ROAD MAINTENANCE: A REVIEW OF CURRENT TRENDS IN ROAD ROUGHNESS DAMAGE DETECTION METHODS

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ABSTRACT

Effective road maintenance strategies require accurate condition assessment, prediction, optimisation and decision-making. Traditional road surface monitoring methods, such as visual inspections and the use of ultrasonic sensors, are often costly, labour-intensive, and prone to human error. With the rapid advancement of advancement of digital technologies such as artificial intelligence (AI), particularly machine learning (ML), and deep learning (DL) have revolutionized road damage detection by offering scalable, cost-effective solutions for road surface condition assessment. The review explores recent developments in AI-driven road damage detection, focusing on machine learning techniques such as Artificial Neural networks (ANNs), deep learning approaches including Convolutional Neural Networks (CNN). It concluded that AI-powered road monitoring systems offer significant advantages over traditional methods in terms of accuracy, efficiency, scalability and predictive capability. However, challenges such as data dependency, model generalization, and real-time implementation remains an area for future research.

Keywords: Road Infrastructure Management, Road Maintenance Strategies, Artificial Neural Network (ANN), Machine Learning, Pavement Deterioration Prediction.

1. INTRODUCTION

Road infrastructure is one of the largest public infrastructure investments globally contributing significantly to economic activities, mobility, and developments. Road facilitates trade logistics, reduce travel time, and enhance productivity. Road investment however come at a hefty cost (Parela & Biligiri, 2020). For example, the German government spent well more than 10 billion euros in 2015 on road maintenance projects (Ramesh *et al.*, 2022), South Africa on the other hand in the 2024/2025 financial year will be spending approximately R50 billion (2.6 billion dollar). However, despite this expenditure, the budget is often insufficient, especially with a road network spanning over 750,000 km, and rising costs due to heavy freight traffic and aging infrastructure. Road infrastructure is vulnerable to deterioration due to environmental variables, aging materials, and rising traffic volumes, despite its importance. Road construction materials can generally be categorized into various types, including asphalt, concrete, block, gravel. Among these, asphalt remains the most commonly used due to its flexibility, ease of application, and lower initial cost. Road damage and distresses can be divided into different types, including longitudinal crack, alligator cracks, potholes, rutting, patching and ravelling. The cause of road distress varies, often resulting from traffic induced has well as environmental factors such as sunlight and rainfall (Guerrieri *et al.*, 2024).

Effective road maintenance requires accurately assessing road conditions, predicting deterioration, optimizing repair strategies, and making data-driven decisions. This process involves four key components:

1. Conditions assessment (CA) – Determining the current state of the road network.

2. Condition prediction (CP) – Estimating future road conditions based on historical data.

3. Optimization (OP) – Allocating resources efficiently to maximize road longevity.

4. Decision making (DM) – Implementing maintenance strategies based on data analysis.

The first stage, conditions assessment, which is road distress detection, can be performed using different techniques including either manual, semi-automated or fully automated (Donev & Hoffmann, 2020). In recent years, automatic road scanning has gained popularity due to its ability to improve driving experience and provide road data quality for government agencies, adding in road maintenance planning (Mihoub *et al.*, 2023). Traditional road surface monitoring requires specialized hardware, such as expensive data collection systems and ultrasonic equipment. However, with the widespread use of smartphones and wearable technology, road monitoring has become more accessible. Modern smartphones are equipped with low-cost sensors, including gyroscopes, accelerometers, and GPS sensors, enabling automatic road condition detection (Chugh, Bansal and Sofat, 2014; Mihoub and Lefebvre, 2019). Additionally, digital images from Charge-Coupled Device (CCD) sensors mounted on vehicles have been used for computer vision-based detection of road surface defects (Zhang et al., 2025).

The study of road maintenance and damage detection dates back several decades. Early research focused on image classification, binarization, and interpretation for road detection (Bertozzi & Broggi, 1998). Recent advancements in computing power and sensor technology have enabled high-accuracy methods, particularly machine learning (ML) and deep learning (DL) techniques (Caltagirone et al., 2019). Machine learning approaches, such as Artificial Neural Networks (ANNs), have been applied to detecting potholes and other road damages. More recently, deep learning techniques, particularly Convolutional Neural Networks (CNNs), have shown great potential for road surface analysis and damage classification. One of the earliest CNN-based road damage detection studies was conducted by L. Zhang et al., (2016) who developed an automatic crack identification system using deep CNNs. Their method extracted features from manually annotated images captured by a smartphone.

