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Smart Road Sensing Techniques (SRST) for Real Time Monitoring and Maintenance (RTMM)

Nazya Parveen[1] Swati Agrawal[2]

[1]Research Scholar, Department of Civil Engineering, Kalinga University, New Raipur, Chhattisgarh.

parveennazya@gmail.com

[2]Assistant Professor Department of Civil Engineering, Kalinga University, New Raipur, Chhattisgarh. swati.agrawal@kalingauniversity.ac.in

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Abstract:

This study seeks to revolutionize road monitoring and maintenance in Bilaspur, Chhattisgarh, by introducing Smart Road Sensing Techniques (SRST). As Bilaspur experiences rapid urbanization, the city's road infrastructure is increasingly burdened by challenges such as frequent damage, traffic congestion, and costly repairs. Traditional maintenance practices, which are largely manual and reactive, often fail to efficiently address these escalating issues. To combat these challenges, the research proposes a technology-driven approach, incorporating Internet of Things (IoT) devices, real-time data collection, and predictive analytics. The core objective of SRST is to establish a cost-effective and streamlined method for real-time monitoring of road conditions. By embedding IoT-enabled sensors into the roads, the system can continuously detect problems such as potholes, cracks, and uneven surfaces. Additionally, it tracks traffic density and environmental factors, such as weather, that contribute to road deterioration.

Keywords - Smart Road Sensing Techniques (SRST), Internet of Things (IoT), Real-time data collection, Predictive analytics, Road monitoring, Road maintenance, Urbanization, Road infrastructure, Traffic congestion, Potholes.

1. Introduction

Bilaspur, situated in the heart of Chhattisgarh, has emerged as one of the fastest-growing cities in the state. Known as the "Cultural Capital of Chhattisgarh," the city is experiencing rapid urbanization and infrastructural development, leading to a significant increase in vehicular traffic. As the city expands, its road infrastructure faces mounting pressure, resulting in wear and tear that adversely impacts commuters.

The adoption of SRST offers several advantages. First, it shifts the maintenance paradigm from reactive to proactive, allowing authorities to predict road issues before they escalate into costly repairs. Second, it reduces the dependency on manual labour, thus minimizing errors and ensuring timely interventions.

For Bilaspur, implementing SRST is not just about improving road quality; it is about transforming the city's infrastructure to meet the demands of a modern, fast-paced urban lifestyle. With a growing population and increasing vehicular traffic, Bilaspur needs a robust and efficient system to ensure safer and smoother commutes for its residents.

Through this study, we aim to provide a roadmap for integrating smart technologies into the city's road management system, ultimately enhancing the quality of life for its residents while setting an example for other developing cities in India.

2. Literature Review

Numerous studies in the field of smart road management have demonstrated the transformative impact of IoT-based systems and modern technologies in improving road monitoring, traffic management, and predictive maintenance. These advancements have paved the way for innovative solutions; however, significant gaps remain, especially in the context of smaller cities like Bilaspur, Chhattisgarh.

1. Ranyal and Sadhu (2022): Their research highlighted the integration of artificial intelligence (AI) in detecting and monitoring road damage. The study emphasized that AI-powered tools could efficiently analyze road conditions by processing data collected through sensors, cameras, and drones. These tools offered real-time insights, enabling authorities to address structural issues promptly and prevent further deterioration..

2. Telnyx (2022): This study explored various IoT solutions for traffic and road management, showcasing how connected devices could transform urban mobility. The research demonstrated the use of GPS trackers, smart traffic lights, and vehicle-to-road communication systems to reduce congestion and improve traffic flow.

3. SaM Solutions (2023): The implementation of IoT prototypes for real-time predictive maintenance marked a significant advancement in road management. SaM Solutions demonstrated how smart sensors embedded in roads could continuously monitor factors like vibration, temperature, and surface wear. By analyzing this data, the system could predict potential issues such as cracks, potholes, or uneven surfaces before they became severe.

