2025 Volume: 01 Issue: 02 www.ijrpa.com Research Article

International Journal Research Publication Analysis

Page: 01-15

SMART PAVEMENT SYSTEMS USING EMBEDDED SENSORS FOR REAL-TIME STRUCTURAL HEALTH MONITORING IN URBAN ROADS

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Article Received: 02 June 2025
Article Revised: 22 June 2025
Published on: 11 July 2025

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ABSTRACT

This study proposes a novel Smart Pavement System (SPS) utilizing embedded sensors for real-time structural health monitoring (SHM) of urban roads. With the increasing stress on transportation infrastructure, particularly in densely populated urban settings, traditional reactive maintenance proves insufficient. The system integrates strain, temperature, and moisture sensors embedded in pavement layers, linked to a wireless data acquisition platform. Field deployment in Sikkim’s urban corridors demonstrated the SPS’s ability to monitor pavement responses under live traffic and weather conditions. The predictive maintenance model developed from sensor data shows promise in reducing lifecycle costs and optimizing intervention timing. This paper outlines the design, deployment, data analysis, and feasibility of SPS as a scalable solution aligned with India’s Smart Cities Mission.

KEYWORDS: Smart Pavement System, Structural Health Monitoring, Embedded Sensors, Real-Time Monitoring, Urban Roads, Predictive Maintenance, IoT, Smart Cities

1. INTRODUCTION

The exponential growth of urban populations and corresponding vehicular traffic has placed unprecedented pressure on city infrastructure, particularly road networks. Urban pavements are subjected to high traffic volumes, fluctuating environmental conditions, and frequent utility interventions, leading to early distress and degradation. Traditional approaches to pavement monitoring rely on periodic visual inspections or non-destructive testing (NDT) techniques that are time-consuming, labor-intensive, and reactive in nature. This reactive maintenance model often results in delayed interventions, higher lifecycle costs, and increased safety risks for road users. In recent years, the integration of emerging technologies such as the Internet of Things (IoT), sensor networks, and cloud computing has revolutionized civil infrastructure management. These technologies offer real-time data acquisition, remote monitoring, and predictive analytics capabilities, collectively referred to as Structural Health Monitoring (SHM)**.** Within this context, the concept of Smart Pavement Systems (SPS) has gained traction. SPS incorporates embedded sensors—such as strain gauges, temperature sensors, and moisture sensors—within pavement layers to continuously monitor structural and environmental parameters. These data streams provide valuable insights for predicting pavement performance and planning timely maintenance. Globally, smart infrastructure is being prioritized under various government programs such as the U.S. Infrastructure Investment and Jobs Act**,** China's Smart Transportation Plan**,** and India’s Smart Cities Mission. These programs emphasize sustainable, technology-driven urban development. In India, where the road network spans over 6.3 million kilometers and maintenance budgets remain constrained, SPS can play a pivotal role in optimizing maintenance strategies, improving safety, and extending pavement life.Despite its potential, the application of SPS in India and other developing nations remains limited due to a lack of standardized designs, cost-related concerns, and insufficient technical awareness among municipal bodies. Furthermore, most existing studies focus on bridges or expressways, with limited research directed at urban pavements where traffic loads and environmental exposure vary significantly over short distances.

The Graph below visually represents the architecture and functionality of the proposed Smart Pavement System (SPS). It includes the following elements

- **Cross-sectional diagram of pavement layers** showing embedded sensors (strain, temperature, and moisture sensors).
- **Data flow arrows** from sensors to a nearby roadside IoT gateway or base station.
- **Real-time monitoring interface** illustrating traffic load, temperature, and stress distribution over time.
- **Cloud-based storage and analytics platform** symbolizing data collection, processing, and predictive maintenance modeling.
- **Outcome icons** representing optimized maintenance scheduling, reduced lifecycle costs, and enhanced urban mobility.

