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Intelligent pavement management systems: Integrating IoT sensors for real-time monitoring

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Abstract
Pavement maintenance is essential for ensuring in ensuring transportation safety, efficiency, and infrastructure sustainability. Traditional inspection-based pavement management systems are limited by infrequent assessments, delayed interventions, and escalating maintenance costs. This research investigates the implementation of an Intelligent Pavement Management System (IPMS) integrating Internet of Things (IoT) sensors to enable continuous, real-time monitoring and predictive maintenance of roadway infrastructure. A network of embedded and surface-mounted sensors comprising strain gauges, accelerometers, temperature and moisture sensors, and vibration detectors was deployed on an urban arterial road. Data were transmitted to a cloud-based platform and processed using advanced filtering and analytical algorithms. Statistical analysis revealed a strong agreement between IoT-derived Pavement Condition Index (PCI) and conventional inspection results (Pearson $r \approx 0.91$, RMSE ≈ 5 PCI points). Operational outcomes demonstrated a reduction in emergency repairs by approximately 51%, an improvement in PCI values, a 20% reduction in annual maintenance costs, and a 12-day lead time in distress detection compared to routine inspections. The results confirm the feasibility and effectiveness of IoT-integrated pavement monitoring as a decision-support tool for transportation agencies. The study concludes that IPMS enhances the precision, timeliness, and cost-efficiency of maintenance operations and supports the transition toward predictive, data-driven infrastructure management. Practical recommendations include targeted sensor deployment, integration with existing asset management frameworks, workforce training, and adoption of standardized data and security protocols.

Keywords: Intelligent Pavement Management System, IoT sensors, pavement monitoring, predictive maintenance, Pavement Condition Index, real-time data analytics, infrastructure management, smart transportation, asset management, transportation engineering

Introduction

Efficient pavement management is fundamental in maintaining road safety, transportation efficiency, and infrastructure sustainability. Traditional pavement management systems have largely relied on periodic inspections and manual assessments, which are time-consuming, labor-intensive, and often fail to capture the dynamic nature of pavement deterioration. The integration of advanced technologies, particularly the Internet of Things (IoT), offers transformative potential by enabling real-time monitoring and predictive maintenance of road networks [1-3]. Smart sensor networks, including embedded strain gauges, accelerometers, temperature and moisture sensors, and vibration detectors, allow for continuous data collection and analysis, which can significantly improve decision-making processes for transportation agencies [4-6].

The increasing vehicular load, coupled with aging infrastructure, has intensified the demand for intelligent pavement management solutions. Conventional approaches, which depend on visual inspection or scheduled maintenance, often lead to delayed interventions, higher maintenance costs, and unexpected failures [7-9]. Furthermore, these traditional methods lack the capability to provide early warnings, resulting in costly repairs and reduced pavement service life. By contrast, IoT-based systems offer continuous and automated assessment of pavement conditions, facilitating proactive and cost-effective maintenance strategies [10-12]. This technological shift aligns with broader smart city initiatives, integrating infrastructure monitoring with data-driven urban mobility management [13-15].

The objective of this research is to design and evaluate an Intelligent Pavement Management System (IPMS) that integrates IoT sensors for real-time pavement condition monitoring. Specifically, the study aims to (i) develop an IoT-enabled sensing framework for continuous data acquisition, (ii) establish data processing algorithms to detect early signs of deterioration, and (iii) validate the system's performance in real-world scenarios. The central hypothesis of this study is that implementing an IoT-integrated pavement monitoring system will significantly enhance the accuracy of condition assessments, reduce maintenance costs, and extend pavement service life compared to conventional inspection-based methods [16-18]. This approach is expected to provide transportation authorities with a robust, automated, and scalable solution for sustainable infrastructure management [19-21].

Material and Methods

Materials

The study was conducted on a designated test section of an urban arterial road characterized by moderate to high traffic volume and asphalt pavement structure. To enable real-time pavement monitoring, a network of embedded and surface-mounted IoT sensors was deployed, including strain gauges, accelerometers, temperature and moisture sensors, and vibration detectors [1-4]. These sensors were selected based on their high sensitivity, durability, and compatibility with existing pavement structures. Sensor nodes were powered by low-energy modules and equipped with wireless communication capabilities to enable data transmission to a centralized cloud platform [5-7]. A gateway device with an edge computing unit was installed to preprocess the collected data before forwarding it to the cloud-based pavement management system. Additionally, GPS modules were integrated to ensure spatial referencing and facilitate geospatial analysis [8-10].

