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Digital Technologies for Road Maintenance Management: A Narrative Review

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ABSTRACT

Effective road maintenance management is vital in the area of transportation safety and mobility as well as infrastructure sustainability. Nonetheless, the traditional methods of road maintenance involve a large degree of manual work and are rather inefficient and costly in nature. Fortunately, recent developments in the realm of digitalization have provided an opportunity to improve road condition evaluation and prediction, maintenance optimization, and other associated operations. In order to provide an overview of digital technologies used in road maintenance management, six different digital tools, namely, Artificial Intelligence, GIS, IoT, Digital Twin, mobile applications, computer vision, and decision support systems, will be discussed. A narrative review method was employed based on the use of the Scopus database. Initially, 413 articles were found; however, applying pre-determined inclusion/exclusion criteria led to narrowing down the list to 35 papers for further discussion. It is evident from the results that digital technologies can help improve the efficiency of the maintenance process via automatic defect detection and identification, monitoring, predictive analytics, maintenance prioritizing, and lifecycle management. Nevertheless, several drawbacks persist, including data issues, implementation expenses, interoperability, integration, and unavailability of standardized frameworks. Moreover, previous studies focus on exploring each technology individually, which emphasizes the necessity of considering several types of technologies together. In this regard, this literature review offers a detailed analysis of the current applications, advantages, challenges, and future areas of research related to intelligent road maintenance management.

1. INTRODUCTION

Road network infrastructure is critical in promoting economic growth, social cohesion, and efficient transport through the facilitation of movement of both people and goods. Efficient road networks are instrumental in increasing mobility and accessibility as well as improving road safety and riding comfort. On the other hand, poorly maintained road networks may lead to traffic disruptions, increased accident rates, and higher cost of maintenance. [1]. It is, therefore, imperative to adopt efficient road maintenance management practices.

Though significant, the standard procedures for maintenance of roads suffer from some problems. For example, traditional approaches to inspection make extensive use of manual inspections that are both expensive and labour-intensive [2], [3]. Other weaknesses include late detection of defects, ineffective data handling, inconsistency in reports and a reactive approach to maintenance. With increasing network size, transport authorities need to adopt automation technologies in order to enhance their maintenance operations.

Recent technological advancements have accelerated the digital transformation of road maintenance management. With the emergence of recent technological advancements, the digitalization of road maintenance management has become much faster. Various technological advancements such as Artificial Intelligence (AI), Machine Learning (ML), Geographic Information Systems (GIS), Internet of Things (IoT), Computer Vision (CV), Digital Twins (DT), and Mobile Sensing Technologies have shown their potential use in

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assessing the condition of pavements and detecting defects on pavements [4], [5]. AI and computer vision techniques can help with automatic defect identification and predictions. On the other hand, IoT and mobile sensing technologies allow one to monitor the road conditions and collect information in real-time [6], [7]. Additionally, GIS and DT techniques allow conducting various activities related to the management of roads [8], [9].

The implementation of these technologies has changed road maintenance management from being reactive to being proactive. Automatic systems for monitoring help to conduct a more accurate assessment of the roads' state, while predictive models allow for planning the maintenance operations beforehand and optimize their resources [3], [4]. In addition, IoT-based monitoring and Digital Twin solutions allow for decision-making based on actual performance and optimized life cycle costs[8], [10], [11].

Nevertheless, existing literature is still fragmented. The majority of studies tend to investigate one technology at a time and evaluate its effectiveness individually, whether that concerns AI-based deterioration prediction, computer vision-based defect detection, GIS-supported maintenance planning, IoT-enabled road condition monitoring, or the application of Digital Twin technology [6], [9], [12]. However, efficient road maintenance management involves several technologies at the same time, such as data acquisition, condition monitoring, spatial analysis, prediction modelling, prioritization, and decision support. In reality, technologies like AI, GIS, IoT, Digital Twins, and mobile sensing systems function as a unified system within intelligent maintenance ecosystems. Yet, few review studies have attempted to synthesise the interrelationships, complementarities, and integration challenges among multiple digital technologies within road maintenance ecosystems.

Thus, this paper strives to provide a critical analysis of the latest innovations in digital technologies related to road maintenance management. Technologies such as Artificial Intelligence, Geographic Information Systems, IoT, Digital Twin, and mobile apps are discussed from the viewpoint of their application, advantages, potential problems, and future areas of research.

2. METHODOLOGY

Literature reviews are widely used to synthesize existing knowledge, identify research trends, and provide comprehensive insights into a particular research domain [13], [14]. Therefore, this study adopted a narrative review approach to examine the application of digital technologies in road maintenance management.

