

Design of a Low-Profile Multi-Source Self-Powered Raised Pavement Marker for Cold Regions

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Abstract: A multi-source self-powered raised pavement marker is proposed for cold-region roads where snowplow impact, freeze-thaw cycles, deicing salts, water accumulation, and surface contamination can degrade structural and optical performance. The concept is developed from a low-profile snowplowable retroreflective marker and integrates solar energy, localized electromagnetic recharging, and traffic-induced vibration energy harvesting. Low-profile protection, combined bonding, drainage and contamination control, material durability, and energy balance are evaluated. A parameterized seven-day analysis is used to compare energy contributions under sunny, overcast, and snow-covered conditions. Under the assumed parameters, the multi-source configuration reduces the sensitivity of the energy balance to solar variability. Localized electromagnetic recharging provides the principal supplemental input during low-solar conditions, while vibration harvesting supplies a continuous low-power contribution. Energy, mechanical, and environmental validation tasks are proposed to support subsequent prototype development and field testing.

Keywords: low-profile raised pavement marker; snowplow; retroreflection; solar energy; electromagnetic recharging; vibration energy harvesting

1. Introduction

Raised pavement markers are widely used for visual guidance at lane boundaries, curves, merge and diverge areas, and other hazardous road sections. The current Chinese national standard classifies raised pavement markers as retroreflective, actively illuminated, or combined types, and specifies requirements for optical performance, mechanical resistance, sealing, vibration resistance, salt-spray resistance, and environmental adaptability [1]. In regions with persistent winter snowfall and extensive use of deicing salts, raised pavement markers are additionally subjected to snowplow blades, wheel loads, freeze-thaw cycling, water and sediment accumulation, and salt-induced corrosion. Excessive projection above the pavement increases the likelihood of direct snowplow impact, whereas overly recessed installation can increase the risk of water, sediment, and snow or ice obscuring the optical surface and reducing effective visibility.

In 2026, the author filed a utility-model patent application for a low-profile snowplowable retroreflective raised pavement marker. The core configuration uses longitudinal snowplow-guiding members to protect the central retroreflective element and incorporates a through-opening, bond-enhancement features, support shoulders, and venting/drainage grooves to improve anchorage, drainage, and maintainability [2]. Building on this configuration, the present study investigates integration of solar energy, localized electromagnetic recharging, and traffic-induced vibration harvesting with the low-profile marker to form a combined guidance device that retains passive retroreflection while providing active illumination.

2. Low-Profile Structural Configuration

The basic configuration adopts a low-profile snowplow-protection arrangement. The retroreflective element is located between two longitudinal guiding members, with its light-transmitting surface positioned below the top of the guiding members so that a snowplow blade or vehicle tire contacts the protective members first. The patent application specifies that the installed marker should preferably project no more than 20 mm above the pavement. For roads subject to frequent snow removal, the top of the guiding members is preferably no more than 7 mm above the pavement, and a protective height difference of 0.5–4 mm is maintained between the light-transmitting surface and the guiding-member top [2]. This arrangement reduces the probability of direct impact on the retroreflective element while preserving drainage and optical visibility.

Anchorage is based on a combined bonding system among the marker body, the retroreflective element, and the pavement. A through-opening in the base communicates with the receiving cavity and allows the installation adhesive to contact the underside of the retroreflective element. Roughened surfaces, grooves, ribs, and inclined internal walls increase bonding area and provide mechanical interlock. Venting and drainage grooves in the receiving cavity reduce void formation during adhesive placement and limit long-term water, sediment, and excess-adhesive accumulation near the optical surface. A replaceable retroreflective element can also be adopted so that, after wear, contamination, or optical degradation, the base body remains embedded in the pavement and only the optical component is replaced, thereby reducing maintenance effort and secondary pavement damage.