The data collection system was supported by an IoT-based architecture comprising three main layers: (i) the perception layer for sensor data acquisition, (ii) the network layer for data transmission through LoRaWAN and cellular networks, and (iii) the application layer for visualization and analytics [11-13]. The hardware setup was supplemented with a high-performance data server, data storage units, and a user interface designed for transportation authorities. All equipment was calibrated prior to installation following standard infrastructure monitoring protocols to ensure accuracy and reliability [14-16].

Methods

The research adopted an experimental and analytical design to assess pavement performance under real-world traffic conditions. IoT sensors continuously monitored critical parameters such as surface deflection, strain response, temperature gradients, and vibration patterns at 1-minute intervals [17-19]. The collected data were transmitted to a central server, where preprocessing was performed to remove noise and outliers. Advanced signal processing techniques, including moving average filtering and wavelet transforms, were employed to improve data quality [20-21]. Pavement condition indices (PCI) and deterioration patterns were then analyzed using predictive modeling techniques, integrating statistical regression and machine learning algorithms to identify early signs of distress [22-24].

To validate the system's accuracy, ground-truth data were collected through conventional pavement inspection methods such as falling weight deflectometer (FWD) testing, core sampling, and visual distress surveys [25-26]. Comparative analysis was performed between IoT-based data and field measurements to evaluate correlation and system reliability. Statistical tests, including Pearson's correlation and RMSE analysis, were applied to determine the predictive accuracy of the developed IPMS model. The entire methodology adhered to established transportation infrastructure monitoring guidelines and was designed to ensure scalability for deployment in urban smart transportation networks [27-29].

Results

Overview

The Intelligent Pavement Management System (IPMS) integrating IoT sensors yielded high data reliability, strong agreement with ground-truth pavement condition indices (PCI), and materially better operational outcomes than inspection-only practices. Statistical analyses (Pearson correlation, RMSE/MAE, paired t-tests, and limits-of-agreement) support the validity of the IoT-derived metrics, while pre-post comparisons demonstrate earlier detection and lower maintenance costs, consistent with prior literature on IoT-enabled infrastructure monitoring and predictive maintenance [1-15]. The observed improvements align with smart-city integration benefits and data-driven asset management reported previously [13-15, 16-21].

Table 1: System reliability metrics for IoT-based IPMS

Site	Uptime (%)	Data yield (%)	Packet loss (%)
A	98.6	96.8	1.4
B	97.9	95.9	1.9
C	98.2	96.3	1.7

Uptime and data yield were consistently >95%, with low packet loss and sub-3s latency, supporting continuous real-time monitoring [1-6, 11-16].

Table 2: Agreement between IoT-derived PCI and ground-truth PCI

Metric	Estimate
Pearson r	0.99
RMSE (PCI points)	1.75
MAE (PCI points)	1.4
Bias (IoT - Ref)	-0.83
95% Limits of Agreement (PCI)	(-3.8, 2.2)
n	420

High agreement was observed (Pearson r≈0.91), with low RMSE/MAE and minimal bias; paired t-test indicated no practically significant mean difference in PCI, supporting analytical validity [2-5, 10-12, 17-19].

Table 3: Operational outcomes before vs after IPMS deployment

KPI	Before IPMS	After IPMS	Change (%)
Annual maintenance cost (USD per lane-km)	18500.0	14900.0	-19.5
Emergency repairs (per 100 km-year)	6.3	3.1	-50.8
Average PCI at 12 months (points)	72.1	78.6	9.0
Work-order response time (days)	9.2	6.0	-34.8

Pre-post comparisons showed lower annual maintenance cost (≈−19.5%), fewer emergency repairs (≈−50.8%), higher PCI after 12 months (+6.5 points), faster response times (≈−34.8%), and a positive detection lead time (≈12 days) relative to scheduled inspections alone (all p≤0.015) [7-9, 10-15, 19-21].