A structured literature search was employed using the Scopus database. The search was conducted using the following search string:

TITLE-ABS-KEY(("road maintenance" OR "pavement maintenance") AND ("artificial intelligence" OR GIS OR "IoT" OR "digital twin" OR "mobile application"))

The initial search resulted with 413 records. Then, the records were subsequently filtered by publication year which is from year 2020 until 2026. Next, document type was limited only to articles and review papers, language (English), and subject areas which are Engineering, Computer Science, Environmental Science, and Decision Sciences. These database filters resulted with 114 studies for screening. The study selection process is presented in Figure 1.

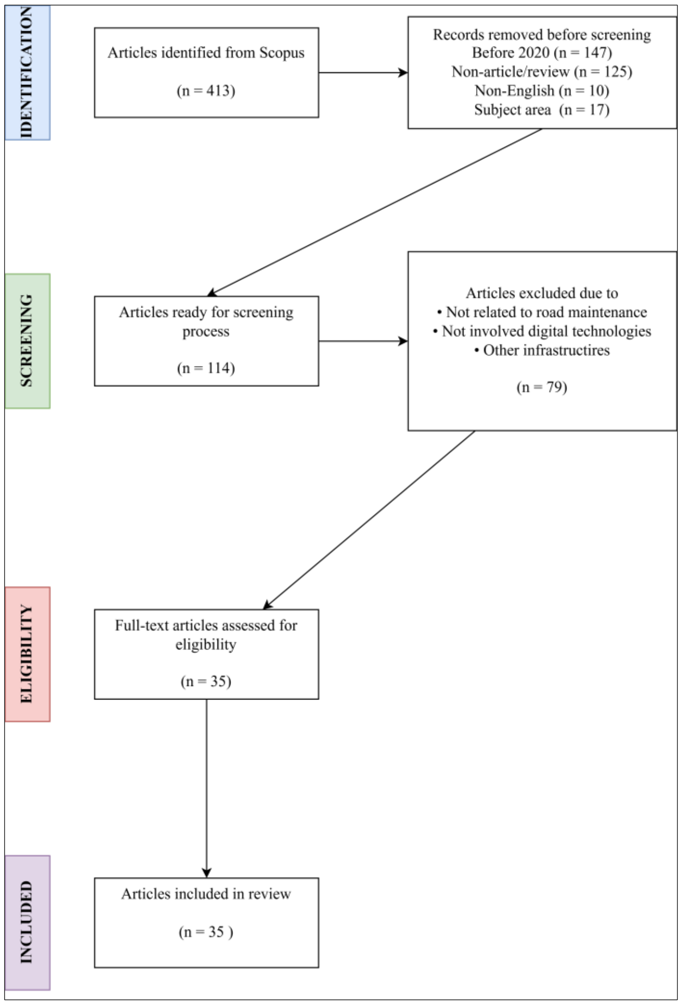

Fig. 1. PRISMA-inspired study selection process illustrating the identification, screening, eligibility assessment, and final inclusion of studies related to digital technologies in road maintenance management.

To gather studies relevant to road maintenance management and digital technology applications, the title and abstract screening were conducted. The inclusion and exclusion criteria adopted during the screening process are summarized in Table 1. Following the screening process, 35 studies were selected for detailed review and synthesis.

Table 1. Inclusion and Exclusion Criteria

Inclusion Criteria	Exclusion Criteria
Road maintenance, pavement maintenance, or road asset management studies	Studies unrelated to road maintenance
Application of digital technologies (AI, ML, GIS, IoT, Digital Twin, Computer Vision, DSS, PMS, and mobile applications)	Studies without digital technology applications
Peer-reviewed journal articles and review papers	Conference papers, book chapters, editorials, and notes
English-language publications	Non-English publications

Inclusion Criteria	Exclusion Criteria
Publications between 2020 and 2026	Publications outside the selected period
Studies relevant to the objectives of this review	Studies lacking relevance based on title and abstract screening

The selected studies were analysed according to technology type, application area, benefits, challenges, and key findings. Subsequently, the studies were grouped into six major technology categories: GIS and Geospatial Technologies, Artificial Intelligence and Machine Learning, Computer Vision and Deep Learning, Decision Support Systems and Pavement Management Systems, Internet of Things and Connected Infrastructure, and Digital Twin Technologies. These categories formed the basis of the results and discussion presented in Section 3.

3. Results and Discussion

3.1 Evolution of Digital Technologies in Road Maintenance

The reviewed literature demonstrates a significant evolution in the application of digital technologies for road maintenance, progressing from geospatial-based assessment approaches toward intelligent prediction models, automated defect detection systems, and integrated smart infrastructure platforms. Based on the 35 reviewed studies, six major technology domains were identified: Artificial Intelligence and Machine Learning (AI/ML), Computer Vision and Deep Learning, GIS and Geospatial Technologies, and Digital Twin, Pavement Management Systems (PMS), and Decision Support Systems (DSS).