This review focuses on current approaches and trends in road damage identification. Emerging research highlights the role of artificial intelligence (AI) in road maintenance, with emphasis on the four main components. AI-driven methods have the potential to revolutionize road maintenance by providing real-time data analysis, ultimately improving decision-making processes. By integrating AI with modern sensing technologies, the future of road maintenance could shift toward fully automated, data-driven strategies, ensuring cost-effective and efficient road infrastructure management.

2. ADVANCES IN ROAD DAMAGE DETECTION

Before the 1980s, the traditional approach to road damage inspection involved manual surveys and visual evaluations evaluation by humans, which were often subjective, this method is time-consuming, incurs high survey expenses, and often yields inconsistent and inaccurate data (Chambon and Moliard, 2011). To address these limitations and drawbacks, especially after 1980, numerous attempts have been made to reduce the subjectivity of visual measurement by developing automated and non-invasive techniques for road damage detection and identification. This approach has been found to usually yield an accurate and non-subjective set of data as well as more cost-effective and efficient than manual techniques, as well as more comfortable and less hazardous for road workers and users (Chambon and Moliard, 2011; Ragnoli, De Blasiis and Di Benedetto, 2018).

Recently, deep neural networks, such as Convolutional Neural Networks, have enabled the analysis of road surface deterioration and road damage identification, from crack detection to classification. Additionally, Asian et al., (2019) provided a framework for automating the roadway condition evaluation that is based on DL. Four types of pavement distress namely, potholes, longitudinal, transverse, and alligator cracks were classified using a CNN, and search engine images were used to construct the crack detection dataset. It was determined that the planned CNN's overall accuracy of 76% was appropriate. Over the years, other articles have explored the use of CNN for road surface and damage identification (Maeda *et al.*, 2018; Arman *et al.*, 2020; Pham, Pham and Dang, 2020; Benallal and Tayeb, 2023).

3. CASE STUDY: SOUTH AFRICA’S ROAD INFRASTRUCTURE

South Africa’s road network is one of the most extensive in the world, ranking 10th globally for total road length and 18th for the length of its paved road network. The total estimated road length in South Africa is approximately 750,000 km, comprising both paved and gravel roads. This network supports a critical public infrastructure system, representing a significant investment valued at R2 trillion in replacement costs. While the network is extensive, challenges such as increasing traffic volumes, aging infrastructure, and funding limitations for maintenance persist. Initiatives like the S’hamba Sonke Programme demonstrate the country’s commitment to addressing these issues, with significant investment in road rehabilitation and job creation. However, sustainable funding and advanced planning are needed to keep pace with growing demands and ensure the network remains functional and efficient. Using South Africa as a case study for this project, the most common pavement distress is potholes, patches, transverse and longitudinal cracking, and rutting.

Some of the challenges of road maintenance in South Africa are highlighted as follows:

- Aging road Infrastructure: In South Africa, many roads, especially gravel roads, need regular maintenance, and there is a huge demand for rehabilitation.
- Resource allocation and capacity: Despite significant efforts under the S’hamba Sonke Programme, such as rehabilitating 1,100 km of surfaced roads and patching 1.4 million square meters of potholes, the sheer scale of maintenance required remains overwhelming.
- Funding Limitations: The vast network requires significant and ongoing financial investment, with replacement costs estimated at R2 trillion. Effective road maintenance and rehabilitation is hampered by limited funding, particularly in rural and unofficial areas.

- Traffic growth: Over 6 million more cars have been on the road since 1994, which has increased traffic and exacerbated wear and tear. During peak hours, many highways already run nearly at capacity, which puts further burden on maintenance requirements.