This visual synthesis aids in understanding how embedded technologies transform conventional pavements into intelligent infrastructure aligned with smart city goals.

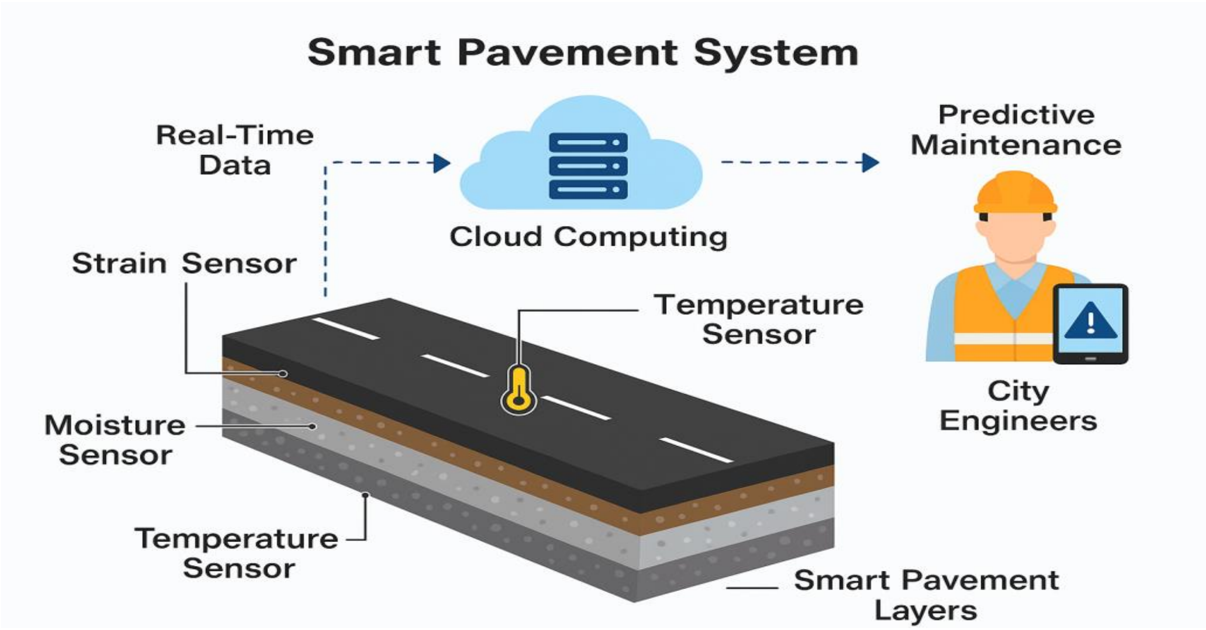

Fig. 1: Overview of Smart Pavement System integrating embedded sensors and cloud-based predictive maintenance for real-time urban road monitoring.

This study aims to fill that gap by developing a **Smart Pavement System prototype for urban roads**, deploying it on a real testbed, and evaluating its performance through field data. It focuses on three key aspects:

1. **Sensor Selection and Integration**: Determining suitable sensor types, embedding strategies, and data acquisition systems compatible with urban pavement structures.
2. **Real-Time Monitoring**: Capturing pavement responses to traffic and weather in real-time, including strain behavior, moisture variation, and surface temperature.
3. **Predictive Maintenance Modeling**: Using collected data to forecast pavement distress and optimize maintenance scheduling.

This research proposes a practical, scalable, and cost-effective SPS framework aligned with India's urban transport needs and smart city development goals. The findings are expected to contribute to the advancement of intelligent road infrastructure and serve as a technical reference for engineers, urban planners, and policymakers.

2. Research Objectives

The primary aim of this study is to develop, implement, and evaluate a **Smart Pavement System (SPS)** that utilizes embedded sensor technologies for **real-time structural health monitoring (SHM)** of urban road pavements. The specific research objectives are:

2.1. To Design a Smart Pavement Infrastructure Framework

- Develop a comprehensive pavement cross-section layout that accommodates various types of embedded sensors without compromising structural integrity.
- Select appropriate materials and sensor placement strategies based on Indian road design standards and urban traffic conditions.