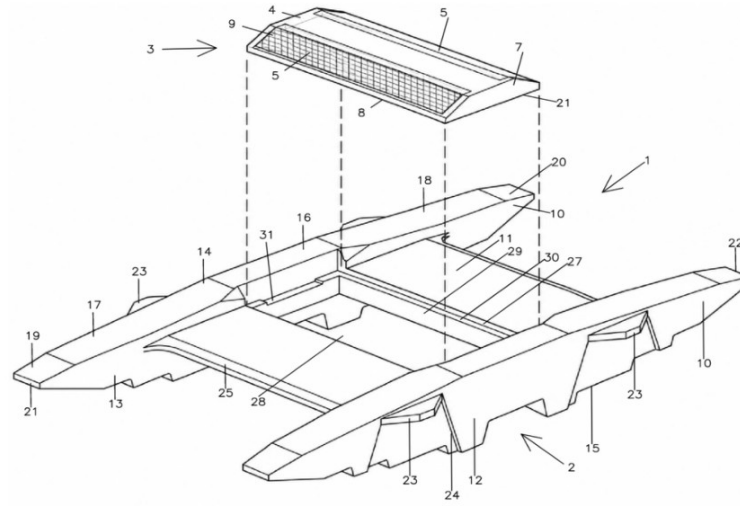


图 1

Fig. 1. Basic structural configuration of the low-profile snowplowable retroreflective raised pavement marker.

3. Multi-Source Self-Powering Scheme

A compact solar-energy collection unit, energy-storage unit, and LED active-lighting unit are integrated into the low-profile base structure. Solar energy serves as the primary routine source and can support nighttime flashing or low-power continuous illumination. Previous evaluations of solar-powered raised pavement markers indicate that solar/LED systems can reduce the need for external power wiring, although performance remains sensitive to solar exposure, contamination, low temperature, water tightness, and optical condition [5]. To maintain baseline visual guidance in the event of electrical-system failure, the retroreflective element is retained as an independent passive function.

Localized electromagnetic recharging is adopted as the primary supplemental power source. A limited number of recharging points may be installed at controlled locations such as maintenance areas, parking areas, toll facilities, critical bridge sections, and port service roads, allowing the storage unit to be replenished during snow cover or prolonged low-irradiance conditions. Contactless energy transfer eliminates exposed metallic charging contacts and reduces the risk of corrosion and contact failure caused by long-term exposure to water, deicing salts, and roadway sediment.

Pavement vibration and small deformations induced by vehicle loading constitute a second supplemental energy source. Previous studies have shown that road-generated mechanical energy can power low-energy sensors and localized transportation devices, although practical implementation remains constrained by output power, conversion efficiency, durability, and life-cycle cost [3-4]. Considering the expected energy level and structural-safety requirements, vibration harvesting is treated as a continuous low-power input. The harvesting element should be arranged to minimize local section loss, stress concentration, and fatigue damage so that the impact resistance, compressive capacity, and fatigue performance of the original marker body are not materially reduced.

Table 1. Functional roles of the three energy-supply pathways.

Energy source	Functional role	Primary advantage	Key engineering issue
Solar energy	Primary routine supply	Independent operation; reduced external wiring	Snow cover, surface contamination, low temperature, water tightness
Localized electromagnetic recharging	Rapid supplementation under low-solar conditions	Contactless transfer; deployable at selected locations	Coupling distance, embedment location, waterproofing, maintenance
Traffic-vibration harvesting	Continuous low-power supplemental input	Utilizes existing traffic loading	Power output, structural fatigue, durability

To compare the relative contribution of the different power pathways under sequential weather conditions, a seven-day parametric energy-balance scenario was established. Daily consumption of the LED and control unit was set at 12 mWh. Solar-energy input was assigned as 18-16 mWh on sunny days, 10-4 mWh under overcast conditions, and 2 mWh under snow cover. Localized electromagnetic recharging was progressively introduced at 4-12 mWh/day during low-solar periods, while traffic-vibration harvesting was set at 1.5 mWh/day. Figure 2(a) presents the daily contribution of each energy pathway, and Fig. 2(b) compares the cumulative energy margin for solar-only and multi-source operation.