GIS and geospatial technologies represent some of the earliest and most established digital approaches in road maintenance. Several studies used GIS for assessing road conditions, optimising routes, planning maintenance, managing infrastructure, and making spatial decisions [15], [16], [17], [18], [19] . These functionalities illustrated the crucial aspect of geospatial technologies in maintenance management, condition evaluation, and budget allocation.

The use of AI and ML in improving road degradation predictions and maintenance planning was initiated by the researchers due to the availability of data concerning pavements. Predictive modeling using ANN, RF, LSTM, and XGBoost were used by different research in predicting the road conditions and their future degradation rates [20], [21], [22], [23], [24]. It should be noted that compared to other conventional statistical methods, the proposed approaches performed better in terms of predicting and maintenance planning.

With recent developments, computer vision and deep learning are increasingly being adopted for automatic inspection of pavements and defects on roads. There have been many different approaches for deep learning using different models such as Convolutional Neural Network, VGG16, YOLO, Mask R-CNN, and binocular vision system used to detect potholes, cracks, and other defects on pavements [25], [26], [27], [28], [29], [30] These technologies provide faster, more consistent, and increasingly automated alternatives to conventional inspection practices.

In contrast, more recent work has focused on intelligent asset management using the incorporation of technologies such as Digital Twins, IoT, Connected Infrastructure, PMS, and DSS. Recent investigations have considered several possible ways to incorporate sensing technologies, predictive analysis, and maintenance management systems within intelligent maintenance environments [31], [32], [33], [34], [35], [36], [37], [38]

In general, through reviewing the literature, researchers can observe the development from individual assessment methods based on geospatial technologies towards more comprehensive and data-oriented maintenance ecosystems. Whereas the use cases of GIS, PMS, and machine learning in road maintenance appear to be quite mature, those related to digital twins and connected infrastructures still tend to focus either on theoretical foundations or practical pilot implementations only [31], [32], [33] This evolution reflects the increasing emphasis on predictive, automated, and intelligent approaches for improving the effectiveness and efficiency of road maintenance management.

3.2 Road Condition Assessment And Monitoring

A. Computer Vision-Based Defect Detection

With the advances in computer vision and deep learning methodologies, automated systems have been developed to detect road defects and monitor pavement conditions. In contrast to traditional methods which depend mainly on subjective assessments, computer vision systems can help in achieving efficient detection of pavement defects, such as potholes, cracks, and deterioration in a short time. As shown in the reviewed literature, there has been a growing use of CNNs, YOLO detectors, VGG networks, Mask R-CNN algorithms, and binocular vision systems in improving pavement assessment efficiency and accuracy.

Many studies have shown high accuracy results for pavement defects identification through deep learning algorithms. For example, Lakshminarayanan has achieved 96.5% classification accuracy through a convolutional neural network model for identifying road pavement distresses [28]. In the same context, Nurulain et al. attained 90.4% accuracy through the VGG16 model for detecting potholes [27]. Likewise, a great level of accuracy has been attained by YOLO-based models. Specifically, Omar and Kumar showed 93% precision rate for pothole detection using the YOLOv7 model [25]. These findings indicate that deep learning models are capable of providing highly accurate road defect detection across different datasets and road environments.

Apart from classification performance, many other researchers focused on the role of detection speed and effectiveness. According to Huang et al., the suggested detection model could analyse images in less than 20 milliseconds per image, thus proving the practicality of applying this technology for almost real-time pavement monitoring [30]. This feature is especially relevant for extensive road networks where manual inspection is quite time- and resource-consuming. The automated detection models designed by Xie et al. and Vu and Pham were also aimed at fast defect recognition without requiring constant human assistance [29], [39].

Despite most studies indicating positive outcomes, the level of performance was not constant among all different architectures of the utilized models as well as varying data sets. For instance, Jana et al. indicated an mAP of 74.6% that was significantly low compared to the accuracy rate attained by several CNN and YOLO-based methods [26]. Such results indicate that different aspects such as the quality of data used, image resolutions, environmental conditions, and type of pavement defects impact model performance. Therefore, any comparative analysis between the results of one study to another should be done carefully since various metrics and testing scenarios differ from one experiment to the other.

Additionally, according to Ashraf et al., their review indicates the significant development of computer vision technology in the analysis of pavement condition [40]. For example, most models using CNN attained precision, recall, and F1-scores greater than 0.80 where one study had the precision value of 0.911, recall value of 0.948, and F1-score of 0.922. These results reinforce the effectiveness of deep learning algorithms for automated crack detection, classification, and characterization.

Overall, these studies showed that the development of computer vision technologies allows one to improve the capacity of road agencies in detecting and monitoring the condition of pavements in a timely manner. The models built using CNN, VGG, and YOLO algorithms turned out to be highly efficient in the process of pavement defects detection; hence, this technique can be viewed not as the experimental project but as something that is ready to use. Nonetheless, there are still some challenges associated with the variability of the data set used, evaluation methods, and environment in which the system operates. Further research should pay special attention to the issue of improving adaptability of the technology and making it applicable along with GIS, IoT, and Digital Twin technologies.

