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IoT and AI-Enabled Smart Pavement for Energy Harvesting and Autonomous De-Icing in Smart Cities

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PREFACE

First and foremost, I am deeply thankful to God for his grace and support have provided me with the strength and determination needed to carry out and complete this research. This thesis “IoT and AI-Enabled Smart Pavement for Energy Harvesting and Autonomous De-Icing in Smart Cities,” has been prepared as a part of my master’s degree in information technology at Metropolia University of Applied Sciences. The main idea of this thesis is to explore how a pavement system could both generate energy and melt ice automatically by using modern technologies like IoT and AI.

The motivation behind this topic came from real-life challenges I noticed, especially in urban areas. Energy use is growing fast, and icy roads cause many problems during winter. I wanted to find out if technology could help solve both of these issues. By studying existing research and developing a conceptual model and doing some technical calculations, this thesis offers a practical approach that combined IoT technology with innovative energy harvesting solutions.

I would like to thank my supervisor, Ville Jääskeläinen who supported me throughout the process. His comments and guidance helped me stay focused. I also thank my teachers, classmates and friends who shared their thoughts and encouraged me during this journey. Special thanks goes to my parents and my wife. Their support and patience truly helped me during my difficult times.

Completing this thesis has been a meaningful achievement for me. It was a great learning experience for me both academically and personally. I hope it can be useful for others who are interested in smart urban infrastructure and energy-efficient technologies.

Finland, 22 May 2025
Ashraf Hossain Khan

Abstract

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Cities around the world are growing fast and with this growth come new challenges like energy shortages, unpredictable weather and the need for safer roads. To deal with these issues, many cities are turning to smart technologies to improve how infrastructure works. This thesis explores one of those ideas: a smart pavement system that can create its own energy and melt ice automatically. This can help cities save power and make roads safer, especially in winter. The main goal of this research is to design a pavement concept that can collect energy from footsteps and car movements. This would be done using special materials called piezoelectric and triboelectric nanogenerators. These materials can turn pressure and motion into electricity. The energy collected could then be used to power things like sensors, and then heat the pavement and remove ice when it’s cold. The system uses small sensors and Internet of Things (IoT) technology to detect when the temperature is low and ice might form. It can then start a heating process to melt the ice before it becomes dangerous. This thesis includes a review of different energy harvesting technologies and de-icing methods used today. It also looks at current smart pavement systems and their challenges. Based on this information, the thesis proposes a new system that combines both energy harvesting and automatic de-icing features. It also includes IoT sensors to help monitor and control the system in real-time. Although this is a design-level study and not a working prototype, the concept shows great promise.

The smart pavement system presented in this thesis could help cities reduce energy costs, lower accident risks from icy roads, and support sustainable development. The design can be developed further through testing and real-life implementation. It also offers ideas for future studies such as using machine learning to make the system smarter and more efficient.

Keywords: Smart pavement, energy harvesting, autonomous de-icing, piezoelectric, triboelectric nanogenerator, IoT, smart cities, sustainable infrastructure.

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List of Abbreviations

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AI	Artificial Intelligence
IoT	Internet of Things
MCU	Microcontroller Unit
AC	Alternating Current
ADC	Analog-to-Digital Converter
AI	Artificial Intelligence
AIoT	Artificial Intelligence of Things
BMS	Battery Management System
BLE	Bluetooth Low Energy
DC	Direct Current
GPS	Global Positioning System
I	Current (Amperes)
I2C	Inter-Integrated Circuit
IoT	Internet of Things
J	Joule
kWh	Kilowatt-hour
LCD	Liquid Crystal Display
LDR	Light Dependent Resistor
LED	Light Emitting Diode
MCU	Microcontroller Unit
ML	Machine Learning
M2M	Machine to Machine
PENG	Piezoelectric Nanogenerator
PZT	Lead Zirconate Titanate
R	Resistance (Ohms)
RTOS	Real-Time Operating System
SPI	Serial Peripheral Interface
TENG	Triboelectric Nanogenerator
USB	Universal Serial Bus
V	Volt
Wh	Watt-hour

1 Introduction

Smart cities use technology and new ideas to improve roads, safety and the environment. Roads and pavements are important parts of a city and used every day by people and vehicles. In the past, pavements were only designed to provide support and safety. But with new technology, pavements can be now do more. It can perform additional functions such as energy generation and automated de-icing.

This thesis focuses on the concept of IoT and AI-enabled smart pavement systems that can harvest energy and then perform autonomous de-icing. These systems use piezoelectric and triboelectric technologies to collect energy from pressure and movement like footsteps or vehicle pressure. At the same time, integrated de-icing mechanisms can detect icy conditions and respond without human intervention. This makes the pavement more useful in cold areas where ice can be dangerous.

The goal of this study is to review current technologies and find limits and propose a conceptual framework for a smart pavement system. The main goal is to help build safer, cleaner and energy-efficient urban infrastructure. The motivation for this research comes from the growing need for smart solutions in public places and the change to lower accidents and energy costs in cities.

1.1 Background and Motivation

Urbanization is rapidly increasing, placing pressure on cities to develop smarter and more efficient infrastructure. Traditional pavement systems serve a single purpose to provide a solid and safe surface for walking and driving. Traditional pavement systems do not produce energy and can not react to weather conditions like snow or ice without manual work. But with recent progress in Internet of Things (IoT), Artificial Intelligence (AI), and energy harvesting, now we have an opportunity to rethink how pavements can be used. Special materials such as piezoelectric and triboelectric can be placed inside pavements to capture energy from the movement of people or vehicles. This energy can then be used to power devices like streetlights or sensors, or it can be stored for later use. At the same time, smart de-icing systems can collect weather data to detect when ice starts to form and automatically switch on heating elements to melt it. The motivation behind this research comes from two main goals. First, to explore how smart pavement technologies can enhance urban sustainability by generating renewable energy. Second, to improve public safety through automated de-icing that can reduce accidents and maintenance costs, especially in extreme cold regions. So far, these two solutions haven’t been combined into one system within a pavement structure.

This topic is important, as more cities around the world are working to become smarter and more efficient. By proposing a design for a smart pavement system that can perform multiple functions. This research hopes to support the growth of safer, more energy-efficient urban environments.

Modern cities, especially those in cold regions face big challenges with energy use and road safety in winter. One ongoing issue is the buildup of ice and snow on roads and walkways which can be dangerous for both pedestrians and vehicles. Common methods for de-icing like using road salt, chemicals, or electric heaters can harm the environment, use a lot of energy or cost too much. At the same time, busy city areas experience constant foot and vehicle traffic, which creates kinetic energy that usually goes to waste.

Also, while solar and wind power are popular renewable energy sources, they rely heavily on location and weather. That makes them harder to use in all city areas. In contrast, a pavement system that collects energy from daily movement can work in many places. By using Internet of Things (IoT) and Artificial Intelligence (AI), such systems could monitor conditions in real time and adjust their performance to work better and save energy.

This research aims to fill the gap by designing a smart pavement system that can collect mechanical energy from traffic and use that energy to power a built-in de-icing feature. The main challenge is figuring out how to design and optimize this system so it works well, saves energy, is environmentally friendly, and can be used in different city settings. If successful, this solution could improve public safety, reduce harm to the environment, and support the move toward greener urban infrastructure.

1.2 Objectives of the Research

The primary aim of this research is to propose a conceptual model for a smart pavement system that have both energy harvesting and autonomous de-icing capabilities. The objectives of this research are as follows:

Design a Conceptual Model for a Smart Pavement System:
This objective involves creating a conceptual framework for a smart pavement system that can generate energy through piezoelectric and triboelectric mechanisms. These technologies convert mechanical energy generated by traffic and pedestrian movement into usable electrical energy. The design will address the system's scalability, efficiency and integration into urban infrastructure.