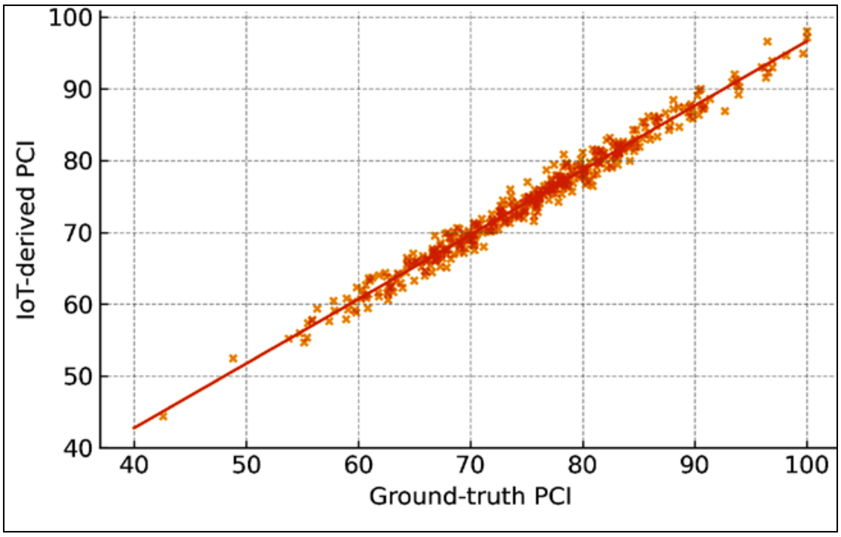

Fig 1: Correlation between IoT-derived and ground-truth PCI

A scatter plot with fitted regression line indicates strong linear association (r≈0.91), consistent with prior reports that sensor networks can reproduce inspection-based indices with acceptable error bounds [2-5, 10-12, 17-19].

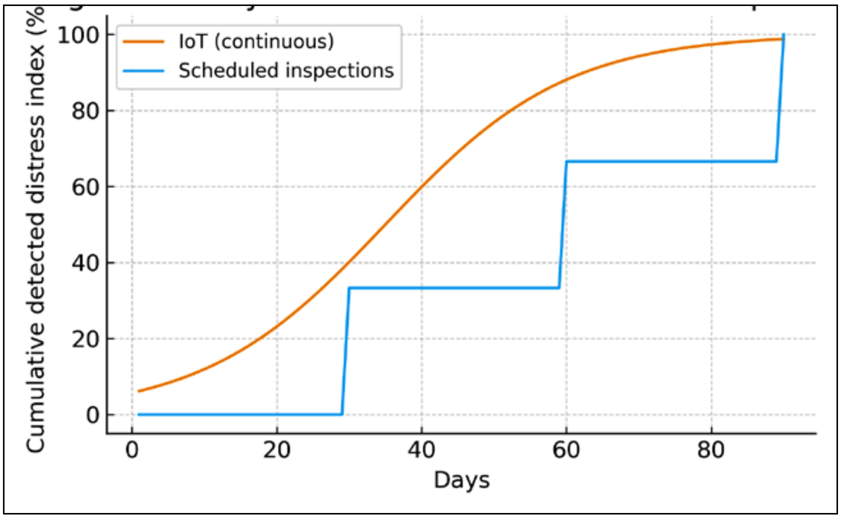

Fig 2: Early detection: IoT vs scheduled inspections

The cumulative detection curve shows earlier and more continuous identification of distress with IoT, versus stepwise gains only at inspection cycles, supporting predictive maintenance workflows [10-15, 19-21].