B. GIS and Geospatial-Based Road Condition Assessment

The use of GIS technologies in the evaluation of road conditions and maintenance is significant today. In contrast to traditional methods of assessing road conditions, which are based on visual inspections on-site and tabular data storage, GIS allows for visualization and mapping of road conditions as well as prioritization of maintenance activities and optimal resource allocation. According to the reviewed sources, GIS has gone beyond map creation and can be used together with remote sensing technologies, UAVs, PCI, and decision-making frameworks.

A few research papers adopted GIS technology for conducting assessments regarding the condition and deteriorations of pavements. Issa et al. adopted GIS ArcMap and other interpolation techniques in assessing the pavement distress condition. The research revealed that the best correlation between GIS-based analysis and traditional PCI was obtained by adopting the spline method of interpolation, with an R^2 value between 0.843 and 0.897 [16]. Mehdi et al., on the other hand, adopted thematic maps generated by GIS in assessing pavement structural conditions and confirmed that GIS is able to analyze pavement degradation in relation to increasing traffic [17]. Al-Mansoori et al. further stated that GIS-based condition assessment can effectively identify road section with poor condition, thereby supporting maintenance planning and budget allocation [36].

Moreover, the combination of remote sensing technology along with GIS and UAVs has been used for the monitoring of roads in some recent research work. The integration of remote sensing, drones, and GIS was carried out by Nyomboi and Mwaniki, and pavement distress hotspot detection was achieved [41]. The use of geospatial technologies has proved to be beneficial in the early detection of pavement distresses to prioritize maintenance works. In comparison to traditional methods, these methodologies cover a greater area and save time during inspections.

Apart from condition assessment, GIS has increasingly been applied to prioritize maintenance operations and aid in decision making. According to Nugraha et al., GIS was used alongside the Analytic Hierarchy Process to determine that Traffic Volume (23.3%) and Road Authority (22.1%) were the most significant criteria influencing maintenance decision-making [19]. The consistency ratio (CR) of 0.048 further validated the accuracy of the decision-making tool employed. In a similar manner, Meiliana et al. established a GIS-based road maintenance management system and tested out several maintenance options, where the 'Do Something 2' option cut down maintenance costs from IDR 23.08 billion to around IDR 9.80 billion [18].These findings highlight the practical value of GIS in optimizing maintenance investments and supporting evidence-based decision-making.

Furthermore, GIS technologies have also proven to be useful in planning and infrastructure management. For instance, Albatayneh et al. employed the use of ArcGIS Network Analyst coupled with route optimization to conduct gravel road data collection and found considerable improvements in terms of travel distances and inspection times when compared to traditional methods of planning [15]. Similarly, Pavard et al. stressed the importance of GIS in facilitating the integration of infrastructure data for sustainable asset management [42].

As shown by these studies, GIS technology and geospatial technology have evolved into efficient tools that are able to facilitate condition assessment, prioritization of maintenance, route optimization, and infrastructural management. While GIS-based techniques offer better visualization and resource allocation than traditional techniques of assessing road conditions, the proper implementation of such techniques is conditional upon obtaining reliable geospatial data and keeping track of information about the conditions of roads. The future direction for further development of GIS technology is expected to revolve around its use alongside AI, remote sensing, IoT, and Digital Twins techniques.

3.3 Predictive Maintenance and Decision Support Systems

A. Artificial Intelligence and Machine Learning Models

There is a rising trend towards the use of Artificial Intelligence (AI) and Machine Learning (ML) techniques to forecast pavement deterioration, predict road condition, and aid in planning maintenance activities. While using traditional statistics for modeling can be difficult because of their inability to account for nonlinear interactions among traffic and pavement condition variables, AI modeling techniques offer an excellent platform to accomplish this task. As seen from the literature reviewed, ANN, RF, LSTM, and XGBoost are some of the models being applied.

A few other studies showed that there were good predictive capabilities with the use of ANN-based models. Elshamy et al. created ANN-based models to predict pavement conditions and found that these models had coefficient of determination greater than 0.94, with the model having the highest coefficient of determination having an R^2 value of 0.9493 [20]. Similarly, Milad et al. reported an ANN prediction model with an R^2 value of 0.93, outperforming the Response Surface Methodology (RSM) model, which achieved an R^2 value of 0.85 [21]. Mahmoud et al. further demonstrated the effectiveness of ANN for maintenance decision forecasting, reporting an overall Mean Square Error (MSE) of 3.019×10^{-2} and an average prediction error of 13.748% [43]. These findings suggest that ANN models can effectively support pavement deterioration prediction and maintenance decision-making.