Develop a Theoretical Framework for an Autonomous De-Icing System:
This objective involves developing a framework for an autonomous de-icing system integrated within the energy-harvesting pavement. The system will activate based on real-time environmental data based on temperature and moisture levels, to prevent the accumulation of ice on the pavement, ensuring road safety in winter conditions.

1.3 Scope and Limitations

This research aims to develop a conceptual model for a smart pavement system that combines energy harvesting and autonomous de-icing. The focus is on designing a system that can generate energy from pedestrian and vehicular movement, and use that energy for de-icing purposes. The study is primarily concerned with evaluating how such a system could be integrated into urban environments, especially in cold climates.

The scope of the research includes:

- **Conceptual Design:** The creation of a theoretical model for a smart pavement system that incorporates both energy harvesting and autonomous de-icing.
- **Energy Harvesting Technologies:** The study will explore how piezoelectric and triboelectric materials can be used to capture mechanical energy from foot traffic and vehicles.

- **Autonomous De-Icing:** The research will consider how the harvested energy can power a self-operating de-icing system to keep pavements clear of ice.
- **Urban Applications:** The focus will be on the potential integration of this system into existing urban infrastructure, particularly in cities that experience harsh winter weather.

While the research will provide a detailed conceptual framework, there are some limitations to consider:

- **Practical Testing:** This research will not involve physical prototypes or real-world testing of the proposed system. It is focused on theoretical design and feasibility.
- **Cost and Implementation:** While the study will assess the energy efficiency and scalability of the proposed system, detailed cost analysis and the practical implementation challenges will not be fully explored.
- **Environmental Variability:** The research will primarily focus on cold climates, particularly those in regions with harsh winters. The system's performance in other climates may require additional consideration.
- **Material Availability:** The research will rely on existing studies and available data to suggest materials for the system, without conducting experiments on material properties or sourcing.

1.4 Thesis Structure

This thesis is structured to give a clear understanding of the smart pavement system, how it is designed and how it can be used in smart cities. The structure is organized as follows:

Chapter 1 Introduction This chapter explains the topic of the research. It includes background information, the problem being studied, the goals of the research, and its scope and limitations. It also introduces the key ideas of energy harvesting and automatic de-icing in smart pavement systems.

Chapter 2 Theoretical Background This chapter reviews the relevant literature and theories behind the technologies that form the foundation of the research. It covers smart pavement systems, piezoelectric and triboelectric energy harvesting mechanisms, and existing autonomous de-icing systems. The chapter provides a theoretical basis for the design and development of the proposed system.

Chapter 3 Current State Analysis This chapter analyzes existing solutions and technologies in the domain of energy-harvesting pavements and autonomous de-icing systems. It evaluates their strengths, weaknesses, and limitations, helping to identify the gaps that the proposed system will address.

Chapter 4 Conceptual Framework and Proposal This chapter presents the core of the research—the conceptual model for a smart pavement system integrated with autonomous de-icing capabilities. The framework will detail the design of the system, including energy harvesting, de-icing mechanisms, and the role of IoT and AI in the system's operation.

Chapter 5 Discussions and Conclusions This chapter summarizes the findings from the previous chapters, discussing the potential impact of the proposed system on urban infrastructure. It addresses the feasibility of the concept, identifies challenges, and provides recommendations for future research and development in this field.

2 Theoretical Background

This chapter provides a comprehensive review of the relevant literature and theoretical frameworks that support the technologies involved in the proposed smart pavement system. It explores the existing research in the areas of energy harvesting, particularly piezoelectric and triboelectric mechanisms, as well as the concept of autonomous de-icing systems, with a focus on their applications in smart cities.

2.1 Smart Pavement Technologies

Smart pavements are an advanced form of infrastructure that extends the traditional role of roadways and walkways. Smart pavements do more than just provide roads, smart pavements are designed to integrate various technologies that enhance energy efficiency, safety, and sustainability in urban environments.

A main feature of smart pavements is their ability to collect energy from things like traffic and people walking on them. This energy is then converted into electrical power, which can be used to run embedded systems or stored for later use. The integration of energy harvesting mechanisms within pavements reduces dependency on external power sources and helps to create self-sustaining urban infrastructures.

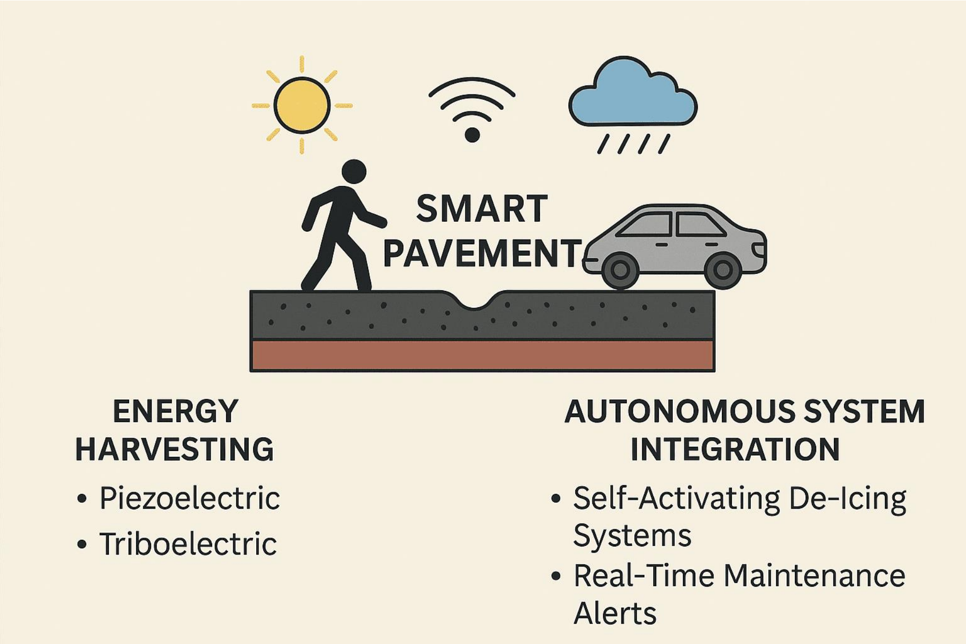

Figure 1. Conceptual Diagram of Smart Pavement System

Smart pavements are defined by the following key components:

- **Energy Harvesting:** This process involves the conversion of mechanical energy from moving vehicles and pedestrians into usable electrical energy. Piezoelectric and triboelectric materials are commonly used to capture and convert the energy generated by these movements.
- **Autonomous System Integration:** Smart pavements can integrate systems that operate autonomously, such as self-activating de-icing systems, real-time maintenance alerts, and health monitoring mechanisms for the pavement structure. These systems enhance the pavement's functionality, allowing it to respond dynamically to environmental changes without human intervention.

By incorporating these technologies, smart pavements can help to address urban challenges such as energy consumption and safety in extreme weather conditions.

2.2 Piezoelectric and Triboelectric Energy Harvesting

Energy harvesting is a critical component of smart pavement systems. It allows for the generation of power from ambient mechanical energy, which can then be used to power embedded sensors and systems. Among the most promising energy harvesting technologies for pavements are piezoelectric and triboelectric mechanisms.

These two mechanisms complement each other in pavement systems. While piezoelectric devices are efficient under compressive stress (like from heavy vehicles), triboelectric systems are more suitable for repetitive, light-force motion (like pedestrian footsteps). Integrating both technologies can improve total energy output and system resilience under different traffic patterns.