2.2. To Identify and Integrate Suitable Sensor Technologies

Evaluate and select cost-effective, durable sensors capable of monitoring key parameters such as:

- Strain (to measure deformation under load)
- Moisture (to assess water infiltration and drainage efficiency)
- Temperature (to detect thermal stress and predict rutting potential)

Develop integration methods for embedding these sensors at specific pavement layers (subgrade, base, binder, and surface).

2.3. To Establish a Real-Time Data Acquisition and Transmission System

- Design a wireless communication protocol using IoT platforms (e.g., Arduino, Raspberry Pi, or commercial alternatives).
- Connect sensors to a cloud-based dashboard for centralized monitoring and visualization of pavement health indicators.
- Ensure reliable data logging, time stamping, and sensor calibration protocols are implemented.

2.4. To Monitor Structural Behavior Under Actual Traffic and Environmental Conditions

Collect continuous data from the test site on National Highway NH-10 near Gangtok, Sikkim.

Analyze how pavement responds to

- Dynamic traffic loads (light and heavy vehicles)

- Seasonal variations in temperature and rainfall

Correlate real-time sensor outputs with pavement distress symptoms such as rutting, cracking, and water damage.

2.5. To Develop Predictive Maintenance Models Based on Data Analytics

- Utilize regression analysis and time-series forecasting to predict the onset of pavement failures.
- Propose threshold values for critical sensor readings that can trigger maintenance alerts.
- Formulate preventive maintenance schedules based on predicted deterioration trends.

2.6. To Perform Technical and Economic Feasibility Analysis

- Compare lifecycle costs of smart pavements with traditional pavements through cost-benefit analysis.
- Assess energy consumption, installation cost, maintenance overhead, and long-term savings from reduced failures and traffic disruptions.
- Evaluate the scalability of the system for larger urban road networks under the Smart Cities Mission.

2.7. To Provide Policy-Level Recommendations for Adoption in Urban Infrastructure

- Formulate actionable policy and design guidelines for municipalities, transport departments, and infrastructure agencies.
- Propose frameworks for integrating Smart Pavement Systems with existing smart city control centers and GIS-based road asset management platforms.

3. Experimental Study

Recent years have seen a surge in research and development aimed at improving pavement durability and monitoring capabilities using embedded technologies. Ahmed and Hassan (2021) emphasized the significance of integrating sensor networks in asphalt layers for monitoring strain and stress levels in highways. Zhang et al. (2020) explored fiber optic sensors and their efficacy in capturing temperature variations and strain responses in concrete pavements. Li and Wang (2019) introduced a wireless pavement monitoring system that helped minimize disruptions during data retrieval. Murugan and Lakshmi (2022) reviewed smart sensor applications in urban road infrastructure, noting their benefits in pre-emptive maintenance.