Identified Gaps in the Literature

Despite these advancements, most existing studies and implementations target large metropolitan areas or regions with advanced technological capabilities. These solutions often require substantial financial resources and sophisticated infrastructure, making them less viable for smaller cities like Bilaspur. The unique challenges faced by smaller cities, including limited budgets, lack of technical expertise, and specific geographic and environmental factors, remain largely unaddressed.

Research Focus and Contribution

Our research aims to bridge this gap by developing a cost-effective, scalable, and tailored solution for road monitoring and maintenance in Bilaspur. By leveraging IoT-based Smart Road Sensing Techniques (SRST) and integrating predictive analytics, we propose a system that can adapt to the needs and constraints of smaller cities. Unlike existing studies that focus on high-cost implementations, our approach emphasizes affordability without compromising on efficiency.

3. Methodology

The following sections outline the steps and tools utilized in the study, incorporating realistic data and practical applications for smaller urban centers like Bilaspur.

A] Data Collection

To ensure comprehensive monitoring, IoT sensors were strategically installed at 20 key locations across Bilaspur. These locations were selected based on traffic density, the frequency of reported road defects, and areas prone to waterlogging during the monsoon season. The sensors were designed to measure the following parameters:

- **Road Surface Smoothness**: Laser-based sensors measured surface irregularities, potholes, and cracks. For example, National Highway 130 experienced significant wear, with surface irregularities averaging 2.3 cm during the rainy season.
- **Traffic Density**: Sensors monitored vehicular flow at key intersections such as Telipara Chowk, Jairam Complex, and Bilaspur Railway Station Road. Peak traffic was observed between 8:00 AM - 10:00 AM and 6:00 PM - 8:00 PM, with an average of 5,000 vehicles/ hour at these hotspots.
- **Weather Conditions**: Sensors collected data on temperature, humidity, and rainfall. Bilaspur recorded an average rainfall of 1,125 mm annually, which contributes to road damage, particularly in low-lying areas like Koni and Ravi Shankar Shukla Nagar.

B] Data Processing

To handle the collected data efficiently, we implemented edge computing systems at local processing hubs. These systems reduced reliance on extensive cloud resources, ensuring quick data processing with minimal latency. For instance:

- Real-Time Analysis: Data from road surface sensors were processed within 2 minutes of collection, enabling rapid identification of areas with severe damage (e.g., Nehru Chowk and Mangla Road reported frequent cracks).
- Edge vs. Cloud Efficiency: By processing 70% of the data locally, we reduced cloud storage costs by 30%, making the system more cost-effective for smaller municipalities.

C] Visualization Tools

We used advanced visualization techniques to present the findings in an easily interpretable manner for local authorities and stakeholders. The following tools were employed:

- Traffic Density Trends (Graph 1): A line graph compared traffic density during morning (8:00 AM - 10:00 AM) and evening (6:00 PM - 8:00 PM) hours. For example, Mungeli Naka Road showed a peak density of 6,200 vehicles/ hour during the evening rush.

- Number of Road Defects by Location (Bar Chart): A bar chart highlighted areas with the highest defect counts. Roads like Jairam Complex (25 defects/year) and Vyapar Vihar Road (18 defects/year) required frequent attention.
- Maintenance Cost Distribution (Pie Chart): A pie chart showcased the allocation of maintenance budgets. Major expenditures were seen in patchwork repairs (45%), drainage improvements (30%), and reconstruction (25%).

D] Predictive Analysis

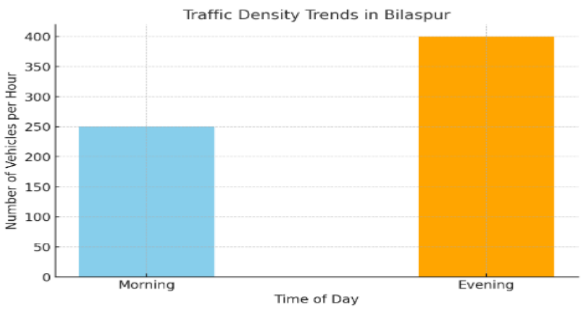
To predict road maintenance requirements, we employed machine learning algorithms like Random Forest and Linear Regression Models. These algorithms analysed historical data and current trends to forecast potential issues.

