Abstract:

Icy road conditions contribute to 1,900 deaths and 135,000 injuries annually in the U.S., posing a major safety risk. Current de-icing methods, such as salts and chemicals, are costly, environmentally harmful, and damaging to infrastructure. This project introduces a biomimetic road surface pattern inspired by nature's hydrophobic structures—specifically, the mint leaf's micro textures and the cicada wing's cavity patterns, combined with angles greater than 150 degrees to create superhydrophobic surfaces.

The team developed a nature-inspired pattern that reduces ice formation while accelerating melting. These patterns can be stamped into road concrete or integrated into pre-molded road materials. Using 3D-printed nano-scale prototypes, the solution will be tested for effectiveness under various conditions. Unlike traditional methods, this approach is cost-effective, environmentally friendly, and scalable to roads, sidewalks, bridges, and other surfaces prone to icing. In collaboration with CDOT, this innovation has the potential to transform winter road safety.

Description

Present Technology: Icy road conditions pose a significant hazard, leading to thousands of accidents and fatalities each year. To combat this issue, several de-icing and anti-icing technologies are currently in use. The most common method is the application of chemical de-icers, primarily rock salt (sodium chloride), calcium chloride, and magnesium chloride. These substances lower the freezing point of water, preventing ice from forming or helping to melt existing ice. Salt is effective due to its ability to break the hydrogen bonds in water, disrupting ice formation. However, it becomes less effective at temperatures below -10°C and can lead to significant environmental and infrastructure. Runoff from salt-treated roads contaminates water sources, harms plant life, and accelerates the corrosion of vehicles and bridges.

Another widely used approach involves abrasives like sand and gravel, which are spread on roads to improve traction. While these materials do not actively melt ice, they increase friction between tires and the road surface, reducing the risk of skidding. However, sand and gravel require frequent reapplication, leading to high maintenance costs and environmental concerns such as clogging drainage systems. Additionally, excess sand on roadways can create dust pollution, which negatively impacts air quality.

Technological advancements have led to the development of heated pavement systems, which use embedded electrical heating elements or hydronic tubing filled with heated liquid to prevent ice formation. These systems rely on principles of thermal conductivity and convection to transfer heat to the road surface. While effective, heated pavement requires high energy input and substantial upfront installation costs, making it impractical for widespread implementation. Additionally, power outages during severe storms can render these systems ineffective.

Despite these existing technologies, icy roads continue to be a persistent issue, highlighting the need for innovative and sustainable solutions. Biomimetic surfaces offer a promising alternative by utilizing nature-inspired microstructures to prevent ice formation and improve surface friction. Superhydrophobic surfaces, such as those found in lotus leaves and cicada wings, repel water and prevent ice adhesion. By integrating these patterns into road surfaces, biomimetic designs can reduce ice accumulation, enhance traction, and minimize the need for chemical treatments. Unlike salt-based de-icing methods, biomimetic surfaces or surfaces based on nature inspired patterns provide a long-term, environmentally friendly, and cost-effective approach to winter road safety, addressing the limitations of current technologies while reducing environmental impact and maintenance costs.

History: Biomimicry, the practice of drawing inspiration from nature to develop innovative solutions, has been studied for centuries. The concept was formally introduced in the 20th century, with the term "biomimicry" gaining prominence in the 1990s through the work of scientist Janine Benyus. However, nature-inspired designs have influenced human engineering and technology for much longer.

The earliest biomimetic discovery was Leonardo da Vinci’s study of birds to design flying machines in the 15th century. Later, in the 1940s, Swiss engineer George de Mestral invented Velcro after observing how burrs clung to his dog's fur. These early examples demonstrated how biological adaptations could inspire functional materials and designs.

The study of biomimicry patterns specifically gained momentum in the late 20th and early 21st centuries, with researchers exploring hydrophobic and self-cleaning properties in nature. The lotus leaf effect, first studied in the 1970s, became a foundation for developing water-repellent surfaces. The microscopic structures on lotus leaves create a superhydrophobic surface, preventing water droplets from adhering to and carrying away dirt or dust. This principle has since been applied to coatings, textiles, and construction materials.

Another significant advancement came from studying the Namib Desert beetle, which collects water from fog using its textured shell. Researchers have applied this discovery to develop water-harvesting materials. Similarly, cicada wings and shark skin have inspired antibacterial and drag-reducing surfaces, respectively.

Biomimetic road surfaces, our project is a novel development, incorporating biomimicry principles to enhance friction and reduce ice formation. By mimicking the hydrophobic textures of leaves and insect wings, these surfaces aim to improve road safety without relying on chemical treatments. As research progresses, biomimetic designs will continue to offer sustainable, efficient solutions across various industries, from transportation to architecture and medicine.

