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A Multi-Criteria Evaluation of Information and Communication Technology-Based Techniques for Road Condition Reporting

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Abstract**:** *Road infrastructure is a critical component of socio-economic development, enabling the movement of people, goods, and services. However, the high cost of constructing new roads has shifted focus toward maintaining existing infrastructure, necessitating efficient monitoring and reporting systems. The advent of Information and Communication Technologies (ICT) has revolutionised road fault monitoring by transforming traditional monitoring approaches through real-time data acquisition and enhanced public engagement. This study adopts a Multi-Criteria Decision Analysis (MCDA) approach to evaluate and compare six road monitoring techniques based on five key performance criteria: cost-effectiveness, accuracy, scalability, accessibility, and community engagement. The criteria were selected for relevance to the practical deployment and impact of ICT-based road monitoring solutions in diverse environments. Each technique was assessed and assigned a score on a 5-point Likert-type scale, where 1 indicates the lowest performance and 5 the highest. The results were visualised using a radar chart created with Python's Matplotlib library. Findings suggest that while GIS and image-based methods offer high accuracy, they require specialised expertise and infrastructure. Call-based and website-based methods, though accessible, suffer from scalability and accuracy limitations. Accelerometer-based techniques provide automated fault detection but are constrained by hardware dependencies. Mobile crowdsourcing (MCS) stands out as the most effective approach due to its affordability, accuracy, scalability, and community-driven nature. However, MCS relies on internet access and may face challenges with data validation.*

Keywords: Road monitoring techniques, information and communication technologies, multi-criteria decision analysis, mobile crowdsourcing, performance evaluation.

1. INTRODUCTION

Roads are critical infrastructures that serve as a basic foundation for a country's social and economic progress by enabling the movement of people and goods, providing access to vital services, and fostering the exchange of information [1][2]. However, the high cost of constructing new road infrastructure has led agencies to prioritize the maintenance of existing roads. Understanding the condition of roads is crucial for ensuring comfort, safety, and cost-effective vehicle operations. Roads naturally deteriorate over time and require regular maintenance to preserve their durability, efficiency, and safety standards [3].

In recent years, the growing accessibility and affordability of Information and Communication Technologies (ICTs) have sparked significant interest in their application for data collection, monitoring, and reporting, particularly in developing nations [4]. Their use offers numerous benefits, including enhanced efficiency in data gathering, faster analysis, diverse reporting options, and simplified information dissemination [5]. ICT's use in road infrastructure monitoring provides a cost-effective solution for monitoring, reporting, and decision-making, driving significant reforms in many developed countries and fostering smarter public engagement [6].

The emergence of digital technologies has transformed road infrastructure reporting by enabling real-time monitoring, data collection, and analysis. Tools such as mobile applications, sensors, and Geographic Information Systems (GIS) allow citizens and authorities to report road issues promptly, offering precise location details and visual evidence like photographs or videos. Advanced systems powered by artificial intelligence and machine learning further improve this process by predicting potential failures and optimizing maintenance planning. These innovations make road fault reporting more efficient and accurate, while also fostering public engagement and transparency in infrastructure management.

Despite these advancements, a comprehensive comparative analysis of road infrastructure fault reporting methods remains necessary. This research examines selected technology-driven techniques for road monitoring, evaluating them based on criteria such as cost-effectiveness, accuracy, scalability, accessibility, and public participation. By comparing their performance, the study aims to highlight each method's strengths and limitations, offering practical recommendations for improving road monitoring and maintenance practices.

2. ICT-BASED TECHNIQUES FOR ROAD INFRASTRUCTURE MONITORING

Many developed and developing nations have adopted and are actively encouraging the use of Information and Communication Technology (ICT) tools for monitoring and reporting road infrastructure development [7]. These tools are highly effective, as they enable diverse methods of data collection and communication, allowing stakeholders to gather road-related data most appropriately, whether remotely or on-site. In this section, a discussion is presented on the selected road monitoring techniques. Table 1 presents their strengths and weaknesses.

Road condition monitoring plays a vital role in ensuring transportation safety, infrastructure maintenance, and efficient urban planning. Various methodologies have emerged to support this task, each offering distinct advantages and limitations. Traditional approaches, such as call-based monitoring, rely on citizens contacting road maintenance agencies via telephone to report road faults. This method is simple, requires no digital tools, and allows direct human interaction. However, it suffers from significant limitations, including unclear communication, lack of visual documentation, and difficulty in accurately identifying the fault location. Additionally, financial cost is borne by the caller, particularly in regions without toll-free non-emergency public service lines. Furthermore, public unawareness of appropriate contact channels and the reliance on the caller's descriptive ability undermine its overall reliability and efficiency.

