large overestimate, due to the per sensor pricing decreasing when more sensors are ordered in bulk.

Figure 18 shows the design team presenting their work publicly at the Mechanical Science and Engineering Capstone presentation day. The team won the prize for the best demonstrator.

Figure 18. Mechanical Science and Engineering student design team capstone presentation (top left), the cast concrete bridge deck specimen with the embedded nichrome wire (top right) and the energy harvesting piezoelectric system under the bridge deck specimen (bottom)

Budget
For this proof-of-concept, purchases are sorted into three categories — energy harvesting, heat generation, and material testing. Most of the expenses that this project incurs are attributed to the piezoelectric sensors that will be used for power harvesting and the unidirectional carbon fiber plate used for heating the concrete slab. A complete look at the bill of materials for this system can be found below in Table 3.

The final budget for this project totaled $903.63, which is well within the $1500 allotted at the beginning of the semester. These costs included purchases from initial iterations, such as the carbon fiber plate. Due to this and the fact that the piezoelectric harvesters get substantially cheaper when purchased in bulk, the total unit cost for implementing this system as a mass scale would be a lot cheaper. The components for this system are selected from reputable vendors such as Amazon and Grainger.

Table 3. Bill of Materials

Part	**Subsystem**	**Price Per Unit**	**Quantity**	**Total Cost**
Unidirectional CF Plate	Heat Generation	$85.62	1	$85.62
Copper Bar	Heat Generation	$27.35	1	$27.35
Conductive Tape	Heat Generation	$4.95	1	$4.95
Nichrome Wire	Heat Generation	$0.00	1	$0.00
Calcium Silicate Plate	Heat Generation	$30.45	1	$30.45
High-Temp Silicone Gasket	Heat Generation	$25.88	1	$25.88
Piezoelectric Harvester	Energy Harvesting	$100.76	6	$604.56
Full Bridge Rectifier	Energy Harvesting	$0.44	6	$2.64
1N5819 Diode	Energy Harvesting	$0.21	6	$1.26
Breadboard	Energy Harvesting	$8.44	1	$8.44
Loctite Epoxy	Energy Harvesting	$8.40	1	$8.40
PLA Filament	Manufacturing/Testing	$.03/g	500	$15.00
Alligator to Banana Plug	Manufacturing/Testing	$7.85	4	$31.40
Banana Plug Jack	Manufacturing/Testing	$1.42	4	$5.68
On-On Switch	Manufacturing/Testing	$3.41	2	$6.82
Multimeter	Manufacturing/Testing	$24.82	1	$24.82
Acrylic Sheet	Manufacturing/Testing	$10	2	$20
Concrete Mix	Testing			
		Total Cost:		$903.63

6. Conclusions and recommendations:

Conclusions

This research successfully demonstrated the feasibility of self-powered deicing system for precast concrete bridge panels using piezoelectric vibration energy harvesting technologies. The key findings include:

- The various modifications to the concrete did yield a change to the thermal transfer properties. The formulation using both the silica fume and the steel fibers had the highest rate of heat dissipation indicating the lowest specific heat. This also suggests that multiple strategies can be employed simultaneously with additive effects.

- Energy Harvesting Performance: A three-sensor PVEH system achieved resonant frequencies of 21 Hz and 33 Hz, generating peak-to-peak voltages of 31.62 mV and 12.29 mV, respectively. Under simulated bridge vibration conditions, the system harvested 0.077 J/day, or approximately 28 J/year. Adjustable tip masses and magnetic spacing effectively tuned the frequency response, broadening the operational bandwidth to match low-frequency bridge vibrations.

- Heat Generation Effectiveness: The Nichrome wire embedded three inches below the concrete surface increased the slab temperature from 24°C to 45°C within four hours. This confirms the system's capability to deliver sufficient heat for ice prevention, even with limited power input.

- System Integration: The integration of AC-to-DC conversion circuitry, energy storage, and automated switching between charging and heating modes created a functional prototype that operates independently of external power sources.