Future Technology:

In the next decade, biomimetic road surfaces will revolutionize winter road safety by significantly reducing ice formation and increasing friction without the need for harmful chemical treatments. Our vision is to integrate nature-inspired, superhydrophobic patterns into road infrastructure, making roads inherently resistant to ice and snow accumulation. Inspired by the mint leaf's micro textures and the cavity structures found in cicada wings, this technology will rely on advanced material science and surface engineering to create self-sustaining, ice-resistant roadways.

Scientific advancements in nanotechnology and materials engineering will play a crucial role in refining these biomimetic surfaces. Over the next decade, roads will be constructed using pre-molded materials embedded with micro- and nano-scale surface modifications, allowing for superior water repellency and reduced ice adhesion. These surfaces will leverage the principle of contact angle hysteresis, ensuring that water droplets slide off before freezing, effectively preventing hazardous ice buildup.

Additionally, emerging advancements in smart materials will enhance these surfaces by incorporating phase-change materials (PCMs) that store and release thermal energy, further accelerating ice melting. The integration of self-cleaning, wear-resistant coatings will ensure long-term durability and effectiveness, even under high-traffic conditions.

Beyond roadways, this technology will expand to bridges, sidewalks, airport runways, and even wind turbine blades—any surface where ice accumulation poses a hazard. Municipalities and department of transportation agencies will adopt this low-cost, eco-friendly solution, reducing reliance on de-icing chemicals that harm infrastructure and the environment.

By 2035, we envision a global shift toward sustainable, biomimetic road designs, enhancing safety while minimizing environmental impact. The continued evolution of 3D printing and nano-manufacturing will allow for widespread adoption, ensuring roads remain safe, resilient, and cost-effective in winter conditions worldwide.

Breakthroughs: To make biomimetic, ice-resistant road surfaces a widespread reality, several key breakthroughs in material science, surface engineering, and large-scale implementation must occur. While nature provides a blueprint for superhydrophobic surfaces, translating these micro- and nano-scale structures into durable, high-traffic road surfaces remains a challenge. Current limitations include material durability, large-scale manufacturing feasibility, and the long-term effectiveness of biomimetic textures under continuous wear and extreme weather conditions.

One crucial breakthrough required is the development of ultra-durable, hydrophobic road materials that can withstand heavy traffic while maintaining their ice-repelling properties. Current road surfaces degrade over time due to mechanical stress, UV exposure, and environmental wear, potentially reducing the effectiveness of biomimetic patterns. Advances in nano coatings, self-healing materials, and wear-resistant polymers will be necessary to make this technology viable for long-term use.

Research Project: Testing the Feasibility of Biomimetic Road Surfaces

To validate the effectiveness of biomimetic patterns in real-world conditions, a structured research project will be undertaken in four key phases:

1. Pattern Research and Identification

We, our team, conducted an in-depth study of biological surfaces with natural hydrophobic and ice-resistant properties. Patterns from sources such as mint leaves, cicada wings, lotus leaves, and Namib Desert beetles were examined to determine which structures are most effective at reducing ice adhesion and accelerating melting.

A series of 3D-printed samples were developed to replicate these patterns. The goal is to evaluate their effectiveness under controlled conditions by measuring:

- Ice formation rate at a consistent temperature
- Melting time under identical conditions
- Impact of humidity using a humidifier to simulate varying moisture levels

Each pattern was tested at the same temperature, with and without added humidity, to determine how well they prevent ice accumulation and enhance melting. The results helped identify the most promising pattern for further testing.

2. Proof of Concept

Once an optimal pattern is selected, a simulated 3D-printed road surface embedded with biomimetic patterns will be created and tested. The primary goal is to assess the icing rate, coefficient of friction, and water retention under different temperatures and humidity levels. The following data will be collected:

- Time taken for ice to form on the surface compared to traditional asphalt
- Changes in friction coefficient at different temperatures and water levels
- Effectiveness of surface patterns in repelling water before freezing

Initial testing will help refine surface designs and identify the most effective patterns for real-world conditions. The results will be shared with the Colorado Department of Transportation (CDOT) to determine feasibility for further testing.

3. Pilot Preparation

Once the best biomimetic pattern is identified, a durable 3D-printed stamp will be developed using polycarbonate or polyamide. This stamp will be tested for ease of application on road surfaces using methods such as a manual stamper, stamping mat, or vibratory plate compactor. The following factors will be assessed:

- Time and labor required for large-scale implementation
- Cost-effectiveness compared to traditional road treatments
- Durability of the imprinted pattern under simulated traffic conditions

4. Pilot Testing

A test road section will be stamped with the optimized biomimetic pattern and monitored under real winter conditions. CDOT friction trucks will be used to measure:

- Friction levels and skid resistance under icy conditions
- Surface texture changes over time
- Water film thickness to evaluate drainage efficiency

By analyzing the data collected, adjustments can be made to improve the pattern's efficiency before considering large-scale implementation.