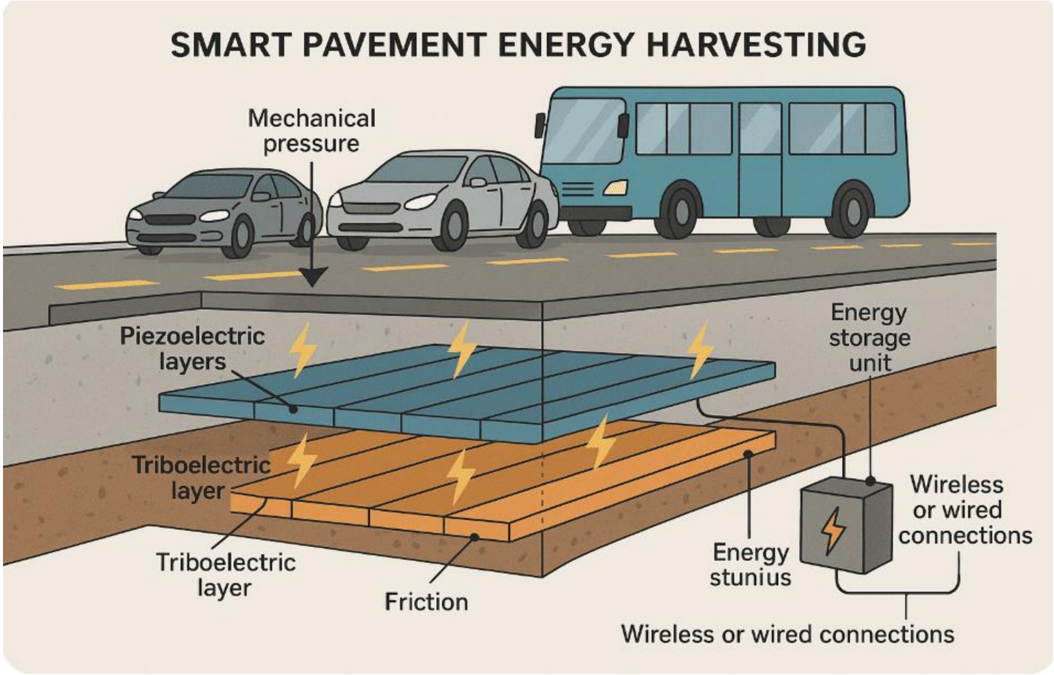

Figure 2. Conceptual Model for a Smart Pavement Energy Harvesting System

1. **Piezoelectric Energy Harvesting:**

Principle: Piezoelectric Energy Harvesting involves materials such as PZT (lead zirconate titanate), which generate electric charge when subjected to mechanical stress. When embedded under road surfaces, these materials can convert the kinetic energy from moving vehicles and foot traffic into electrical energy.

According to research by Qabur, A., & Alshammari, K. (2018) from the University of Waterloo, Canada, piezoelectric materials embedded under highway could generate approximately 200 KWh/KM for a single lane and 1 MWh/KM on four lanes electrical energy in converting mechanical stress from vehicular movement [1]. The study examines various piezoelectric materials, such as Lead Zirconate Titanate (PZT) and evaluates their efficiency in converting mechanical stress from vehicular movement into electrical energy.

Another study by Papagiannakis, A. T., Dessouky, S., Montoya, A., & Roshani, H. (2016) explored piezoelectric energy harvesting from roadways. The research assumed 30,000 vehicles per day AADT (Average Annual Daily Traffic) on highway.

Several companies were compared: Treevolt claimed up to 720 kW/km with 600 vehicles/hour, Genziko estimated 13,600 kW under similar conditions, Innowattech reported 200 kW with modules placed under both wheel paths [2].

A study by Vaux, A., Anwar, S. (2024) studied the use of piezoelectric devices on highways to generate renewable energy from moving vehicles. Roads in California, Israel, India and Italy are being tested for this purpose. According to the California Energy Commission, could produce up to 72,800 kWh of energy per year, depending on traffic speed, volume and force. The study found that power output increases with higher traffic and speed. The results support continuing research on piezoelectric highways and their benefits for reducing energy waste and pollution [4].

Another study developed a high-density piezoelectric energy harvesting device designed for highway traffic. The system tested in real-world conditions and demonstrating its capability to harvest significant amounts of energy from roadway traffic [6].

Applications: In smart pavements, piezoelectric devices are embedded within the pavement surface, where they are subjected to the stress and strain caused by traffic loads. This electrical energy can be harnessed and used to power sensors, lights, or other components of the smart pavement system. The ability to capture energy from vehicle and pedestrian movements makes piezoelectric materials an ideal choice for energy generation in urban environments.

2. **Triboelectric Energy Harvesting:**

Principle: Triboelectric Nanogenerators (TENGs) generate electricity from the contact and separation between materials with differing electron affinities. In pavement applications, TENGs can be integrated into surface layers to capture energy from footfall or tire interactions.

A study by Rayegani, A., Nazar, A. M., & Rashidi, M. (2023) explains how triboelectric nanogenerators (TENGs) have improved and become more efficient and sensitive for self-powered sensing. It highlights that many road accidents happen due to poor road conditions, bad weather and air pollution. The study focuses on how TENGs can help monitor driving behavior and road surroundings while also collecting energy, especially in smart roads like bridges, tunnels and highways [3].

According to research by Selim, Kyrillos K., Yehia, H. M., & Saleeb, D. A. (2024) demonstrated that a TENG pavement generate usable electrical power energy from repeated footsteps [5].

In a research study, a prototype of the Triboelectric Energy-Harvesting Floor Tile (TEHFT) was built using a 0.2 mm thick PTFE (polytetrafluoroethylene) layer for energy harvesting. When a 60 kg person stepped on the tile at a frequency of 2 Hz, the device generated a peak voltage of 344 V and was capable of illuminating up to 150 LEDs at full brightness. The optimal resistive load for this setup was found to be 1.1 MΩ and resulting in a peak current of 109.8 μA and a power output of 13.26 mW. These results demonstrate the potential of TEHFTs to harvest significant energy from human movement and suitable for powering small electronic devices and also for sensor nodes [7].

Applications: Triboelectric systems are particularly useful for capturing energy from the constant movement and friction created by vehicles and pedestrians. These systems can be integrated into pavement surfaces or placed strategically in areas with high levels of foot and vehicle traffic. Triboelectric energy harvesting offers a low-cost, efficient way to generate power from mechanical movements in urban environments.

The electricity harvested from these two sources suitable for powering localized systems such as streetlights, environmental sensors, and in this study's context, autonomous de-icing components.

Table 1: Comparison of Energy Harvesting Mechanisms

Mechanism	**Description**	**Advantages**	**Challenges**
Piezoelectric	Converts mechanical pressure into electrical energy through materials like crystals or polymers.	High efficiency, continuous energy generation	Requires specific materials, costly to scale.
Triboelectric	Harvests energy through friction between two materials.	Low cost, adaptable to various materials.	Lower efficiency than piezoelectric.
Hybrid Systems	Combines both piezoelectric and triboelectric methods to maximize energy harvesting potential.	Increased efficiency, versatile applications.	Complex design, higher initial cost.

2.3 Autonomous De-Icing Techniques

Autonomous de-icing systems are designed to improve road safety by preventing the formation of ice on pavements and roadways during cold weather. Traditional methods of de-icing, such as road heating systems and the use of salt, are often energy-intensive and can have negative environmental impacts. Autonomous de-icing systems, on the other hand, aim to provide a more sustainable and efficient solution.