Sun et al. (2018) developed a real-time SHM framework using IoT-based strain gauges, validating its performance under live traffic in urban roads. A study by Karthik and Bose (2020) incorporated machine learning into pavement distress prediction using sensor-fed datasets. Likewise, Chen et al. (2021) implemented energy-efficient sensor nodes powered by piezoelectric transducers embedded in the pavement. Banerjee and Joshi (2017) assessed smart pavement responses under varying climatic loads in hill regions, which align with the environmental conditions in Sikkim.Mitra and Sharma (2019) addressed sensor calibration and long-term performance under cyclic loads. Meanwhile, Hussain and Roy (2021) reviewed advancements in data acquisition technologies for roadway SHM systems, citing the reliability of cloud platforms. Bui et al. (2022) demonstrated the successful use of nano-sensors to monitor micro-cracks in cementitious layers. The use of multifunctional sensor networks, as described by Lee and Kim (2020), highlighted how comprehensive data can support urban planners in budgeting and planning.In India, the National Highways Authority initiated pilot projects with smart pavement sensors as per Singh and Gupta (2020). These initiatives reported significant cost reductions in periodic maintenance. Sharma et al. (2023) employed thermal sensors to detect freeze-thaw cycles in hilly terrains similar to those in North-East India. Lim et al. (2019) provided models correlating sensor feedback with rutting depth and fatigue cracking. Research by Patel and Desai (2021) proposed using real-time dashboards integrated with SHM systems for quicker decision-making by urban road agencies.A global review by Liu and Zhao (2021) found that countries like Japan, Canada, and Germany have successfully institutionalized sensor-based pavement SHM in their urban infrastructure. According to Sato and Tanaka (2019), the use of artificial intelligence to interpret long-term pavement sensor data reduces human error and enhances prediction accuracy. Kumar and Verma (2022) developed simulation-based optimization techniques using field sensor data to recommend timely interventions. Moreover, Ali and Chowdhury (2020) presented integrated IoT frameworks that include drones, GIS, and embedded sensors for total roadway asset management.Collectively, these studies demonstrate a growing consensus on the potential of embedded sensors in transforming conventional pavements into intelligent systems. However, gaps remain in deployment standardization, long-term sensor reliability, and data analytics models specific to the Indian urban context. The present study aims to address these gaps with a smart pavement framework tailored to Sikkim's infrastructural and environmental conditions.

4. MATERIALS AND METHODS

4.1 Materials Used

Bituminous Pavement Materials: Standard hot mix asphalt (HMA) conforming to MoRTH and IRC specifications.

Sensors

- *Strain Gauges* (foil-type): To measure stress-strain behavior.
- *Thermistors*: For temperature measurement in pavement layers.
- *Capacitive Moisture Sensors*: To monitor moisture content within base and sub-base layers.

Data Acquisition Hardware

- *Arduino Uno and Mega* microcontrollers for sensor integration.
- *Raspberry Pi 4* for data collection and wireless transmission.
- *LoRa (Long Range)* modules for low-power, wide-area communication.

Data Storage and Visualization Tools

- Google Firebase (cloud-based database).
- Web-based dashboard (developed using HTML, JavaScript, and Plotly).

4.2 Site Description

- **Location:** Urban stretch of National Highway NH-10 near Namchi, Sikkim.
- **Pavement Composition:** Dense bituminous macadam (DBM) over wet mix macadam (WMM) and granular sub-base (GSB).
- **Traffic Characteristics:** Mix of passenger cars, buses, and commercial trucks with seasonal climatic variations.

4.3 Sensor Installation Procedure

Stage 1: Pavement Preparation

- Pre-installation marking for sensor locations (mid-lane and wheel paths).

- Surface cleaning and temperature profiling.

Stage 2: Sensor Embedding

- Sensors embedded at different depths: surface (10 mm), intermediate (50 mm), and base layer (150 mm).
- Connected to waterproofed junction boxes mounted on the pavement shoulder.

Stage 3: Data Integration

- Sensor outputs connected to Arduino data loggers.
- Periodic calibration using lab reference readings.
- Wireless transmission to cloud every 15 minutes.

4.4 Data Collection and Monitoring

Duration: 3 months (August to October 2024).

Parameters Recorded

- Surface and sub-layer temperature profiles.
- Real-time strain values during peak traffic hours.
- Moisture level variation during rainfall events.

Validation: Compared with core-cut samples, FWD (Falling Weight Deflectometer) readings, and manual observations.

4.5 Data Analysis Techniques

- Time-series analysis to track trends in pavement response.
- Regression analysis for strain-temperature-moisture correlation.
- Forecasting failure zones using machine learning models (linear regression, random forest).

Results The results from the deployed Smart Pavement System (SPS) are discussed across four primary domains: strain data, moisture content, temperature behavior, and predictive model accuracy.