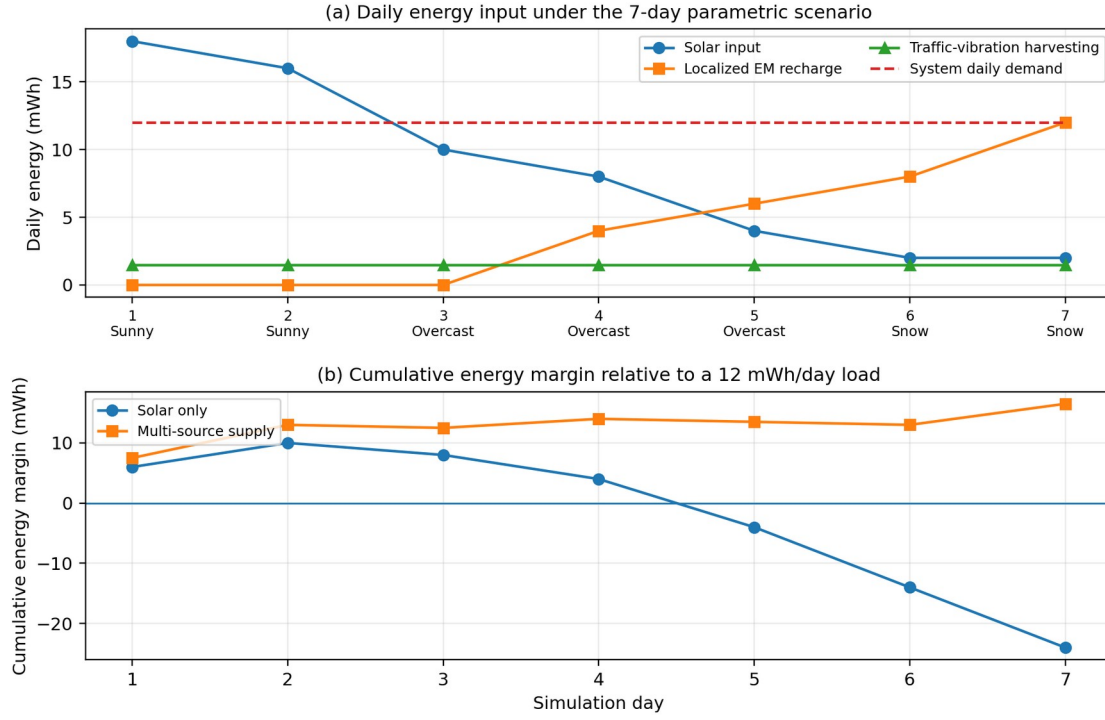


Fig. 2. Parametric simulation curves for multi-source energy supply under different weather conditions.

The parameterized results show that, over the seven-day scenario, the cumulative energy margin of the solar-only case decreases after Day 4 and becomes negative on Day 5. With localized electromagnetic recharging and vibration harvesting included, the cumulative energy margin remains positive at the end of Day 7. The results indicate that localized electromagnetic recharging provides a substantial supplemental contribution during snow-covered and prolonged low-irradiance periods, while vibration harvesting provides a stable low-power input. The multi-source configuration therefore reduces the energy-balance risk associated with solar variability.

4. Material Durability and Field-Validation Layout

Engineering implementation of the multi-source system requires coordinated consideration of energy balance, structural load resistance, sealing, and environmental durability. The transparent protective cover should provide adequate light transmission, abrasion resistance, impact resistance, and low-temperature performance. The metallic base should be protected against corrosion caused by deicing salts and moisture. Sealing and bonding materials should retain waterproofing and adhesion after freeze-thaw cycling, vibration, and temperature variation. Active-lighting, energy-storage, and control components should be located within sealed spaces protected by the snowplow-guiding members, and additional openings, thin sections, or local stress concentrations should not reduce the overall structural capacity of the marker body.

Field validation should include synchronous acquisition of solar irradiance, temperature and humidity, marker acceleration, energy-storage voltage and current, LED luminous intensity, and traffic loading, together with the number and duration of localized electromagnetic recharge events. Multi-parameter monitoring can establish the relationships among environmental conditions, energy input, structural response, and optical performance and can provide baseline data for service-life assessment and parameter optimization. Figure 3 illustrates the proposed field-validation layout and primary monitoring parameters.