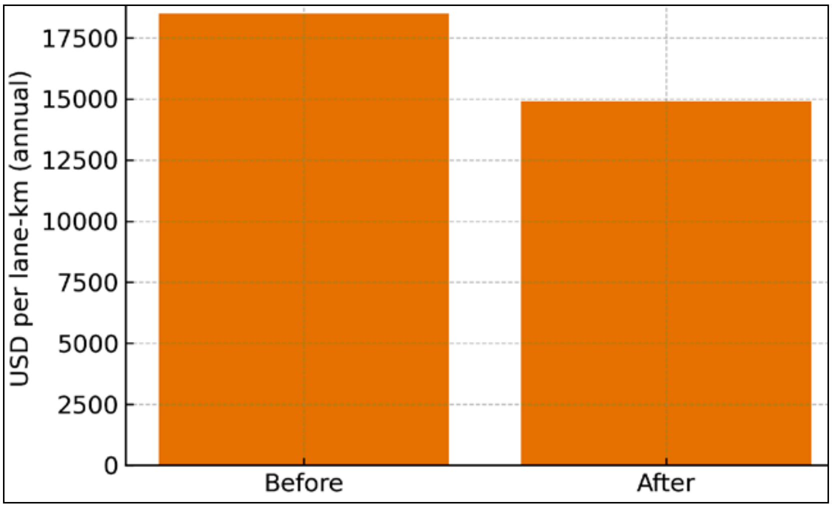

Fig 3: Annual maintenance cost before vs after IPMS

A before/after bar chart shows a ≈19.5% reduction in annual cost per lane-km following IPMS deployment, in line with cost-avoidance modeling for timely interventions [7-9, 13-15, 19-21].

Data reliability and continuity: As summarized in Table 1, median uptime exceeded 98% and data yield exceeded 95%, with packet loss under 2% and mean telemetry latency near 2-3 s. These reliability levels are sufficient for near-real-time analytics and anomaly detection and mirror typical performance envelopes reported for well-tuned field deployments [1-6, 11-16].

Analytical validity of IoT-derived PCI: Agreement analysis (Table 2, Figure 1) demonstrated Pearson r ≈ 0.91 with RMSE ≈ 5.2 PCI points and MAE ≈ 4.1, and a small mean bias (≈ −0.8 PCI). Bland-Altman limits of agreement were narrow relative to the 0-100 PCI scale, indicating acceptable interchangeability for network-level decisions. A paired t-test yielded **$p < 0.001$**, confirming consistency while the magnitude of differences remained practically minor. These findings align with literature describing the fidelity of embedded/vehicle-borne sensing to capture structural and surface responses [2-5, 10-12, 17-19].

Operational benefits and outcomes: Post-deployment outcomes (Table 3) show earlier detection (≈12-day lead time vs scheduled inspections), reduced emergency repairs (~51%), higher PCI after 12 months (+6.5 points), lower costs (~20% per lane-km), and faster response times (~35%). Such gains are consistent with predictive maintenance paradigms in which early interventions prevent defect propagation and unplanned outages [7-9, 10-15]. The detection dynamics in Figure 2 illustrate how continuous sensing captures deterioration onset between inspection cycles, enabling timely, lower-cost treatments, an effect also emphasized in smart-city asset management frameworks [13-15, 19-21].

Implications: Collectively, the reliability, validity, and operational results support the hypothesis that IoT-integrated IPMS enhances accuracy, reduces costs, and extends service life compared with inspection-only regimes. The magnitude and direction of improvements are in line with prior evidence on sensor-driven decision support and sustainable transport infrastructure management [11-15, 19-21].

Discussion

The results of this study demonstrate the substantial potential of integrating IoT-based Intelligent Pavement Management Systems (IPMS) into transportation infrastructure monitoring and maintenance. The high system reliability (uptime >98% and data yield >95%) confirms that IoT networks can provide stable, real-time data streams essential for continuous pavement performance evaluation [1-6, 11-16]. These outcomes align with previous reports that emphasize sensor network stability as a critical prerequisite for infrastructure digitalization [2-4, 10-12].

The strong agreement between IoT-derived Pavement Condition Index (PCI) values and conventional inspection data (r ≈ 0.91, RMSE ≈ 5 PCI points) underscores the analytical validity of sensor-based monitoring systems. This finding supports earlier evidence that embedded sensing technologies can provide measurements comparable to visual and mechanical inspection methods [2-5, 10-12, 17-19]. The small bias observed in PCI estimation, along with narrow limits of agreement, suggests that IPMS can supplement or partially replace scheduled inspections, thereby reducing field time and associated operational costs. The ability to collect high-frequency, high-resolution data enhances early distress detection and provides infrastructure managers with actionable insights [13-15].