- **Sensor-Driven Activation:** Autonomous de-icing systems rely on sensors that monitor environmental factors such as temperature, moisture, and surface conditions. When conditions are favorable for ice formation, the system automatically activates de-icing measures. This activation is based on real-time data, allowing the system to respond dynamically to changes in the environment.
- **Data Integration:** By integrating IoT devices with weather and surface condition data, autonomous de-icing systems can optimize the timing and location of de-icing actions. This helps to ensure that de-icing measures are applied only when necessary, reducing energy consumption and minimizing waste.

- **Sustainable De-Icing Materials:** One of the key advantages of autonomous de-icing systems is the use of sustainable, environmentally friendly de-icing materials. Traditional salt-based de-icing systems can cause significant damage to infrastructure, plants, and wildlife. In contrast, autonomous systems can use non-toxic, biodegradable substances or other sustainable alternatives, reducing their environmental impact.

Modern autonomous systems use a combination of sensors, actuators, and control logic enhanced by IoT and AI algorithms to activate heating only when necessary. These systems monitor real-time temperature, humidity, and surface conditions, allowing the pavement to operate reactively and efficiently.

To estimate how much ice can be melted using the harvested energy by consider following:

"The energy required to melt 1 kg of ice at 0 °C is approximately 333.55 (~334) kilojoules (kJ), which is equivalent to 0.09265 kilowatt-hours (kWh) [8]."

If a piezoelectric pavement generates around 200 kWh/day/km generated per kilometer for single lane and 1,000 kWh/day/km for four lanes (Qabur & Alshammari, 2018) [1], it could theoretically melt up to ~ 2,150 (200/0.093) kg of ice/day for single lane and ~ 10,750 (1000/0.093) kg of ice/day for four lanes (based on the 0.093 kWh required to melt 1 kg of ice). These estimates assume that piezoelectric road systems have the potential to melt between 2,150 kg and 10,750 kg of ice per day per kilometer depending on traffic volume and road configuration.

This supports the feasibility of powering a localized autonomous de-icing system, especially in pedestrian pathways or intersections and the feasibility of implementing such a system in northern cities that experience frequent snowfall.

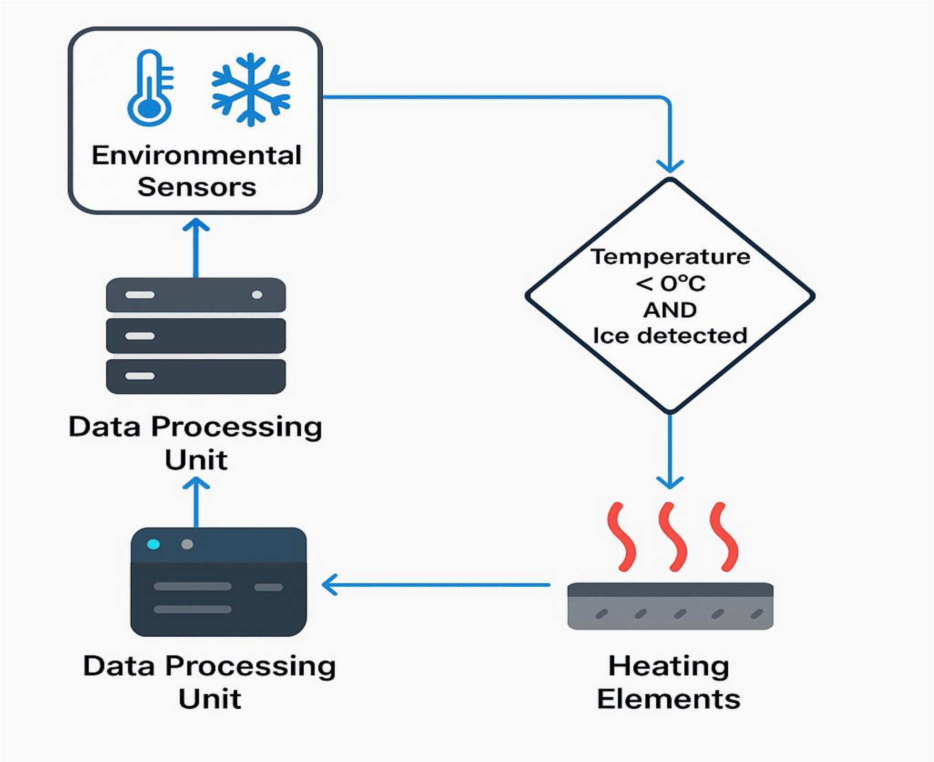

Figure 3. Temperature Processing Unit for an Autonomous De-Icing System

The temperature processing unit as shown in Fig 3, which forms part of the system designed in this research, will integrate data from surface-level sensors and initiate the de-icing process when specific thresholds are crossed. The collected energy will be stored in a battery or supercapacitor system and managed using energy-efficient algorithms.

Table 2: Types of De-Icing Systems

System Type	**Working Principle**	**Key Features**	**Example Use Case**
Resistive Heating	Electrical heating elements embedded in the pavement to melt ice.	Quick response, effective in low temperature.	Urban roads with frequent ice accumulation.
Hydronic Heating	Heated fluid circulates through pipes embedded in the pavement.	Uniform heat distribution, efficient.	High-traffic roads with heavy snowfalls.

Inductive Heating	Electromagnetic fields induce heating in metal components within the pavement.	Long-term solution, energy-efficient.	High-speed highways in cold regions.

In this thesis, the autonomous de-icing framework will be powered by harvested energy and controlled through temperature and humidity sensors. This approach contributes to a self-sustained, smart urban infrastructure that ensures safety during extreme winter without external power dependency.

3 Current State Analysis

This chapter reviews the current state of smart pavement systems and focusing on two key components relevant to this thesis, energy harvesting technologies and autonomous de-icing methods. It evaluates real-world developments, existing prototypes and research studies to highlight what has been achieved so far and where gaps remain.

3.1 Existing Energy Harvesting Pavement Systems

Energy harvesting pavements are still arising area of smart infrastructure. Some pilot projects and research studies have shown that it is possible to generate electricity from the mechanical pressure of pedestrian and vehicle movement. Most systems use piezoelectric materials while fewer use triboelectric mechanisms. In general, current implementations remain at a small or experimental scale.

Piezoelectric-Based Pavements:

Piezoelectric systems use materials that generate an electric charge in response to mechanical stress. For example, piezoelectric pavements have been installed in places like railway stations, shopping centers and sidewalks in Japan and the UK. These systems typically consist of tiles embedded with piezoelectric materials which produce electricity when compressed by foot traffic. The generated energy is often used to power nearby streetlights or information displays.

Several research institutions have also developed road-based energy harvesting prototypes. These systems are usually installed under asphalt layers and tested for their ability to generate energy from heavy traffic. The results have shown promising energy output levels, especially under high-load conditions such as highways or bus lanes. However, installation costs, durability and long-term efficiency remain significant concerns. One of the earliest experiments was conducted in Israel by the company Innowattech, which installed piezoelectric devices under road surfaces to harvest energy from traffic. Their system was reported to produce up to 200 kW per kilometer of roadway, depending on traffic conditions [15].

Another significant project was funded by the California Energy Commission, which tested piezoelectric transducers embedded in highways. The aim was to assess their potential to generate renewable electricity from vehicle motion. Preliminary results indicated that up to 72,800 kWh/year could be generated under heavy traffic [16].