Some other studies have investigated the application of advanced machine learning algorithms to increase prediction accuracy. The study of Sandamal et al. involved comparison of different machine learning algorithms and showed that the Random Forest model produced the best results in terms of predictive power with R^2 equal to 0.906 and MAE equal to 0.310 [22]. On the contrary, SVM models performed much worse with an R^2 value of only 0.503. Moreover, Asadi stated that the XGBoost algorithm performed better than Logistic Regression in terms of predicting pavement failure, having an AUC of 0.871, while Logistic Regression had AUC equal to 0.845 [24]. These results indicate that ensemble learning approaches may offer improved predictive capability compared with traditional machine learning methods.

Another application of deep learning techniques that has yielded impressive results is the prediction of pavement deterioration. Plati et al. assessed the performance of LSTM networks and found the MSE values to be between 0.001 and 0.004, which is much smaller compared to the ones obtained using MLP and conventional regression algorithms [23]. Given that LSTM networks can model temporal patterns of pavement performance, they can be used effectively for predicting future deterioration trends.

In summary, all the above-mentioned studies indicate the advantage of artificial intelligence and machine learning methods in relation to traditional statistical models in the prediction of pavement conditions. Good predictive results were achieved by applying ANN, Random Forest, XGBoost, and LSTM algorithms; however, the best predictive model depended on the features of the analyzed data set and the task at hand. Taken together, the results obtained in the literature provide grounds to state that AI-based predictive models have developed quite matured and can potentially be used for proactive maintenance, failure prevention, and effective maintenance resource management.

B. *Intelligent Decision Support and Pavement Management Systems*

Apart from predictive models, there has been a shift towards developing Intelligent Decision Support System (DSS) and Intelligent Pavement Management Systems (PMS) in order to help in maintenance planning, prioritization, and allocation of resources. Such systems have been developed to use pavement condition data to generate maintenance suggestions that can be followed by road authorities. Unlike other predictive models, DSS and PMS combine several types of information and tools for decision making related to pavement maintenance.

A number of research articles have proved the efficiency of data-driven decision support systems for maintenance and treatment planning purposes. Dabous et al. proposed a hybrid CBR (Case-Based Reasoning) and random forest model for preventive maintenance selection with an average accuracy of 95% and a Kappa value of 0.94 [37]. Additionally, the suggested approach showed good agreement with inspection recommendations on 87% of validated samples. This proves the efficiency of intelligent decision support models that improve objectivity in making decisions related to maintenance and treatment without the need for subjective assessment of situations.

Similarly, Tejasri et al. compared pavement prioritization techniques and found that Random Forest performed better than other techniques used for pavement prioritization, as it had coefficients of determination that ranged from 0.8733 to 0.9878 and MAEs that ranged between 0.140 and 0.417 [44]. These outcomes show the applicability of machine learning-based prioritization systems to enhance the accuracy of maintenance planning activities and optimize budget allocation in such cases. In addition, Yamany et al. designed a hybrid prioritization model based on pavement quality indices and multi-criteria analysis techniques and received a correlation coefficient of 0.85 between various ranking techniques used within the developed model [45]. The research shows the benefits of using several factors in decision making when developing prioritization models. Likewise, Saini et al. emphasized the importance of predictive technologies in the management of road assets, stressing their ability to facilitate maintenance planning, road infrastructure evaluation, and ensure the sustainability of road assets in the future[46].

The incorporation of predictive analytics into pavement management systems has also been considered extensively. Ali et al. came up with a Pavement Maintenance Management System (PMMS) using Multiple Linear Regression models and found out that 64% of the total road stretches were in poor condition, whereas the other 36% was rated as fair condition [47]. The regression models used offered an appropriate prediction accuracy for pavement conditions and helped in making plans for pavement maintenance. Such systems allow agencies to identify deteriorating road sections and allocate maintenance resources more effectively.

Moreover, besides analytical modeling, there have been more research efforts that combine modern technologies like sensing systems and visualization tools within the PMS framework. Specifically, in a study carried out by Moradi & Assaf, an intelligent pavement management system was designed, which used technologies such as GIS, mobile LiDAR, RGB images, and convolutional neural networks to evaluate pavement distresses automatically [35]. These technologies played an important role in improving monitoring efficiency and visualizing pavement status. Compared with traditional PMS platforms that rely primarily on inspection records, intelligent PMS frameworks provide richer datasets and improved decision-making capabilities.

In general, from the findings above, DSS and PMS systems have developed from mere recording condition systems to advanced intelligent decision-making systems with capabilities of prioritizing maintenance activities and optimizing resource allocation. Systems based on machine learning techniques were more accurate in predicting and prioritizing than traditional ones, whereas PMS-based systems helped manage large volumes of pavement condition data. In this regard, intelligent DSS and PMS systems appear to be important tools that can link the predictive analysis with maintenance activities. Nevertheless, for them to be implemented effectively, some preconditions need to be ensured, particularly data quality and system integration.