Geographic Information Systems (GIS) have become indispensable tools in urban and infrastructure planning, offering sophisticated capabilities for the collection, storage, and analysis of spatial data. In the context of road condition monitoring, GIS technologies support the identification of faults through the analysis of satellite or aerial imagery, which is then mapped and analyzed within platforms such as ArcGIS or ESRI's ArcView [8]. The integration of GIS with commonly used tools like Google Maps and Microsoft Virtual Earth has increased accessibility to geographic data [9, 10]. In practical applications, road fault data is spatially referenced and analyzed using geodatabases, allowing maintenance agencies to visualize and prioritize interventions [11]. Despite these advantages, GIS implementation is constrained by high costs associated with satellite data acquisition, hardware, software, and technical personnel. Additionally, integration with traditional map structures is often complex, making real-time deployment challenging [12 - 14].

Another approach that emphasizes public engagement is website-based road monitoring. This system allows users to report road defects by submitting online forms through official agency websites, such as the platform operated by Nigeria's Federal Road Maintenance Agency (FERMA) [15]. Users provide detailed location information and may upload multimedia evidence to support their reports. This enhances fault assessment capabilities by offering both visual and location data. However, user engagement is hindered by the manual nature of the process, high data costs, and the burden of form completion. Limited internet access, low digital literacy, and language barriers further restrict participation, especially in rural or underserved areas. Public awareness of these reporting platforms also remains low, contributing to underutilization.

Recent technological advances have led to the development of accelerometer-based road monitoring systems. Accelerometers are electromechanical sensors that measure acceleration forces along multiple axes and are commonly embedded in smartphones and vehicles. Accelerometer-based Road monitoring has emerged as a technical alternative that automates fault detection using embedded sensors within vehicles or smartphones. These sensors capture vibration data along multiple axes as the host vehicle traverses road surfaces. The collected signals are analyzed to identify anomalies, using either statistical methods, or machine learning models [16 - 19]. This approach facilitates scalable and objective monitoring across road networks. Nonetheless, its application is limited to vehicles equipped with accelerometers, and detection accuracy is sensitive to vehicle speed and road type. Additionally, it is less effective in detecting anomalies on unpaved surfaces or areas beyond the tire track [20].

Image-based Road monitoring systems further augment fault detection by analyzing visual data from digital or smartphone cameras. These systems rely on either classical image processing techniques or machine learning algorithms trained to recognize specific fault types such as cracks, potholes, or surface wear [21-23]. The use of computer vision allows for detailed inspection and classification of surface conditions. However, the effectiveness of these systems is heavily influenced by environmental factors, including lighting conditions, shadows, and occlusions such as traffic or roadside objects. Proper camera positioning and calibration are critical to maintaining data accuracy, and the variability of device hardware poses additional challenges. High computational demands also limit real-time deployment, particularly in settings with constrained resources.

Mobile crowdsourcing (MCS) introduces a more participatory and community-driven model for road monitoring. This approach leverages smartphones to report road conditions using built-in cameras for image capture, GPS for geolocation, and mobile networks for data transmission [24 - 26]. Unlike vehicle-based or technical monitoring systems, MCS empowers any community member, not just drivers, to contribute reports. This inclusivity enhances data coverage and relevance, particularly in areas underserved by formal infrastructure. MCS systems offer flexibility in the type of information they collect, accommodating various road issues beyond the detection scope of GIS, accelerometers, or image-based systems. Furthermore, automated geotagging addresses the location inaccuracy found in traditional call-based systems. However, the success of MCS depends on smartphone availability, network reliability, and sustained user engagement. Disparities in technology access and motivation can affect the consistency and quality of reports submitted.

Table 1: Selected techniques for road infrastructure monitoring

Method	Strengths	Weaknesses
Call-Based Monitoring	• Simple and does not require internet access. • Allows direct human interaction. • Low technical requirements.	• Lacks visual evidence. • The Caller bears the cost. • Inaccurate location reporting- Requires knowledge of the agency contact. • Prone to miscommunication.
GIS-Based Monitoring	• Provides accurate spatial analysis. • Useful for large-scale mapping. • Integrates with digital maps and databases.	• High cost of implementation. • Time-consuming analysis. • Requires technical expertise. • Dependent on satellite data and map accuracy.
Website-Based Monitoring	• Enables uploading of visual evidence. • Structured form-based data collection. • Direct reporting to official agencies.	• Manual and time-consuming process. • Limited by internet access and digital literacy. • Users may forget to submit reports. • High data and energy costs to users.
Accelerometer-Based Monitoring	• Automated data collection. • Effective for detecting bumps and potholes. • Can operate in real time- Useful for statistical or ML analysis.	• Requires hardware installation. • Affected by vehicle speed. • Less effective for unpaved roads or off-path faults. • Limited to equipped vehicles or smartphones.
Image-Based Monitoring	• Visual evidence improves accuracy. • Can detect fine surface defects. • Supports automated processing using ML.	• Sensitive to lighting and weather conditions. • Requires correct camera positioning. • High processing power needed. • Potential misclassification due to obstructions.
MCS-Based Monitoring	• Community-wide participation. • Combines camera, GPS, and network features. • Automated location tagging. • Broad fault detection capabilities.	• Dependent on smartphone usage. • Requires mobile data and app access. • Variable user engagement. • May suffer from inconsistent or biased user-reported data.