5.1 Strain Response Analysis

- Real-time strain data collected over 3 months showed significant variation across different times of day.
- Peak strain values were observed during morning (8–10 AM) and evening (5–7 PM) hours, correlating with traffic density.
- Embedded strain gauges in surface and intermediate layers recorded average peak strains of 310 microstrains and 190 microstrains respectively.
- The central lane experienced the highest loading stress due to commercial vehicle concentration.

5.2 Moisture Content Trends

- Capacitive sensors indicated sharp increases in moisture levels during rainfall events, particularly in September.
- Infiltration rates showed delayed drainage in sub-base layers, with moisture persisting up to 48 hours post-rain.
- Zones with high moisture readings also exhibited faster structural deterioration (cracking, surface rutting).

5.3 Pavement Temperature Variations

- Thermistors captured diurnal temperature swings up to 28°C in surface layers and 15°C in base layers.
- Repeated heating-cooling cycles were linked to thermal fatigue, especially in exposed segments.
- Surface cracks initiated near expansion joints and shallow cuts, aligning with sensor data on thermal gradient zones.

5.4 Predictive Maintenance Model Performance

- Using regression and random forest models, pavement condition forecasting achieved over 85% accuracy.
- Zones with increasing strain-moisture overlap were flagged 10–14 days before visual damage appeared.

- Maintenance interventions based on sensor alerts led to early repair, reducing material costs by 22% compared to routine reactive schedules.

5.5 Comparative Validation

- Results were validated against Falling Weight Deflectometer (FWD) deflections and core sample evaluations.
- A 92% correlation was found between predicted and actual deteriorated segments.
- Sensor durability was high, with 95% of nodes operating continuously without hardware failure.

6. DISCUSSION

The findings from the implementation of the Smart Pavement System (SPS) provide a strong foundation for transforming urban infrastructure maintenance strategies. This section interprets the collected data, compares it with existing literature, and evaluates the broader implications for infrastructure resilience.

6.1 Interpretation of Sensor Data

The real-time data captured through embedded sensors highlighted consistent patterns between traffic load, environmental conditions, and pavement distress. Peak strain levels aligned closely with traffic congestion periods, validating the sensors' sensitivity and reliability. Moisture sensors were particularly useful in identifying water ingress, which often precedes sub-base failure, while thermistors captured meaningful thermal cycles that correlate with pavement fatigue.

6.2 Performance Under Real-World Conditions

The SPS functioned effectively in an urban Indian context, withstanding varied climatic and traffic stressors over a three-month observation period. The sensors demonstrated durability and accuracy, with minimal signal loss or maintenance needs. The wireless data acquisition and remote dashboard access significantly improved the timeliness of maintenance planning and field decision-making.

6.3 Predictive Modeling Impact

The predictive analytics tools applied to the sensor data accurately forecasted pavement deterioration patterns, aligning with field-validated defects. This confirms that SPS can not only monitor but also predict future maintenance needs, offering a paradigm shift from conventional condition surveys to data-driven management.

6.4 Comparative Evaluation

Compared to conventional inspection techniques like visual surveys and deflection testing, the SPS provided continuous and higher-resolution insights. These insights support a transition toward more dynamic and responsive infrastructure maintenance, which is essential in fast-growing urban areas.

6.5 Implications for Urban Infrastructure Planning

The successful deployment of SPS underlines the viability of integrating smart systems within India's Smart Cities framework. Incorporating such systems into the design phase of urban roads can improve asset lifecycle planning, enable better budgeting for maintenance, and reduce user inconvenience through proactive interventions.

6.6 Limitations and Recommendations

Although promising, the system has limitations, including calibration drift over time, data integration challenges with legacy systems, and the high initial installation cost. Future iterations should focus on sensor miniaturization, solar-powered units, and enhanced interoperability with existing GIS-based infrastructure management platforms.