3.4 Smart Infrastructure and Digital Twin Technologies

A. IoT and Connected Infrastructure

The introduction of IoT technology and networking infrastructure into road maintenance management has opened up several possibilities in terms of effective road condition monitoring. In contrast to the traditional way of inspecting roads that required physical presence at the location of inspection, the implementation of IoT has allowed constant data gathering from the network of sensors and connected devices. This makes it easier for authorities to detect problems related to pavement.

The authors of Adeniran-Bakare et al. developed a proactive road maintenance model by incorporating IoT-based sensors together with machine learning algorithms for assessing the state of the road surface and identifying road maintenance needs in a proactive manner [48]. The results of their research showed classification accuracy above 99% for k-NN and linear SVM methods, proving the possibility of utilizing data from sensors together with intelligent approaches. The proposed framework also highlighted the potential of IoT technologies to reduce site visits, improve operational efficiency, and support preventive maintenance practices.

In a similar study, Hijji et al. proposed a system model for a 6G-connected vehicle that utilizes deep learning algorithms and data fusion With this system, the precision reached by the method was 87.2%, its recall was 92.7%, and its F1-Score was 89.9%. It can be clearly seen from these figures that 6G-connected vehicles can continuously gather information about road conditions and facilitate timely identification of any defects. Compared with conventional monitoring approaches, connected infrastructure systems offer greater scalability and enable more responsive maintenance interventions.

Overall, based on the above-discussed findings, IoT and connected technology offer great potential for improving road maintenance processes due to their ability to provide continuous monitoring and automated data processing. While the use of connected technologies is currently less widespread than that of GIS and machine learning approaches, the results obtained clearly confirm the technical possibility of using connected technologies in road maintenance processes.

B. Digital Twin for Intelligent Road Asset Management

The digital twin is one of the most innovative methods that can be used for intelligent road asset management due to its ability to create dynamic digital twins of physical assets. The digital twins differ from the traditional road pavement management systems which use only historical data about the asset condition because the digital twins incorporate real-time data collection, sensors, analytics, and visualization techniques. Recent studies have paid growing attention to using digital twins for road asset management purposes.

In their research paper, Villaverde et al. suggested the idea of implementing a road maintenance scheme using Digital Twin technology which incorporates unmanned aerial vehicles (UAVs) and AMRs to support automation processes during inspection and measurements [31]. It was shown that it is possible to implement several different types of sensing equipment into one digital twin framework that would allow collecting better data and improve the accuracy of inspection results tracing. Such integration provides opportunities for reducing manual inspection efforts while enhancing the quality and consistency of maintenance data.

In the same vein, Xu et al. put forward the idea of a Highway Digital Twin-Enabled Autonomous Maintenance Plant incorporating robotics, sensors, artificial intelligence, and computer vision under one umbrella of a maintenance ecosystem [32]. This model helps demonstrate the use of Digital Twin environments for carrying out autonomous maintenance activities as well as interactions in real time between physical infrastructure and their digital counterparts. The study also highlighted the increasing role of automation in future road maintenance systems.

Although the interest in Digital Twin technology has increased, a number of limitations have been found by researchers in this regard. Oditallah et al. discussed the Cognitive Digital Twin applications and stated that there is a shortage of predictive modeling in the existing research, insufficient incorporation of decision-making features, and the absence of scenario analysis techniques [33]. Likewise, Malihi et al. pointed out the requirement of integration between multimodal sensors, Digital Twin systems, and maintenance processes [34].

Compared to the existing body of knowledge about GIS, machine learning, and pavement management systems, the existing evidence regarding applications of Digital Twin is still very scarce. In most cases, research revolves around conceptual approaches, review papers, or even case studies conducted on small scale. Thus, despite all possible opportunities provided by Digital Twin technologies, in terms of improved infrastructure surveillance, predictive maintenance, and asset management, these technologies are still not widely applied and developed enough to be used in practice.

In conclusion, it may be said that the existing literature indicates that Digital Twin technologies could be viewed as a promising trend for future use in road asset management systems. These technologies are able to provide a combination of different functions including integration of sensing devices, predictive analysis, and intelligent decision-making within one platform. However, more research is needed before claiming that Digital Twin technologies are applicable in practice.

3.5 Benefits of Digital Technologies for Road Maintenance

A. Improved Accuracy and Decision-Making

Among other advantages brought about by digital technology in road maintenance is the increase in accuracy and decision-making capability. Previously, maintenance decisions have been made based on engineering judgment, and thus, have been prone to inaccuracies due to lack of information. However, digital technologies have provided road agencies with the capability to use data-based techniques for predicting the condition, prioritizing, and selecting treatment methods.