3. METHODOLOGY

The Multi-Criteria Decision Analysis (MCDA) approach was used to evaluate and compare the six road monitoring techniques based on five performance criteria: cost-effectiveness, accuracy, scalability, accessibility, and community engagement. The evaluation used a 5-point Likert-type ordinal scale, where: 1 = Very Low, 2 = Low, 3 = Moderate, 4 = High, and 5 = Very High. This scale allowed for the classification of each technique's performance under consistent metrics. The criteria were selected to reflect both technical and social dimensions of road monitoring, ensuring a holistic evaluation.

Each technique received a score per criterion, and the scores were obtained from their performance based on literature analysis, real-world implementation cases, and expert judgement. No weighting was applied to the criteria; all five performance indicators were considered equally important in the final assessment.

The resulting values were presented in a comparative matrix. Then, the ranking of techniques was performed by summing the scores across all five criteria, yielding a total performance score for each method. This total score was then used to identify the most effective and participatory road monitoring approach under the evaluated dimensions.

To implement the methodology, two tables were produced, Table 2 and Table 3. Table 2 qualitatively summarizes technique attributes, which were then quantitatively scored in Table 3 to facilitate performance comparison using the 5-point Likert-type scale. A radar chart was then created from the data obtained from the performance table to enhance the visualization of comparative performance data.

Table 2: Comparative analysis of the selected road monitoring techniques

Technique	Cost-Effectiveness	Accuracy	Scalability	Accessibility	Community Engagement
Call-based	High (phone call costs).	Low (no visual evidence, relies on the caller's description).	Low (limited to those with agency contact info).	Moderate (requires knowledge of the correct agency number).	Low (individual reporting, no broad community participation).
GIS-based	Low (expensive satellite data software, training, etc.).	High (precise geographic data, advanced spatial analysis).	Moderate (requires integration with other data sources).	Low (requires expertise, specialized software).	Low (primarily expert-driven, not citizen-friendly).
Website-based	Moderate (website development & maintenance).	Moderate (users can upload images/videos for verification).	Moderate (depends on internet penetration).	Moderate (requires internet access and digital literacy).	Moderate (depends on public awareness and participation).
Accelerometer-based	Moderate (hardware, data processing).	Moderate (effective for detecting potholes and vibrations within a vehicle's tyre path).	Moderate (limited to equipped vehicles or smartphones, driver dependent).	Moderate (requires compatible devices and apps, only for vehicles equipped with the system).	Low (primarily used by researchers or its operators).
Image-based	Moderate (camera hardware, processing power).	Moderate to High (can detect road defects accurately with AI/ML, affected by lighting image quality, and obstructions).	Moderate (data processing can be resource-intensive).	Moderate (requires compatible devices and apps, only for vehicles equipped with the system).	Low (requires dedicated setups, not general public-driven).
Mobile Crowdsourcing (MCS)	High (leverages existing smartphones and mobile networks).	High (can use GPS geotagging, image verification).	High (anyone with a smartphone can participate).	High (user-friendly, no special expertise needed).	High (encourages broad public participation).

Table 3: Performance Analysis of The Selected Road Monitoring Techniques

Method	Cost-Effectiveness	Accuracy	Scalability	Accessibility	Community Engagement	Total
Call-Based	4	1	1	2	1	9
GIS-Based	1	4	3	3	1	12
Web-Based	3	3	3	3	3	15
Accelerometer-Based	3	3	3	3	2	15
Image-Based	3	4	3	3	2	15
MCS	4	4	5	5	5	23

3.1 Radar Chart for The Study

Radar charts offer a clear comparative visualization of multidimensional data, enabling the quick identification of strengths and weaknesses across performance criteria. In the context of this study, they offer an intuitive way to assess the road monitoring techniques across key dimensions such as cost, accuracy, scalability, accessibility, and community engagement. This visualization facilitates the identification of the most balanced and effective solutions by providing a comprehensive overview of how each method performs across these criteria. Figure 1 shows the Radar chart for the study plotted using Python's matplotlib library.