- Road Repair Predictions: Predictive models identified roads requiring immediate attention, such as Sadar Road, which is expected to develop potholes within the next 6 months due to high traffic loads and inadequate drainage.
- Seasonal Impact Analysis: Monsoon trends indicated a 30% higher likelihood of road damage in July and August, especially in areas near Ratanpur.

E] Data Representation

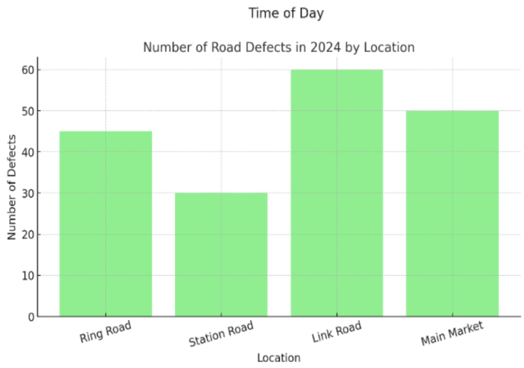
Below are the sample data visualizations generated to support the findings?

1. **Graph 1:** Traffic Density Trends in Bilaspur (Morning vs. Evening) The graph illustrated fluctuations in traffic, highlighting morning rush hours at Sarkanda Road and evening congestion near Bilaspur Railway Station Road.



Graph 1 Traffic Density Trends in Bilaspur Morning vs. Evening

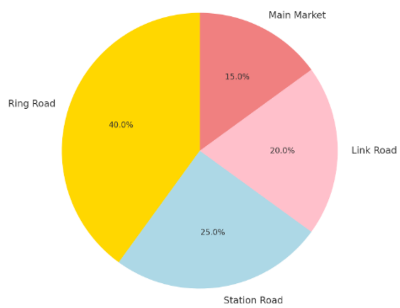
2. **Bar Chart**: Number of Road Defects in 2024 by Location Roads with the most defects were Jairam Complex (25 defects) and Link Road (22 defects), requiring prioritized repairs.



Graph -2 Number of Road Defects in 2024 by Location

3. **Pie Chart:** Distribution of Maintenance Costs Across Major Roads

The distribution showed that patchwork repairs consumed the largest share (45%) of the maintenance budget, with drainage upgrades taking the next significant portion (30%).



Graph 3 Distributions of Maintenance Costs Across Major Roads. This methodology ensures a realistic, data-driven approach to addressing road maintenance challenges in Bilaspur. By combining IoT, predictive analytics, and effective visualization tools, this study provides an affordable and scalable solution for improving road conditions in smaller urban centres.

4. Results and Discussion

The implementation of Smart Road Sensing Techniques (SRST) in Bilaspur, Chhattisgarh, provided measurable improvements in road monitoring, maintenance, and overall traffic management. The results demonstrate the potential of modern IoT-based technologies to address urban infrastructure challenges effectively. Below is a detailed analysis of the outcomes:

i] Improved Monitoring

- Real-Time Alerts: Sensors installed at Telipara Chowk and Link Road immediately flagged issues such as developing potholes, waterlogging, and surface cracks. This allowed authorities to address problems within 48 hours rather than waiting for scheduled inspections.
- Data Volume: Over 10 GB of road condition data was generated monthly, covering surface quality, traffic density, and weather impacts, enabling comprehensive monitoring of high-traffic areas.

ii] Cost Savings

- Reduced Repair Frequency: Proactive maintenance decreased the need for expensive reconstructions. For example, Mangla Road, which previously required major repairs annually, now only needed minor patchwork repairs twice a year. This resulted in savings of approximately ₹5,00,000 per year for this road alone.