Figure 4. Piezoelectric Energy Harvesting System Developed by Xiong (2014) [2]

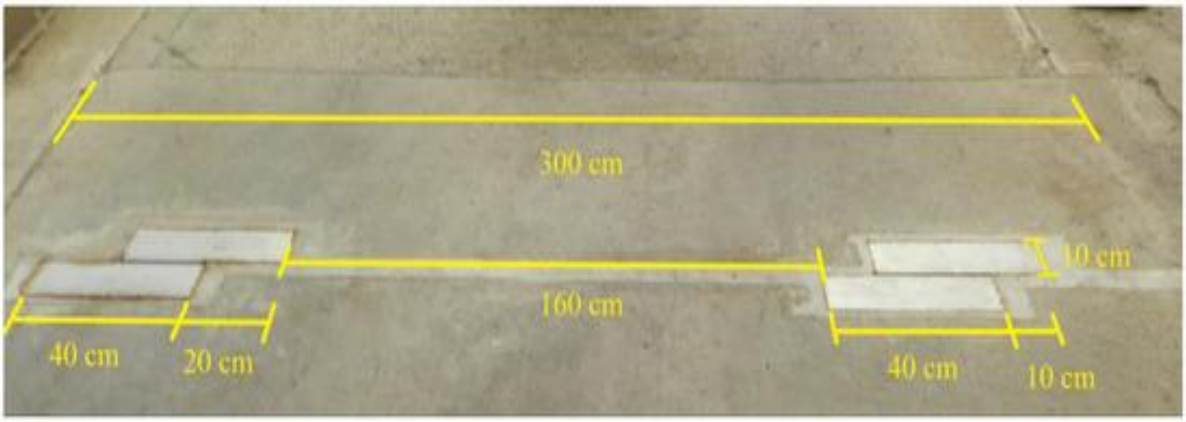

Figure 5. Prototype of the lane using four boxes to optimize coverage of the wheel path [21]

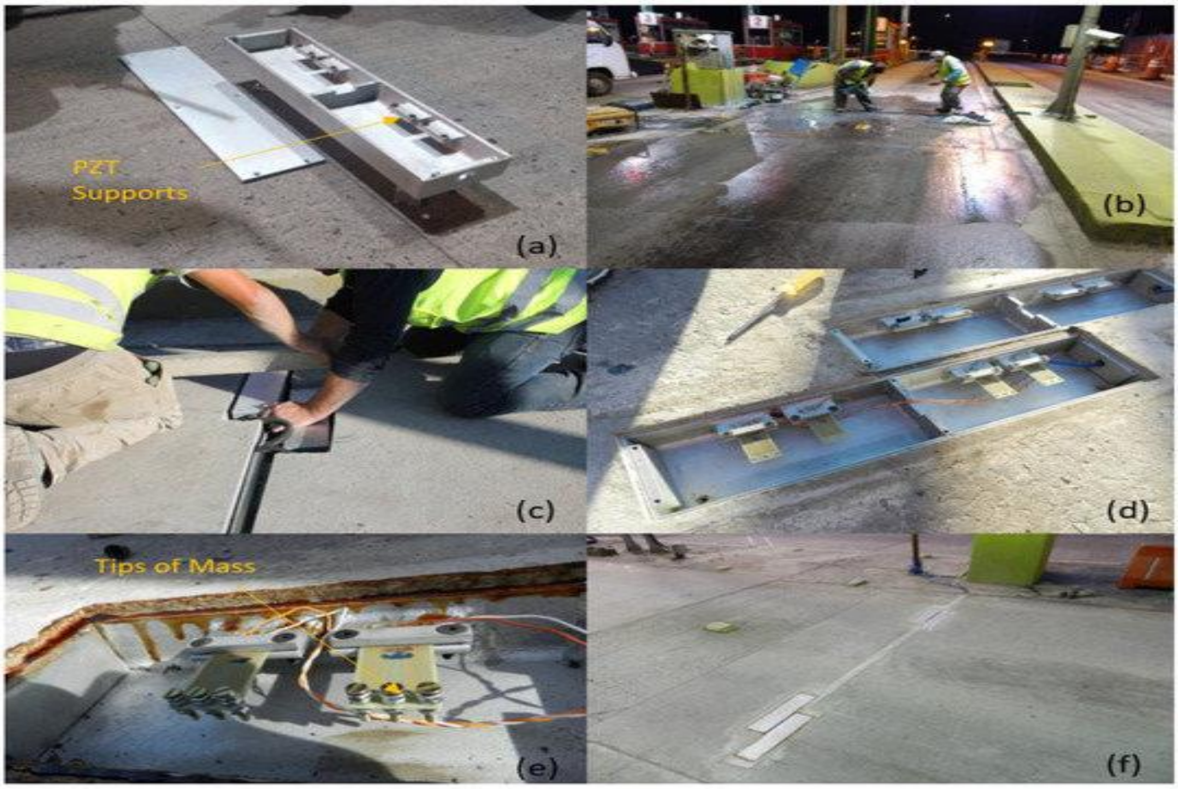

Figure 6. Prototype image of a construction site [21]

Figure 6 illustrates in the first image PZT Prototype box image. Then the preparation for installing the prototypes in the automatic toll lane, prototypes leveled with pavement surface, then prototypes embedded in the pavement with transducers. Transducer equipped with tip masses and finally results of the top surface.

Triboelectric-Based Pavements

Triboelectric nanogenerators (TENGs) generate energy from contact and separation between materials. These systems are more suited for lightweight and frequent movements, such as foot traffic. While triboelectric systems are less common in pavement applications, recent developments in triboelectric nanogenerators (TENGs) suggest potential for integration in smart infrastructure. TENG-based floor tiles have demonstrated the ability to light LEDs or power low-energy sensors. However, triboelectric technologies are still at an early stage and require more research to assess their suitability for outdoor pavement systems.

For example, a study from the University of Alberta explored triboelectric energy-harvesting floor tiles. The prototype was able to power 150 LEDs using the pressure of a human step. The setup used PTFE (Polytetrafluoroethylene) as the triboelectric layer [17].

Limitations of Existing Systems

Though they have potential, current energy-harvesting pavement systems face several challenges:

- Durability: Piezoelectric parts can break easily and wear out under heavy traffic.
- Efficiency: Triboelectric systems have lower power output and are sensitive to environmental conditions like humidity.
- Scalability: Full integration into urban infrastructure has not yet been fully used on a large scale.
- Cost: The initial cost of installation and materials is still relatively high.

Overall, existing energy harvesting pavements demonstrate technical feasibility but have not yet reached mass adoption. Challenges such as cost, system lifespan and energy conversion efficiency limit their wide spread deployment.

3.2 Current Approaches to Autonomous De-Icing

Autonomous de-icing systems have gained interest in recent years, specially in northern countries with rough winter conditions. Different traditional de-icing methods which rely on chemical salts or manual heating. However, modern systems use sensors and automated controls to detect ice formation and respond accordingly.

Some commercial systems already use resistive heating elements embedded in pavement surfaces to prevent ice buildup. These systems are usually activated by temperature and humidity sensors. For example, heated driveways and airport runways in colder regions take such solutions to ensure safety. These systems are effective but require a constant power source which may not be energy-efficient or environmentally friendly. In research, newer approaches focus on smart control systems that optimize when and how heating is applied. Edge computing and IoT-based de-icing platforms are being explored to reduce energy consumption. These systems rely on real-time environmental data to activate heating only when necessary and then improving efficiency. Several technologies are being used to reduce ice formation on roadways and walkways. These include electric heating systems, hydronic systems and inductive heating. However, many existing systems are energy-intensive and rely on the traditional power grid.

Figure 7. A heated sidewalk in Holland, Michigan [22]

Figure 8. Installation of a geothermal snowmelt system on a street in Reykjavík, Iceland [22]

Figure 9. System installed snowless, Brandenburg, Germany [22]

Electric Resistive Heating

In Norway and Canada, resistive heating cables have been used in sidewalks and roads. These systems are effective but consume a large amount of electricity [18][19].