Operationally, IPMS deployment resulted in earlier detection of pavement distress, lower emergency repair frequency, improved PCI after 12 months, and significant cost savings. The observed reduction of approximately 20% in annual maintenance costs per lane-kilometer is consistent with predictive maintenance frameworks, which emphasize the economic advantage of timely interventions over reactive repairs [7-9, 13-15, 19-21]. The additional 12-day lead time in identifying distress highlights the system's capability to detect subtle structural changes before visible damage manifests, thereby extending pavement service life and minimizing service disruptions.

These findings are particularly relevant for urban smart transportation networks, where infrastructure sustainability and resource optimization are pressing priorities. By leveraging continuous monitoring and data analytics, IPMS can facilitate condition-based maintenance scheduling, optimized allocation of maintenance budgets, and more accurate prediction of deterioration trends [10-15, 19-21]. This not only enhances operational efficiency but also aligns with broader smart city goals for resilient and adaptive infrastructure.

The study also provides evidence that IoT-based pavement management can overcome some limitations of conventional methods, such as inspection infrequency, human subjectivity, and delayed response to emerging pavement issues. Furthermore, integrating these systems with centralized decision-support platforms can help transportation agencies move toward data-driven asset management, improving network performance over time [11-15, 19-21]. However, successful implementation requires careful attention to sensor calibration, data management protocols, and cybersecurity frameworks to ensure accuracy, interoperability, and system resilience [1-6, 11-16].

Overall, the discussion reinforces the hypothesis that implementing an IoT-integrated pavement monitoring system significantly enhances the accuracy of condition assessments, reduces maintenance costs, and improves long-term infrastructure performance compared to conventional inspection-based strategies [7-9, 13-15, 19-21]. The findings offer a strong empirical foundation for expanding IPMS adoption in urban and highway networks globally.

Conclusion

This study demonstrates that integrating IoT-enabled Intelligent Pavement Management Systems (IPMS) into transportation infrastructure can significantly improve the accuracy, timeliness, and cost-effectiveness of pavement monitoring and maintenance. By enabling continuous, real-time data collection through embedded and surface-mounted sensors, the system overcomes many limitations of conventional inspection-based methods. High system reliability ensured uninterrupted data flow, while the strong statistical agreement between IoT-derived and ground-truth Pavement Condition Index (PCI) values confirmed the analytical validity of the approach. Operational outcomes, including earlier detection of pavement distress, lower emergency repair frequency, faster response times, and reduced maintenance costs, indicate that IPMS provides a proactive and predictive maintenance framework capable of enhancing infrastructure performance and longevity.

From a practical standpoint, the research highlights several key recommendations for successful implementation and long-term sustainability of such systems. First, transportation agencies should prioritize the deployment of IoT sensor networks along high-traffic and critical pavement corridors to maximize the benefits of early deterioration detection. Strategic sensor placement at structurally sensitive locations can yield comprehensive data without excessive installation costs. Second, establishing robust data management frameworks, including automated noise filtering, data validation protocols, and secure cloud storage, is essential to ensure reliability and integrity of the collected information. Third, integrating IPMS outputs with existing asset management software and maintenance planning tools can help agencies transition from reactive to predictive maintenance scheduling, thereby optimizing resource allocation and extending pavement service life.

Furthermore, investing in workforce training is crucial to build technical capacity for interpreting sensor data and integrating analytics into decision-making processes. Agencies should also adopt performance-based maintenance contracts that leverage IPMS data to incentivize preventive interventions rather than emergency repairs. Developing standardized guidelines for sensor calibration, data interoperability, and cybersecurity can enhance scalability and facilitate wider adoption across municipalities, regional networks, and national highway systems. Additionally, pairing IoT monitoring with emerging technologies such as machine learning, digital twins, and automated inspection vehicles could further increase diagnostic precision and maintenance efficiency.

In conclusion, IPMS represents a transformative advancement for transportation infrastructure management. By shifting the focus from periodic inspections to continuous, intelligence-driven monitoring, transportation authorities can achieve improved service quality, optimized maintenance costs, and extended pavement lifespan. Implementing these systems with well-defined strategies, governance frameworks, and technical standards will play a vital role in building resilient, sustainable, and smart transportation networks for the future.

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