In this exploratory research, two groups of undergraduate students worked together to develop a prototype of a pavement that would harvest energy which could be used to melt ice. The key challenge to this work was the short timeline for the project which limited the number of variables that could be studied for both the energy generation system and the concrete formulations. Despite the time constraint, this work will serve as a critical foundation to build future research where both the concrete and mechanical system can be optimized to find a feasible solution for self de-icing pavements.

Recommendations

Energy Harvesting Optimization: Future development should focus on enhancing energy capture efficiency through:

- Test varying magnet configurations and adjust spacing to improve resonance and output.
- Use sensors with lower resonant frequencies to better align with typical bridge vibration amplitudes.
- Conduct comprehensive field testing on actual bridges to characterize vibration profiles and validate lab-based performance estimates.

Heat Generation Efficiency: Thermal performance can be enhanced through:

- Repositioning the heating element closer to the concrete surface (reducing from 3 inches to 2 inches depth).
- Optimization of nichrome wire density and configuration for more uniform heat distribution
- Installation of thermocouples throughout the concrete to monitor temperature gradients and enable feedback control.
- Investigation of alternative heating materials with higher energy efficiency ratios

System Reliability and Durability: Long-term performance improvements require:

- Transition from breadboards to printed circuit boards (PCBs) with soldered joints and weather-resistant epoxy coatings.
- Develop automated switching systems that respond to environmental cues (e.g., temperature or humidity) without manual input.

Concrete Mix Optimization: Collaboration with materials engineers to:

- Develop mixes to explore the interaction of the mixture formulation on thermal properties.
- Reconcile the impacts of the various mixture modifications on durability standards.
- Evaluate long-term structural integrity of modified concrete under repeated thermal cycling and load exposure.

Future system development will need to focus on efficiency, longevity, and long-term performance. Experimenting with different magnets and adjusting distances between them will optimize the energy harvested from oscillation and overall power for energy harvesting. More funding could involve the use of sensors with lower resonant frequencies to increase energy harvesting from lower-amplitude bridge vibrations. Pairing better configurations with more testing will also help benefit efficiency. Testing vibration amplitudes on actual bridges will help determine the typical frequency and amplitude ranges, allowing for the selection of sensors to be best fit for real world applications producing data that can help accurately estimate the energy produced.

On the circuit side, the next steps are to connect the breadboard to external energy storage and power support devices. This will make it possible to continuously log data over multiple hours up to weeks at a time. The setup will allow very accurate measurement of how much energy is harvested daily, something that will be enlightening about sensor functionality and will inform system design refinement. Permanent electrical connections between components and the breadboard will make it more reliable. The transition to a soldered joint printed circuit board and an epoxy overlay that will be non-conductive will make it more durable and resistant to environmental stress. Another aim is to automate by having an incorporation of a switching system in which the breadboard would switch among various modes of operation based on various input conditions. Moving the heat generation subsystem closer to the surface of the concrete and winding the nichrome wires more tightly will provide for more efficient power consumption when heating. This would be aided with an optimized concrete formulation. Thermocouples can be added to monitor temperature gradients through the concrete so that there can be improved control and optimization via feedback using data. Varying concrete mix proportions may also influence thermal conductivity and heating efficiency. Since the current system draws a lot of power in comparison to the energy that is capable of being harvested, alternate sources of heating with greater energy efficiency will need to be investigated. In addition, heating may be limited to high-impact zones such as the tire track, which will further reduce power consumption without sacrificing deicing effectiveness.

7. Practical application/impact on transportation infrastructure:

The impact of this research would have numerous benefits for both the environment, highway safety and infrastructure longevity. As is well documented, bridge decks are the first infrastructure to freeze, and require regular application of de-icers to maintain a safe roadway. Eliminating the need for de-icers would reduce the rate of corrosion on bridge infrastructure and reduce unwanted runoff. A self de-icing system, as presented herein, would employ precast pavement that harvest energy from the vibrations of passing vehicles and transfer it into heat for de-icing.

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10. Appendices (if applicable