Hydronic Heating

Hydronic systems circulate heated fluid through pipes embedded in pavements. While efficient in snow melting, these systems are expensive and complex to maintain. They are typically used in high-end facilities, airports and bridges [20].

Sensor-Based Activation

Newer systems integrate temperature and humidity sensors with microcontrollers to activate heating only when needed. This reduces power consumption and supports autonomous de-icing. However, most existing implementations still depend on grid power and are not energy self-sufficient.

Identified Gaps

Although many components of smart pavement exist such as energy harvesting, resistive heating and environmental sensing but there is a lack of a fully integrated solution that:

1. Uses self-harvested energy from pedestrian and vehicular movement.
2. Powers an autonomous de-icing system without grid dependency.
3. Integrates IoT and edge intelligence for real-time and data-driven control.

Many of the current de-icing technologies are either expensive or dependent on grid power. They are not yet widely integrated with renewable energy sources, such as those harvested from pavement. Moreover, full automation in public infrastructure remains limited. To summarize, there is a clear gap in integrating de-icing systems with on-site renewable energy sources, which this thesis addresses these gaps by proposing a conceptual model that combines all of these features in a modular and scalable system.

4 Conceptual Framework and Proposal

The conceptual model for energy harvesting pavement uses piezoelectric and triboelectric materials placed under the road surface. These materials collect energy from the movement of vehicles and people. The pavement is built in modular layers, making it easier to maintain and adapt to different city infrastructures.

4.1 Design a Concept for Pavement-Based Energy Harvesting

This chapter presents a conceptual model for a smart pavement system. It is designed to harvest energy and used that energy for an autonomous de-icing system. Then energy harvested is stored in a rechargable battery system and that is responsible for reliable power management.

Energy Flow Overview:

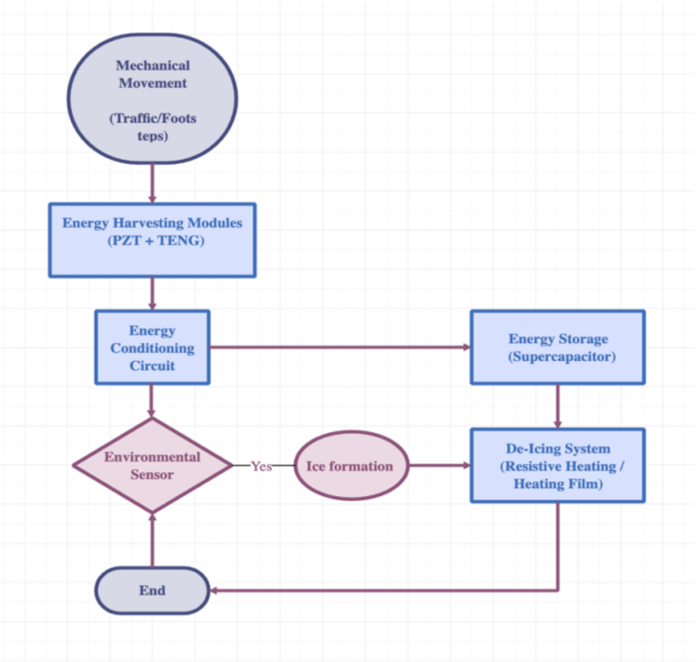

Figure 10. Proposed System Energy Flow

The framework is designed to utilize mechanical energy from vehicular traffic and environmental sensing to ensure sustainable and responsive operation in urban environments. Figure 10 illustrates the conceptual framework for the proposed smart pavement system that enables energy harvesting and autonomous de-icing functionality. The system begins with mechanical movement generated by traffic loads or pedestrian steps which is captured by the Energy Harvesting Module composed of piezoelectric and triboelectric nanogenerators (PZT + TENG). These components convert mechanical vibrations into electrical energy. The harvested energy is then sent to an Energy Conditioning Circuit which adjusts the voltage and current to suitable levels. After processing, this energy is stored in an Energy Storage Unit, such as a supercapacitor to ensure availability for continuous use. An Environmental Sensor constantly monitors external conditions such as temperature and humidity. When these sensors detect a high probability of ice formation, the system activates the De-Icing Module. This module may use resistive heating elements or heating films embedded within the pavement surface to melt ice and maintain road safety. This closed-loop system enhances urban infrastructure by making road surfaces more intelligent, energy-efficient and capable of responding to environmental hazards autonomously.

System Components:

The proposed system consists of several key components that work together to enable smart energy harvesting and autonomous de-icing functionality.

The top pavement layer is built using high-durability materials such as asphalt composites, which are capable of effectively transmitting mechanical pressure from traffic and pedestrians.
Below this layer is the energy harvesting layer, which is embedded with piezoelectric ceramics and triboelectric nanogenerators (TENGs). These components are responsible for converting the mechanical stress generated by vehicles and foot traffic into electrical energy.

Next, the Energy Storage and Management System (ESMS) includes a lithium-ion battery bank equipped with a smart charge controller. This system regulates voltage levels and stores the generated energy and making it available for operating the de-icing system.

Finally, an insulation and protection layer surrounds the sensitive internal components. This layer is designed to be waterproof and resistant to vibration, ensuring the durability and reliability of the system under various environmental conditions.

System Operation Flow:

The system operates by converting mechanical energy from traffic or footsteps into electrical energy. As vehicles or pedestrians move across the pavement, mechanical vibrations are generated. These vibrations are captured by the piezoelectric layers which convert the mechanical stress into electrical energy.

The generated energy is then stored in a dedicated battery unit for later use. Meanwhile, system sensors continuously monitor the surface temperature and humidity to assess environmental conditions in real time. When these sensors detect or predict ice formation, the AI-based control system activates the de-icing module automatically. Once the de-icing process is completed, the system returns to standby mode to conserve power until further action is needed.

4.1.1 Energy Generation Model

The energy generation model is based on the conversion of mechanical stress into electricity using piezoelectric and triboelectric mechanisms. This model estimates the amount of energy produced based on traffic intensity and environmental factors.

Traffic-Based Piezoelectric Harvesting (PZT Modules):

According to a previous research [1] indicates that a 1 km of road embedded with piezoelectric (PZT) materials can generate around 200 kWh of energy per day. If this 1 km segment contains 1,000 piezoelectric tiles, each measuring 1 m² (1 m × 1 m), the energy generated per tile can be estimated by dividing the total energy by the number of tiles.

So, energy per tile per day = 200 kWh/1000 = 0.2 kWh/day

This results in approximately 0.2 kWh of energy produced per tile per day, which can be utilized for de-icing heating needs within the smart pavement system.

Pedestrian-Based Triboelectric Harvesting:

Based on the TEHFT prototype research [7] shows that a single human step (approximately 2 Hz from a 60 kg person) can generate around 13.26 mW of power. If the triboelectric tile has an area of 1 m² (1 m × 1 m) and it takes approximately 1 second for a person to step across it. Then the energy harvested per person is about 13.26 mW × 1 s = 13.26 mWs.

Assuming a busy hour where approximately 1,000 people walk over the same tile, the total energy collected would be 1,000 × 13.26 mWs and spread over an hour (3,600 seconds), this results in an average power output of approximately (1000 × 13.26 mWs)/ 3600 s = ~ 3.36 W per tile.

Energy (kWh) = $\frac{Power\ (W) \times \text{Time (hours)}}{1000} = \frac{3.36 \times 1}{1000}$ = 0.003 kWh = 0.003 kWh × 24 hours = 0.072 kWh.

Sothat, triboelectric energy harvesting from pedestrian movement of $1m^2$ is theoretically 0.072 kWh but the energy generate is relatively low.

Finally, based on the above calculation, combining piezoelectric energy (~ 0.2 kWh/m²) and triboelectric energy (~ 0.072 kWh/m²) can total energy harvested per square meter is approximately 0.272 kWh in a worst-case scenario.