4. CURRENT AND FUTURE TRENDS

Artificial intelligence (AI) developed in the 1950s, focuses on a systems capacity to mimic human understanding and rationality. With the development of artificial intelligence tools, it is now possible to analyse non-linear or multi-linear interactions to receive accurate and realistic. Two of the main aspects of AI are the Artificial neural network (ANN) and the Convolutional neural network (CNN). ANN adapts human brain functioning to data processing, utilising the learning aspect of artificial intelligence (Roxas *et al.*, 2019). ANNs consist of densely coupled processing elements called neurons. ANN or AI-based models function on the premise that, when trained with trained with input-output patterns from representative operating conditions, they can predict outputs for unseen inputs derived from similar conditions(Harzallah *et al.*, 2018).

4.1 AI (ML and DL) as Cost-Effective Method for Road Monitoring

The use of Machine Learning (ML) and Deep Learning (DL) has been found to be a more efficient and cost-effective process than the traditional approach. ANN algorithms have been used to detect road damage from the data obtained from the smartphone's motion sensor and camera. The results demonstrated that ANN learning models on the dataset achieved a good prediction accuracy, Additionally, detections from multiple vehicles can be grouped and merged using the cloud-based fusion approach. Table 1 highlights some studies showcasing the applications of AI and ML in various aspects of road infrastructure maintenance.

Table 1: Application of ML (ANN) in road infrastructure maintenance

Area	Important Points to Note	References	Road Maintenance Strategy
Road Condition Monitoring and Inspection (Diagnosis)	ANN has been used for the detection of damage/cracks and monitoring road conditions; also, tools for diagnosing road health.	*(Boucetta et al.,* 2021*; Cano-Ortiz et al.*, 2022)	CA
	Using ANN applied with Smartphone data for efficient, low-cost damage detection; cloud-based fusion used to aggregate data.	(Ramesh *et al.*, 2022)	
	Time-frequency domain processed data from sensors used to evaluate road surface condition in real-time.	(Martinelli *et al.*, 2022)	
	ANN reconstructed surface profiles using vehicle acceleration measurements with high accuracy (20% error, 94% correlation).	(Hugo *et al.*, 2008; Ngwangwa *et al.*, 2010)	

Table 1: Cont'd

Area	**Important Points to Note**	**References**	**Road Maintenance Strategy**
Road Maintenance Needs/ Maintenance Strategy Selection	ANN applied to optimize maintenance strategies for national road networks based on traffic volume, road classification, and condition severity.	(Ramesh *et al.*, 2022)	DM
	ANN models developed to allocate limited resources efficiently for road maintenance and rehabilitation decisions.	(Bosurgi & Trifirò, 2005; Domitrović et al., 2018)	
	Combined ANN and genetic algorithms to optimize resurfacing operations on flexible pavements for efficient financial resource utilization.	(Bosurgi and Trifirò, 2005)	
Road Deterioration Prediction (Prognosis)	ANN used to predict future deterioration trends based on data such as environmental and operational parameters	(Hamdi et al., 2017; Kumar et al., 2021)	CP
Road Design and Construction	Predicting fatigue performance of road materials (e.g., hot mix asphalt, cement emulsified asphalt) using ANN with results aligned with experimental data.	(Wang *et al.*, 2018)	OP, DM
	ANN model developed to assess the ageing behavior of asphalt mixtures, predicting characteristics under different ageing conditions.	(Seitllari *et al.*, 2019)	
	ANN used for selecting materials and designing roads to ensure cost-effectiveness and performance optimization.	(Androjicá and Dolaček-Alduk, 2018; Naderpour, Hossein Rafiean and Fakharian, 2018)	
	ANN used for road project cost estimation, improving budget accuracy by analysing 15 factors, including surface class, GDP, and soil condition.	(Roxas *et al.*, 2019)	

Over the past decade, advancements in ANN have driven significant progress in object and feature detection through image analysis, culminating in the development of convolutional neural networks (CNNs), which excel in image classification and visualization (Krizhevsky, Sutskever & Hinton, 2017). Deep neural networks, such as CNNs, have enabled the analysis of road surface deterioration and identification of road surface damage. One of the pioneering studies employing CNNs to detect road cracks is by Zhang et al. (2016) who proposed a convolutional neural network-based automatic identification technique. This method automatically extracts features from manually annotated image patches captured by a smartphone, facilitating real-time detection of road cracks in a cost-effective and integrated system. Various CNN algorithms have been employed in studies spanning road condition assessment, condition prediction, optimization, and decision making. Table 2 illustrates a summary of the reviewed paper that utilized deep learning models.