Why doesn't technology exist today: Despite the proven effectiveness of biomimetic surfaces in controlled environments, several challenges prevent widespread adoption:

1. **Scaling Nano-Patterns to Road Surfaces** – While hydrophobic and anti-icing properties have been successfully demonstrated on small-scale materials,

applying these microstructures to miles of roadway while maintaining durability is complex.

2. **Material Longevity** – Current road materials wear down due to traffic and environmental conditions. New high-strength hydrophobic coatings or materials are needed to maintain long-term effectiveness.
3. **Implementation Costs** – Road construction is an expensive, large-scale endeavor. The cost-effectiveness of biomimetic road patterns must be demonstrated before municipalities invest in their adoption.
4. **Regulatory Approval** – Any new road technology must pass rigorous safety and environmental testing before being implemented at scale.

By conducting structured research and real-world testing, these breakthroughs will bring biomimetic road surfaces closer to reality, offering an environmentally friendly and highly effective solution for winter road safety.

Design process: During the development of our biomimetic road surface technology, we explored multiple alternative solutions to address icy road conditions. Each idea was carefully considered based on effectiveness, environmental impact, cost, and feasibility using a feasibility of 4 square matrix from the “Young innovator’s Guide to STEM” book by Gitanjali Rao. After thorough analysis and testing, we determined that a biomimetic surface pattern was the most promising solution. Below are three alternatives we explored and the reasons they were ultimately rejected in favor of the biomimetic road surface approach.

1. Environmentally Friendly Salts

One of the first alternatives considered was the use of biodegradable or environmentally friendly salts as a replacement for traditional road salts. These alternatives, including calcium magnesium acetate (CMA) and beet juice-based deicers, were studied for their ability to melt ice while minimizing negative environmental impacts.

Why we rejected:

- Even though CMA and beet juice-based solutions are less corrosive than traditional salts, they still require continuous application, leading to high maintenance costs.
- These substances can still alter soil chemistry and harm aquatic ecosystems when runoff enters nearby waterways.
- Salt alternatives only lower freezing points and do not prevent ice from forming, meaning roads remain slippery under extreme conditions.

Unlike salt-based solutions, our biomimetic pattern offers a passive, long-term solution that does not require constant reapplication, reducing cost and environmental harm.

2. Biochemical Ice-Resistant Coatings

Another idea considered was the use of biochemical coatings derived from natural, anti-freezing proteins found in cold-adapted organisms, such as arctic fish and insects. These coatings could theoretically inhibit ice formation by interfering with ice crystallization at the molecular level.

Why we rejected:

- Developing these coatings requires complex and expensive biochemical synthesis, making large-scale road application unrealistic.
- The effectiveness of bio-based coatings diminishes over time, requiring frequent reapplication similar to chemical deicers.
- UV radiation, vehicle friction, and weather conditions would degrade the coating, reducing its longevity.

Biomimetic Surface road patterns do not degrade or require reapplication and work by physically repelling water before it freezes, eliminating the need for constant chemical intervention.

3. Ice-Resistant Tire Patterns

The team also explored the idea of modifying tire tread patterns to improve grip and prevent ice formation on roads. The concept involved designing hydrophobic or microtextured tire surfaces that could actively break down ice while driving.

Why we rejected:

- Tire-based solutions only help individual vehicles, meaning pedestrians, cyclists, and public transportation would still face hazardous conditions.
- Ice-resistant tire designs would require every vehicle to adopt new tires, making widespread adoption challenging.
- The impact on road safety would be limited, as vehicles still rely on external road conditions for stability.

Unlike tire-based solutions, biomimetic road patterns provide passive safety benefits for all road users, including pedestrians and cyclists, and work without requiring changes to vehicle designs.

After evaluating these alternatives, we concluded that a biomimetic, superhydrophobic road surface is the most sustainable, cost-effective, and long-lasting solution. The design:

1) Prevents ice formation naturally rather than reacting to ice after it has formed.

2) Reduces long-term costs by eliminating the need for repeated chemical applications.

3) Works for all road users, including cars, bikes, and pedestrians.

4) Minimizes environmental impact, as no harmful chemicals or salts are introduced into ecosystems.

By harnessing nature's designs, this technology provides a breakthrough in winter road safety, making icy conditions less dangerous without harming the environment.

Consequences: The biomimetic road surface technology offers significant positive consequences, including enhanced road safety, reduced accidents, and lower maintenance costs by eliminating the need for constant salting. It is environmentally friendly, preventing soil and water contamination from salt runoff. Additionally, it improves road longevity by reducing chemical and ice-induced damage. However, potential negative consequences include high initial implementation costs, challenges in large-scale adoption, and possible wear over time, requiring long-term durability testing. There may also be unexpected interactions with existing infrastructure **and** regulatory hurdles before widespread approval. Despite these challenges, its benefits outweigh its drawbacks, making it a promising solution.

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- This book gave us a innovation process and tools such as feasibility matrix and fish bone diagram to select a problem-solution combination.