4.1.2 Calculation:

Case Study: Zebra Crossing Scenario

1. Assume a piezoelectric tile at a busy zebra crossing:

Number of footfalls per hour 5,000 and average force per footfall is 438 N [9]. Piezoelectric energy conversion efficiency theoretically ~ 80% [10]. Energy per footfall (approx.):

E = F × d × efficiency, Where displacement d = ~ 0.0015 m, F = 438 N

$E = 438 \times 0.0015 \times 0.8 = \sim 0.53$ J

Energy per hour = 0.53 J × 5,000 = 2650 J ÷ 3600 s = 0.736 Wh

Then, Assume the size of one tile: 0.5 m × 0.5 m = 0.25 m^2, total area to cover $10m^2$ (5m × 2m), total number of tiles needed for Zebra Crossing are 10 ÷ 0.25 = 40 tiles.

Sothat, deploying 40 such tiles could generate hourly 0.736 × 40 = 29.44 Wh

2. Assume triboelectric can generate energy:

1 m^2 can produce = 17 Wh**.** So, 10 m^2 can produce hourly = 170 Wh

3. Energy Harvested per Vehicle Pass (Estimate):

Now, consider the weight and vibration from cars or buses which generate far more pressure than human footsteps. Advanced piezo and tribo systems embedded in roadbeds or under zebra crossings can harvest significantly more energy. Vehicle weight and vibration produce about 1 Wh to 2 Wh per car over high-efficiency piezo strips [12].

Assume, 1.5 Wh energy per vehicle pass over embedded energy harvesters across the 5m zebra crossing and 2000 vehicles over the zebra crossing per one hours of city traffic in busy areas.

So, energy generate = 2000 × 1.5 Wh = 3000 Wh

Total gathered energy from the Zebra Crossing area ($10m^2$)/ hour = Padestrain Footstep from (piezoelectric + triboelectric) + Vehicle Pass

= 29.44 Wh + 170 Wh + 3000 Wh = 3,199.44 ÷ 1000 = ~ 3.2 kWh (hourly)

This harvested energy is stored into the ESMS (Electricity Safety Management Schemes) and later used to activate heating components.

4.2 Autonomous De-Icing System Proposal

The de-icing system will use stored energy to activate a heating mechanism embedded below the pavement surface. Activation is based on real-time input from temperature and moisture sensors and enabling autonomous operation without manual intervention. The heating model will consider two main technologies.

4.2.1 Heating Element Models

The following are two proposed heating systems integrated under the pavement surface for surface ice removal:

Model 1: Resistive Heating Wire (Nichrome or Alloy Wires)

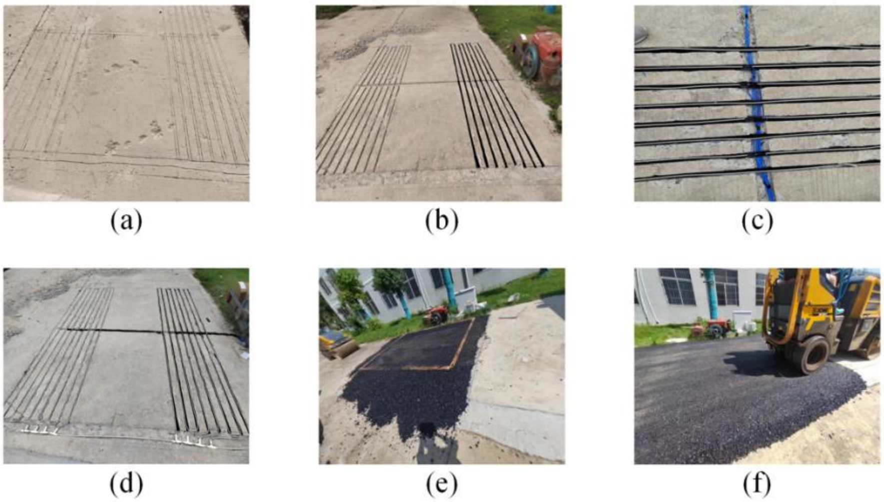

Figure 11. Resistive Heating Wire [14]

In this model, resistive heating wires such as nichrome or other suitable alloys are embedded under the surface layer of the pavement. The heating operates on the principle of Ohmic heating, where electrical power is converted into heat based on the formula $P = V^2 / R$. These wires are typically installed in a serpentine pattern to ensure uniform heat distribution. A microcontroller or edge computing device receives real-time data from environmental sensors to control the system effectively. The power source is a battery system that stores harvested energy. This model is considered simple, reliable and has been widely used in applications such as heated driveways.

Example specifications include a resistance of approximately 15 Ω/m, operating voltage in the range of 48V to 120V and energy delivery of about 200–300 W/m².

Model 2: Heating Film (Carbon or Polyimide Layer)

Figure 12. Heating Film

The second model employs carbon-based or metal-alloy heating films that are thin and flexible. These films are installed directly under surface tiles and offer a uniform distribution of heat with relatively lower energy consumption. This model is particularly efficient in localized areas such as pedestrian islands, walkways and cycling lanes. Due to their flexibility, these films can be customized to shape and easily integrated with sensors and helping reduce unnecessary energy usage. The heating elements are placed directly under the top layer and making installation straightforward, especially in modular pavement designs. This system is most suitable for narrow paths such as zebra crossings. Technical specifications indicate a heating rate of approximately 150–250 W/m² and the films are designed for efficient integration under smart pavement tiles.

Energy Storage and Smart Management:

To ensure consistent system performance, a smart battery energy storage and management unit is incorporated. The proposed battery type is a lithium-ion pack with an estimated capacity of around 5 kWh per 10 m^2 of pavement. Charging of these batteries typically occurs during the day through continuous energy harvesting from traffic flow. Full charge cycles are expected to take between 12 to 24 hours depending on traffic volume. The system always triggering mechanisms using environmental sensors. These sensors monitor real-time conditions, such as temperature falling below 0°C and surface moisture presence to determine when de-icing is necessary. This approach minimizes unnecessary energy usage and ensures targeted heating only when needed. Ice formation generally occurs during the early morning or overnight hours.

Table 3. System Architecture Overview

Component	**Role**
Piezo & Tribo Generators	Harvest energy from traffic and pedestrians
Battery Pack (5 kWh)	Store harvested energy for use when needed
Sensors (Temp + Moisture)	Trigger de-icing logic intelligently
Microcontroller (Edge AI)	Monitor weather, manage battery, control heating
Heating Film / Resistive Wire	Deliver heat to melt surface ice

Table 3 describes the piezoelectric and triboelectric generators serve as the primary energy harvesting units, converting mechanical stress and surface interactions into electricity. The energy is stored in a 5 kWh battery pack designed to support heating demands across a 10 m^2 pavement area. Environmental sensors continuously measure surface temperature and moisture levels to determine de-icing needs. An edge device or microcontroller processes this data and activates the heating components accordingly. Depending on the pavement location and energy requirements, resistive heating wires or heating films are employed to deliver heat for ice melting. The system is modular and scalable and making it adaptable for various urban infrastructure applications.

4.2.2 Calculation

Case Study: Zebra Crossing De-Icing

Ice Melting Energy Requirement Breakdown. We have a zebra crossing of 5 meters × 2 meters (10 m^2) and ice thickness of 5 mm (0.005 m).

Step 1: Volume of Ice

The first step is to calculate the volume of ice that we need to melt.

Volume of ice (m^3) = Area (m^2) × Thickness (m)

Volume of ice = 10m2 × 0.005m = 0.05m3

Step 2: Mass of Ice

Next, we calculate the mass of the ice and knowing that the density of ice is approximately 917 kg/m^3.