Table 2: Deep learning in road maintenance strategy

References	Road Maintenance Strategy	Deep Learning Model Used
Zhang et al., (2016)	CA, OP, DM	ConVNet
Akagic et al., (2017)	CA	CNN (unspecified
Ochoa-Ruiz et al., (2020)	CA, OP	RetinaNet, VGG16
Almeida et al., (2020)	CA, CP, DM	Enet, LaneNet
Park et al., (2021)	CA	YOLOv4, YOLOv4tiny, YOLOv5s
Aparna et al., (2022)	CA	ResNet101
Zhang et al. (2022)	CA, OP, DM	Faster R-CNN
Zhang et al., (2025)	CA	YOLOv5s

Table 3: Comparative of AI-Based and traditional methods for road damage detection and maintenance

Area/Aspect	AI-Based Methods (ANN, CNN)	Traditional Methods
Accuracy	Reach a high level of cost prediction accuracy (Roxas *et al.*, 2019).	Limited accuracy because of tedious calculations, especially when time and data are limited (Roxas *et al.*, 2019).
Cost	Economical for larger scale uses, making use of easily accessible resources like smartphones (Ramesh *et al.*, 2022).	Costly since it requires a lot of labour, material testing, and manpower (Ngwangwa *et al.*, 2014).
Efficiency	Once trained, it is faster in predicting road profiles and fatigue performance (Ngwangwa *et al.*, 2010; Wang *et al.*, 2018).	Lengthy processes, particularly for frequent material testing or manual computations (Ngwangwa, 2020).
Scalability	Scalable for a variety of applications using cloud-based data fusion (Ramesh *et al.*, 2022).	Scaling can be difficult because it depends on manual interventions and has limited resources. (Martinelli *et al.*, 2022).
Handling Complexity	Handles multi-variable, nonlinear problems such as surface profile reconstruction and aging behaviour. (Ngwangwa *et al.*, 2010).	Struggles with complicated connections and often uses linear approximations. (Seitllari *et al.* 2019).
Implementation Time	Requires time for initial setup and training but after that, offers rapid application thereafter (Ngwangwa *et al.*, 2010).	lengthy procedure because of repeated computations and validation (Martinelli *et al.*, 2022).
Data Dependency	Requires high-quality datasets for training models, (Seitllari *et al.*, 2019).	can operate with less data, but frequently results in a reduction in predicted quality and accuracy. (Roxas *et al.*, 2019).
Human Dependency	Reduces human dependency in repetitive tasks, relying more on data models (Ramesh *et al.*, 2022).	Mostly reliant on human expertise and manual effort (Roxas *et al.*, 2019).
Predictive Capability	Accurately predicts fatigue life, road profiles, and costs (Roxas *et al.*, 2019).	Limited predictive capability, relying on static data and historical trends (Ngwangwa *et al.*, 2014).

Comparative analysis of AI-Based methods and traditional approaches is indicated in the Table 3 above.

5. SUMMARY

The evolution of road damage detection methods from manual inspection to AI-driven automated systems represents a significant leap in infrastructure management. This review consolidates current AI-based methodologies, emphasizing the practical application of ANNs and CNNs in detecting road distresses such as potholes, cracks, and rutting. Compared to traditional methods, these approaches offer improved accuracy, reduced operational costs, and enhanced scalability. The South African case study underscores the pressing need for cost-effective monitoring systems, especially in regions with limited funding and high traffic volumes. From a technical standpoint, AI models demonstrate strong potential for real-time diagnostics, predictive maintenance, and data-driven planning. The findings are valuable not only for engineers and infrastructure managers in South Africa but also for stakeholders globally seeking efficient road maintenance strategies. Future research should focus on standardizing datasets, improving algorithm robustness in variable conditions, and integrating AI tools with existing pavement management systems for broader adoption and impact.

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