Various researchers have confirmed the efficiency of Artificial Intelligence (AI) and Machine Learning (ML) algorithms for improved accuracy in estimating the state of pavements. Elshamy et al. used ANN models and succeeded in attaining determination coefficients greater than 0.94, while the best model among those developed attained an R^2 value of 0.9493 [20]. On the other hand, Sandamal et al. found that Random Forest provided better results, recording an R^2 of 0.906 as compared to various other machine learning models in predicting the roughness of pavements [22]. Plati et al. went ahead to confirm the efficiency of LSTM models by attaining Mean Squared Error (MSE) values between 0.001 and 0.004, which were far much lesser than those recorded using traditional regression approaches[23]. These findings indicate that advanced AI models can significantly enhance the reliability of pavement deterioration forecasting.

Enhanced capabilities were also seen in maintenance prioritization and treatment selection schemes. For example, Dabous et al. proposed a framework based on a combination of Case-Based Reasoning and Random Forest, which managed to obtain a general accuracy rate of 95% and a Kappa coefficient value of 0.94; at the same time, it was able to match the recommendations of the inspectors 87% of the times in their validation tests [37]. Likewise, In a similar fashion, Tejasri et al. concluded that random forest-based prioritization models could achieve coefficients of determination values of between 0.8733 and 0.9878, showing great predictive capabilities [44]. These results suggest that intelligent decision-support systems can improve consistency and reduce uncertainty in maintenance decision-making processes.

Furthermore, geospatial technologies help in proper prioritization of maintenance work and resource allocation. According to Nugraha et al., who combined GIS and AHP to prioritize maintenance tasks based on their influence using Traffic Volume (23.3%) and Road Authority (22.1%), a CR of 0.048 was attained to establish a valid decision making process [19]. Such findings demonstrate how digital technologies can support transparent and evidence-based prioritization strategies.

Overall, it can be concluded that through the use of technology, the ability to accurately predict the condition of pavements is greatly increased. Artificial intelligence-based models showed great efficiency in making predictions, while decision support and geospatial systems made it easier to prioritize the maintenance of pavements due to their objective nature.

B. Enhanced Maintenance Efficiency and Resource Allocation

The digital technologies have made major contributions toward enhancing the effectiveness of maintenance work through optimizing inspection scheduling, maintenance priorities, and asset management. The use of GIS technologies has received considerable attention for improving operational efficiency and maintenance planning. According to Albatayneh et al., the combination of the ArcGIS Network Analyst with the process of route optimization resulted in lower costs of travel time and inspection time, and the application by Nugraha et al. of AHP-GIS enabled proper maintenance prioritization. [15], [19].

Furthermore, the implementation of GIS for maintenance management systems has shown considerable advancements in terms of efficiencies. In a study by Meiliana et al., an optimized maintenance strategy helped reduce the estimated cost from IDR 23.08 billion to around IDR 9.80 billion without compromising on road performance conditions [18]. Likewise, Ali et al. designed a PMMS system that enables the prediction of pavement conditions in order to plan maintenance activities, while Moradi and Assaf devised a combination of GIS, mobile LiDAR, RGB camera images, and deep learning algorithms to automate pavement distress assessment process [35], [47].

Further efficiencies in maintenance operations have been highlighted using IoT-based monitoring systems. The work of Adeniran-Bakare et al. indicated that IoT-based approaches could help in minimizing repeated site inspections while simultaneously facilitating continuous monitoring of infrastructure as well as preventive maintenance practices [48]. Collectively, these findings indicate that digital technologies improve maintenance efficiency by optimizing inspection activities, supporting data-driven prioritization, and enabling more effective utilization of available resources.

C. Cost Reduction and Lifecycle Optimization

Some of the advantages of digital technologies in road maintenance are cost savings and lifecycle optimization. Traditional methods of road maintenance involve reactive maintenance that comes in after the pavement has deteriorated to an extent where repair would require higher amounts of money to fix, as well as reducing the lifespan of the pavement. Digital technologies allow for predictive maintenance, which saves money and optimizes the lifecycle of assets.

Some research was dedicated to showcasing the capability of predictive analytics to cut costs due to enhanced forecast precision. Asadi found out that with the help of machine learning algorithms for predictive maintenance, maintenance costs for roads could be reduced by 10% to 20% while also increasing the life span of infrastructure structures by 30% [24]. Moreover, the study pointed out that with the use of predictive models, the number of unexpected breakdowns could be minimized by 70% while minimizing emergency maintenance costs by 25% to 40 %.

In this context, Gundogdu et al. have noted that there is a shift from traditional statistics-based methodologies to more soft computing and artificial intelligence-based methodologies used for the forecasting of the cost associated with road maintenance activities [49].

PMS and DSS also assist in optimizing the life cycle through proper maintenance and treatment recommendations. For instance, Ali et al. designed a pavement management and maintenance system that can predict the pavement condition and make decisions related to maintenance schedules [47]. Such capabilities help agencies maximize pavement lifespan while minimizing long-term maintenance costs.