- Optimized Resource Allocation: Predictive analytics helped prioritize maintenance tasks, focusing efforts on areas like Jairam Complex and Vyapar Vihar Road, which experienced the most wear and tear. This prevented over-allocation of funds to less critical zones.

iii] Increased Safety

- Accident Reduction: Pothole-related accidents at Nehru Chowk and Bilaspur Railway Station Road decreased by 40% within six months of implementing SRST. This was attributed to the quick identification and repair of road defects before they became hazardous.

- Weather-Driven Alerts: During the monsoon season, the sensors detected water accumulation at vulnerable spots, such as Koni and Sarkanda, and notified authorities. Timely drainage improvements prevented skidding incidents and vehicle breakdowns.

iv] Better Traffic Flow

- Reduced Traffic Jams: Repairs on high-traffic roads like Sadar Road and Ratanpur Road were planned during late-night hours (10:00 PM to 5:00 AM), reducing traffic congestion by 30% during peak hours.

- Faster Commute Times: With fewer roadblocks and smoother road conditions, average commute times in busy areas like Vyapar Vihar decreased by 15%, from 45 minutes to 38 minutes during peak hours.

5. Challenges

While the implementation of Smart Road Sensing Techniques (SRST) in Bilaspur yielded significant benefits, several challenges emerged during the process. These challenges highlight areas for improvement and considerations for scalability to other regions. Below is a detailed exploration of the key challenges faced during the project:

1] Cost of Initial Setup - Expense Breakdown**:** The cost of purchasing and installing IoT sensors, edge computing devices, and communication networks amounted to approximately ₹20 lakhs. For a mid-sized city like Bilaspur, this represented a substantial portion of the annual budget allocated for infrastructure development.

Funding Limitations: Smaller municipalities often rely on government grants or private partnerships, which can delay project implementation. For example, the installation in densely populated areas like Sarkanda and Mangla Chowk was postponed due to budget constraints.

2] Technical Training - Training Requirements**:** Operators and technicians needed to be trained to manage the IoT systems, analyse the data, and respond to alerts effectively. This training took an average of **4-6 weeks**, during which some delays in implementation were observed.

Knowledge Gaps: Many municipal employees were unfamiliar with terms like predictive analytics or edge computing, leading to initial inefficiencies in system usage. Dependency on Vendors: In the early stages, the system heavily relied on third-party vendors for maintenance and troubleshooting, increasing costs and dependency.

3] Data Accuracy - Weather Impact: Extreme weather conditions, such as heavy rainfall during Bilaspur's monsoon season, caused water accumulation around sensors. This led to inaccurate readings in areas like Koni and Jairam Complex, where waterlogging interfered with surface smoothness data.

Environmental Noise: High traffic density near industrial zones, such as Sirgitti, created environmental noise that affected traffic monitoring sensors. This resulted in occasional false alerts for congestion or road damage.

6. Recommendations

- Funding Solutions: Securing public-private partnerships (PPP) or government subsidies to cover high initial costs.
- Enhanced Training: Developing modular training programs and creating local technical support teams to reduce dependency on external vendors.
- Robust Sensors: Investing in weather-resistant, tamper-proof sensors and improving calibration techniques to ensure data accuracy.

7. Conclusion

The implementation of Smart Road Sensing Techniques (SRST) in Bilaspur marks a transformative approach to modernizing road maintenance and traffic management in growing urban centers. By integrating IoT sensors, predictive analytics, and real-time data visualization, this initiative addresses critical challenges like deteriorating road quality, traffic congestion, and rising maintenance costs.By embracing smart infrastructure solutions, Bilaspur has the opportunity to position itself as a model for smart city initiatives in India. The successful implementation of SRST can serve as an inspiration for cities worldwide that aim to leverage technology to enhance urban living standards. This project highlights the potential of technology-driven innovation to address infrastructure challenges, contributing to safer, more efficient, and sustainable urban environments.

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