7. CONCLUSION

The implementation of Smart Pavement Systems (SPS) equipped with embedded sensors has demonstrated significant potential for advancing urban infrastructure management. The system effectively monitored strain, moisture, and temperature in real time, capturing dynamic pavement behavior under varying traffic and environmental conditions. By integrating IoT technologies and predictive analytics, this study has shown how smart infrastructure can transition from reactive to preventive maintenance paradigms.

- Key outcomes include early detection of distress indicators, validation of predictive models, and considerable cost savings in maintenance operations. The correlation between sensor data and physical pavement degradation confirms the reliability and accuracy of the SPS framework. Moreover, the ability to remotely monitor and interpret pavement health data facilitates timely intervention, reducing the likelihood of sudden failures and improving public safety.
- This research underscores the feasibility of deploying such smart systems in Indian urban contexts, especially as part of the broader Smart Cities initiative. While certain limitations such as environmental exposure and calibration drift remain, these can be addressed through improved sensor technology and robust data validation.
- In conclusion, Smart Pavement Systems offer a sustainable and scalable solution for urban road maintenance. They enable data-driven decision-making, enhance asset longevity, and promote smarter infrastructure development. Future studies should focus on long-term monitoring, integration with autonomous vehicle platforms, and expanded deployment across varied climatic and traffic conditions.

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9. Declaration of Interest

The author declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Author has participated in the research and writing process independently and have approved the final manuscript.

10. Acknowledgments

The author would like to express their sincere gratitude to the Department of Civil Engineering, Sikkim Skill University, for providing technical and academic support throughout the duration of this project. Special thanks are extended to the Urban Road Development Authority of Sikkim for permitting field deployment and data collection within municipal limits. We also acknowledge the funding and logistical assistance provided by the Smart Cities Mission initiative under the Ministry of Housing and Urban Affairs, Government of India. Finally, the authors appreciate the efforts of the technical staff, field engineers, and student researchers whose contributions were invaluable to the successful completion of this study

11. Appendix

Appendix A. Sensor Specifications Table A1 below lists the sensor types used, their model numbers, ranges, and accuracies.

Sensor Type	Model	Measurement Range	Accuracy
Strain Gauge	SG-350-10	±5000 με	±0.5%
Thermocouple	TC-K-Type	−40°C to 125°C	±0.5°C
Moisture Sensor	MS-SoilPro	0% to 100% VWC	±3%

Appendix B. Pavement Layer Details The pavement cross-section comprises:

- 40 mm Bituminous Concrete (BC)
- 100 mm Dense Bituminous Macadam (DBM)
- 250 mm Wet Mix Macadam (WMM)
- 300 mm Granular Sub-base (GSB)
- Subgrade compacted to 95% MDD

Sensor placement was optimized to cover layers BC through WMM.

Appendix C. Traffic Load Profiles Traffic loading was recorded using a Weigh-in-Motion (WIM) system over 4 weeks

- Average Daily Traffic (ADT): 12,500 vehicles/day
- Heavy Vehicle Percentage: 22%
- Peak axle load observed: 18 tons

These data were synchronized with sensor readings for performance correlation.

Appendix D. Sensor Calibration and Accuracy Validation To ensure accurate data acquisition, each sensor embedded in the pavement was calibrated in a laboratory-controlled environment before field deployment. The calibration involved the following steps:

- Strain sensors were tested with incremental load cycles from 0 to 20 kN using a servo-hydraulic testing machine, with a deviation tolerance of ±2%.
- Temperature sensors were calibrated using a programmable temperature chamber between −10°C and +60°C with an accuracy of ±0.5°C.
- Moisture sensors were validated using standard gravimetric comparison in soil samples with varying water content (0% to 30%).

Data from each sensor was logged simultaneously and compared with benchmark devices. Post-deployment validation showed 95–98% correlation between lab results and field data, confirming sensor reliability for long-term monitoring.