Proposed field-validation layout and monitoring parameters

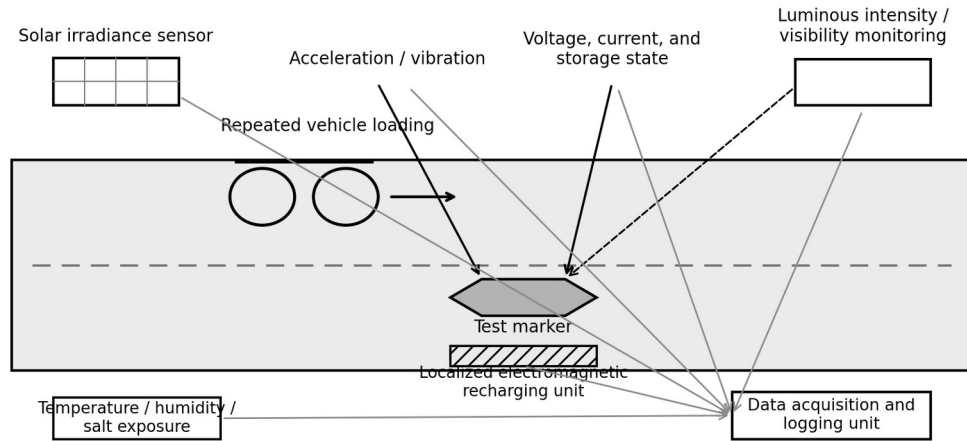


Fig. 3. Proposed field-validation layout and principal monitoring parameters.

Cold-region ports, terminal access roads, freight-collection and distribution corridors, and bridge approaches are priority application scenarios for the proposed scheme. These environments commonly combine high proportions of heavy vehicles, frequent winter snow removal, intensive use of deicing salts, and elevated visual-guidance requirements during nighttime and adverse weather. The low-profile configuration reduces direct snowplow-impact risk, the multi-source power system improves supply stability under prolonged low-light conditions, and the passive retroreflective unit maintains basic visual guidance in the event of electrical-system malfunction.

5. Conclusions and Recommendations

(1) The low-profile snowplow-protection configuration reduces direct impact on the retroreflective element by controlling the guiding-member height, protective height difference, and embedment depth. The through-opening, bond-enhancement features, and venting/drainage provisions improve combined bonding among the base, retroreflective element, and pavement while reducing water and contamination accumulation.

(2) Solar energy, localized electromagnetic recharging, and traffic-vibration harvesting can form a hierarchical energy-supply system. In the parameterized seven-day scenario, the cumulative energy margin of the solar-only case becomes negative on Day 5, whereas the multi-source configuration remains positive through Day 7. Localized electromagnetic recharging effectively compensates for energy deficits caused by snow cover and prolonged low irradiance, while vibration harvesting is suitable as a continuous low-power supplement.

(3) Material and structural durability are fundamental to engineering implementation of the multi-source power module. The transparent protective cover, metallic base, sealing and bonding system, and internal electronic components should satisfy requirements for abrasion resistance, impact resistance, corrosion resistance, waterproofing, low-temperature performance, and cyclic loading. Integration of additional power components should not reduce the load-carrying capacity or snowplow-protection performance of the original low-profile structure.

The next stage of research is planned to use a physical prototype for three categories of validation. The first category is energy testing, including direct measurement of the contributions from solar energy, localized electromagnetic recharging, and traffic-induced vibration under different operating conditions and comparison with the consumption of the LED and control unit. The second category is mechanical testing, including wheel loading, snowplow contact or impact, and long-term repeated vibration. The third category is environmental-adaptability testing, including freeze-thaw cycling, salt spray or saline-water exposure, water immersion, and abrasion of the transparent protective surface. Validation will focus on identifying the dominant failure modes of the base structure, sealing system, and power modules, followed by iterative optimization of structural parameters and system integration based on test results.

Acknowledgments

The author thanks Professor Bryan Huey of Purdue University for his suggestions on electromagnetic induction recharging and the use of traffic-induced vibration energy during technical discussions. The author independently carried out the subsequent scheme refinement, structural integration, parametric analysis, and preparation of this manuscript.

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