Mass of ice (kg) = Volume (m^3) × Density of ice (kg/m^3)

Mass of ice = 0.05m^3 × 917kg/m^3 = 45.85kg

Sothat, the mass of ice to melt is 45.85 kg.

Step 3: Energy to Raise the Temperature of the Ice

To raise the temperature of the ice from -5°C (typical freezing temperature) to 0°C (just before melting), we need to calculate the specific heat capacity of ice which is approximately 2.1 kJ/kg·°C.

Q1=Mass of ice (kg)×Specific heat capacity of ice (kJ/kg·°C)×Temperature change (°C)

Q1 = 45.85 kg × 2.1 kJ/kg·°C×(0−(−5)) °C

Q1 = 45.85 × 2.1 × 5 = 481.4kJ

The energy is required to heat the ice from -5°C to 0°C is 481.4 kJ.

Step 4: Energy to Melt the Ice

Once the ice is at 0°C, we need to provide the latent heat of fusion to change the ice from solid to liquid without changing its temperature. The latent heat of fusion of ice is 334 kJ/kg.

Q2 = Mass of ice (kg) × Latent heat of fusion of ice (kJ/kg)

Q2 = 45.85kg × 334kJ/kg = 15,312.9kJ

The energy is required to melt the ice is 15, 312.9 kJ.

Step 5: Total Energy Requirement for Ice Melting

Finally, the total energy required for both raise the temperature of the ice to 0°C and then melt it is the sum of Q_1 and Q_2:

Q $_{\mathbf{(total)}}$ = Q1+Q2 = 481.4 kJ + 15,312.9 kJ = 15,794.3 kJ

Converting this to kilowatt-hours (kWh) for a more practical energy unit:

Energy in kWh = 15,794.3 kJ ÷ 3,600 kJ/kWh = 4.39 kWh

Table 4. Summary of Energy Breakdown

Step	Energy (kJ)	Energy (kWh)
Heating ice from -5°C to 0°C	481.4 kJ	0.1348 kWh
Melting ice at 0°C	15,312.9 kJ	4.26 kWh
Total Energy Required	15,794.3 kJ	4.39 kWh

Table 4 contains the summary of total energy is approximately 4.39 kWh needed to melt the ice on the zebra crossing.

Table 5. Summary of Technical Feasibility

Metric	Value
Area	10 m²
Ice thickness	5 mm
Total energy required	~ 4.4 kWh
Energy source	Piezoelectric + Triboelectric
Energy use timing	On-demand via battery
Heating system	Heating film / Resistive wire
Battery backup	5 kWh (per 10 m²)

Table 5 outlines the technical parameters considered for the proposed energy harvesting and autonomous de-icing system and designed for a 10 m² pavement area. It assumes 5 mm ice thickness which needs about 4.4 kWh of energy to melt. The energy comes from piezoelectric and triboelectric sources that generate electricity from traffic and footsteps. This energy is stored in a battery and used on demand when ice is detected. The heating system uses either heating film or resistive wire and 5 kWh battery backup supports each 10 m² section.

Assumption: The hybrid energy harvesters (piezoelectric and triboelectric) operate continuously and can generate around 3.2 kWh per hour. This energy can be stored over a period of 2 to 6 hours depends on traffic. Since a full de-icing event requires about 4.5 kWh for a Zebra Crossing (10m^2) and the system can meet this demand. With enough pedestrian or vehicle activity and smart battery storage the system can self-sustain de-icing on zebra crossings and other high-footfall areas.

5 Discussions and Conclusions

This chapter presents a discussion of the proposed system's key findings, its limitations and suggestions for future improvements. It summarizes how the smart pavement system combines energy harvesting and autonomous de-icing that supports safer and more sustainable urban environments. The section uses information from the previous chapters to explain what the study has shown, what difficulties still exist and what should be done in future research.

5.1 Summary of Findings

This thesis presented a concept for a smart pavement system that can collect energy and remove ice automatically. The system uses special materials like piezoelectric and triboelectric layers under the pavement surface. These materials generate electricity when people walk or vehicles pass over the pavement. The electricity is stored in batteries and later used to source of power heaters that melt ice on the surface.

The system also includes sensors that can detect changes in temperature and moisture. When the system detects cold and wet conditions that may cause ice, it activates heating wires or heating films placed below the surface. A small controller (microcontroller) reads the sensor data and decides when to turn on the heating system. This makes the pavement smart and able to work without human interactions.

The energy harvesting part of the system can generate around 0.2 kWh per square meter from piezoelectric sources and about 0.072 kWh per square meter from triboelectric sources. This gives a total of about 0.272 kWh per square meter. Also, A real-life case study of a zebra crossing (10 m^2 area) showed that the system could generate up to 3.2 kWh of energy in one hour, depending on traffic and footfall. The energy required to melt 5 mm of ice over a 10 m^2 area is about 4.4 kWh. This shows that the system could collect enough energy for de-icing if there is enough activity.

The smart pavement system combines two useful functions. These are energy generation and road safety through ice removal. It is designed to be modular and easy to install in cities. The findings show that using known technologies in a new way can help cities save energy, reduce accidents and create smarter roads.

5.2 Limitations and Challenges

Although the system shows many benefits, there are also some limitations and difficulties. One major limitation is that the system has not been built or tested in real-world conditions. The results in this study are based on estimates and examples from other research. Real-life performance may be different because of changing weather, traffic and pavement conditions.

Another challenge is the cost of the materials and installation. Piezoelectric and triboelectric components can be expensive. Installing them under pavements may need special construction tools and skills. Also, these materials need to last a long time and handle heavy loads, moisture and changes in temperature. More testing is needed to confirm their long-term durability.

Battery storage and energy management are also challenging. The battery must be able to store enough energy, charge properly and work well in cold weather. If the battery fails or runs out of power, the heating system will not work which could cause dangerous conditions on the road.

Integrating all parts of the system is complex like energy harvesters, sensors, controllers, heaters and batteries. These components must work together smoothly. If one part fails, the system might stop working. Keeping the system easy to repair and maintain is also important.

The environmental impact is another concern. The materials used in the system must not harm the environment. Damaged parts must be easy to replace without needing to rebuild the whole pavement. These issues must be solved before cities can use the system on a large scale.

5.3 Recommendations for Future Work

To improve and test the smart pavement system, some steps are suggested for future research. First, a small working model or prototype should be built and tested in real outdoor conditions. This will help check how much energy the system can really collect and how well it can melt ice in different weather conditions. Second, researchers should test other materials for energy harvesting. Some new materials may be cheaper, more durable or produce more energy. Finding the best materials is important to reduce costs and improve the system's performance. Third, better control systems can be developed. Smart software and machine learning could help the system learn when ice usually forms and plan heating in advance. This could save energy and make the system work better. Fourth, the system should be tested with city engineers and planners. They can help plan where and how to install the system in real roads and pavements. Working with experts in construction and public infrastructure can make the system easier to use in real life.

Finally, battery systems should also be studied more. Batteries need to store enough energy and work well even when the weather is freezing. Tests should check how long the batteries last and how often they need to be replaced.

The system can also be expanded to include other smart features. For example, the harvested energy could power streetlights, signs or other devices. The smart pavement can become part of a larger smart city network.

In summary, this thesis presents a smart idea that combines two technologies in one pavement system. This system offers a new way to solve two big problems in cities like energy use and winter safety. There are still problems to fix, careful testing and planning can turn this idea into a real solution. Future work should focus on building prototypes, testing materials, improving control systems and planning real world use. With continued research, smart pavements could become a useful part of safe and sustainable cities.

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