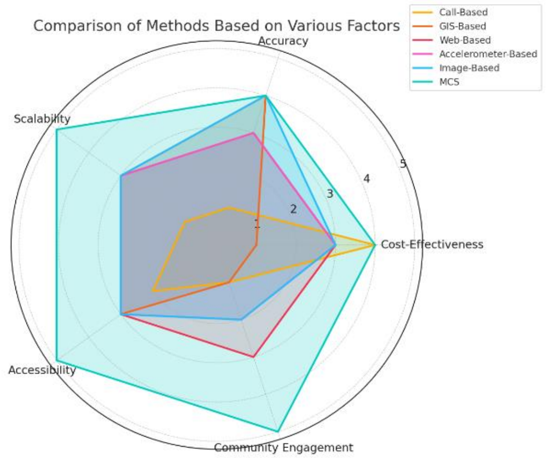

Figure 1: Radar chart comparing the performance of six ICT-based road monitoring techniques based on five evaluation criteria

4. DISCUSSION

The radar chart depicts the relative strengths and weaknesses of various road condition monitoring techniques across five critical performance dimensions. Mobile Crowdsourcing (MCS) stands out as the most well-rounded and comprehensive approach, exhibiting a broad, nearly circular shape that extends consistently across all criteria. This not only indicates robust technical capabilities but also high levels of inclusivity, rendering MCS particularly suitable for urban settings with extensive smartphone use and mobile network access. Its scalability and ability to foster active community involvement make it a highly effective tool for participatory governance and real-time reports on road conditions.

In contrast, GIS-based monitoring reveals a sharply peaked profile, indicating outstanding accuracy yet limited performance regarding cost-effectiveness, accessibility, and community involvement. While this approach is especially valuable for precise mapping and strategic infrastructure planning particularly by urban planning authorities and transport agencies it may not be feasible for regular, large-scale applications. In rural areas, GIS could be utilized intermittently for high-precision evaluations, supplemented by more affordable, community-driven methods for continuous monitoring.

Call-based systems display the most uneven profile, demonstrating considerable constraints in accuracy, scalability, and public engagement, despite being cost-effective. They may serve as a temporary solution in resource-constrained rural environments with inadequate digital infrastructure, yet their ongoing use highlights the digital divide in road monitoring. This points to the necessity of gradually transitioning to more sophisticated digital systems as connectivity and digital proficiency advance.

Web-based, accelerometer-based, and image-based methods show moderate, relatively balanced performance, suggesting their potential as supplementary tools rather than primary solutions. Accelerometer-based techniques hold particular promise for integration into urban fleet vehicles, enabling passive data collection during routine operations. Likewise, image-based approaches, especially when enhanced through AI-driven analysis, can be deployed effectively in both rural and urban areas for scheduled surveys, particularly when mounted on official service vehicles.

5. CONCLUSION

Traditional methods, such as call-based and GIS-based monitoring, offer certain advantages, they are constrained by limitations in scalability, cost, and community engagement. Website-based, accelerometer-based, and image-based methods provide a moderate approach. However, MCS represents a paradigm shift, offering a synergistic combination of high accuracy, scalability, accessibility, and active citizen participation. This analysis suggests that MCS is a highly promising approach for contemporary road infrastructure monitoring, particularly in contexts where citizen engagement and resource optimization are paramount. Further research should focus on refining MCS methodologies and addressing potential challenges related to data quality and privacy. The results indicate that road monitoring technologies need to be suitable for specific regions, as urban and rural environments necessitate distinctly different approaches. Mobile Crowdsourcing (MCS) is identified as a particularly promising approach for road condition monitoring, especially in low-resource environments. Compared to conventional and other technology-based methods, MCS offers a compelling combination of affordability, scalability, and citizen participation, positioning it as an effective strategy for large-scale infrastructure surveillance. Additionally, public-private partnerships with telecom providers and tech firms could improve accessibility by subsidizing data costs and developing offline-capable reporting applications. Policymakers should prioritize digital literacy programs to broaden participation while establishing incentive mechanisms to sustain long-term public engagement in crowdsourced monitoring initiatives. Further research is needed to address key challenges in MCS implementation to address the limitations associated with data reliability, user privacy, user bias, inconsistent reporting, and limited internet access, it is recommended that MCS be implemented alongside complementary techniques. For instance, integrating image-based verification or periodic GIS-based audits can help validate user-submitted reports and enhance data credibility. Moreover, the use of incentivization models, such as gamification or mobile data rewards, can sustain long-term user engagement. Policy frameworks should also be developed to regulate data privacy, standardize report formats, and ensure interoperability among platforms. By adopting a hybrid monitoring framework that centers on MCS but leverages the strengths of other ICT techniques, road agencies can achieve a more inclusive, efficient, and data-driven infrastructure maintenance system.

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