In general, these findings suggest that technological innovations play a major role in helping cut costs and optimize the life cycle through prediction of maintenance needs, better deterioration forecasting, optimized maintenance plans, and effective treatments. Through early intervention and making better-informed decisions, these technologies help minimize rehabilitation efforts that require more expenses.

D. Real-Time Monitoring and Safety Improvement

Another significant advantage of the use of digital technologies in road maintenance refers to their potential for monitoring road conditions in real time and ensuring road safety. Computer vision and machine/deep learning technologies showed high efficiency in pavement defect detection. A precision of 93% was reached by Omar and Kumar using YOLOv7 model for pothole detection, while Lakshminarayanan and Nurulain et al. managed to achieve an accuracy of 96.5% and 90.4% based on the use of CNN-based and VGG16-based models respectively[25], [27], [28].

Furthermore, the reviewed studies reveal the role of IoT and connected infrastructures technologies in continuously monitoring roads. Adeniran-Bakare et al. showed that they have achieved a level of accuracy higher than 99% through the use of IoT-based monitoring system, while Hijji et al. attained a precision rate of 87.2%, a recall rate of 92.7%, and an F1 score of 89.9% by using 6G connected vehicles framework for pothole detection [38], [48]. These technologies enable continuous data acquisition and facilitate earlier identification of pavement defects compared with conventional inspection approaches.

New smart infrastructure technologies allow further enhancement of monitoring processes and increased operational safety. Thus, while Villaverde et al. combined UAVs and autonomous mobile robots to create a Digital Twin system for automated road inspections, Xu et al. suggested an Autonomous Maintenance Plant with Robotics, Sensors and Artificial Intelligence based on Highway Digital Twin approach[31], [32]. Moreover, according to Ashraf et al., most models based on CNN algorithms were able to deliver accuracy, recall and F1-scores greater than 0.80; furthermore, in one of the reviewed studies, accuracy scores reached 0.911, recall reached 0.948, and F1-score was equal to 0.922 [40].

Overall, based on the above analysis, it can be concluded that use of digital technologies improves monitoring processes and increases safety of roads due to automated defect detection, ongoing assessments and immediate repairs.

3.6 Challenges and Limitations of Digital Technology Adoption

A. Data and Technical Constraints

However, despite the many advantages that come with the utilization of technology, there are certain issues that affect the successful implementation of digital technology in road maintenance. The first issue that needs to be addressed is the availability and quality of data. This is because modern technologies like AI, ML, and CV depend highly on huge amounts of accurate data. For instance, research conducted by authors such as Elshamy et al., Sandamal et al., Plati et al., and Asadi have shown that the prediction of future events using machine learning algorithms performed well using datasets related to pavement conditions and traffic records [20], [22], [23], [24]. However, incomplete records, inconsistent data collection practices, and limited historical datasets may reduce prediction accuracy and restrict model transferability across different road networks.

Other constraints are, variations in lighting conditions, image resolution, weather conditions, and pavement surface characteristics that may affect detection reliability and model efficiency. Similarly, GIS-based systems require accurate and regularly updated geospatial databases to support effective maintenance planning and decision-making [16], [18].These requirements may limit implementation, particularly among agencies with constrained technological resources.

B. Integration and Implementation Challenges

The convergence of multiple technological solutions into one coherent road maintenance framework poses another critical issue. Even though each technology, such as AI, GIS, Computer Vision, IoT, and Digital Twins, has shown effective performance independently, the level of compatibility between these technologies is still low. Moradi and Assaf incorporated GIS and mobile LiDAR together with RGB images and applied deep learning techniques into their intelligent pavement management system. At the same time, Nyomboi and Mwaniki combined remote sensing technologies with GIS-based assessment methods [35], [41]. Although these approaches improved analytical capabilities, they also increased system complexity and integration requirements.

Integration challenges are particularly evident in Digital Twin environments. Villaverde et al. and Xu et al. proposed frameworks that combine UAVs, autonomous robots, sensors, artificial intelligence, and computer vision technologies within a single digital ecosystem [31], [32]. Similarly, Oditallah et al. and Malihi et al. emphasized the need for stronger interoperability between Digital Twin platforms, predictive analytics, sensing technologies, and maintenance management systems [33], [34].The lack of standardized data structures, communication protocols, and integration frameworks continues to limit large-scale implementation.

Apart from technology integration, there might be issues related to deployment costs, software compatibility, organizational preparedness, and workforce capabilities that could hinder the use of the technology. Thus, a successful technology transformation process is not only dependent on technology but also requires an investment in system management.

C. Challenges in Developing Countries and Tropical Regions

Deployment of digital road maintenance technologies is likely to pose challenges in developing countries based on various factors. For example, advanced technologies including IoT-based systems, Digital Twin technology, and pavement management technologies require significant digital infrastructure investment, sensors, and technical know-how that might limit deployment especially by agencies operating on a tight budget. The environmental condition of the road network in some regions could also affect the use of digital technologies. In tropical countries, road networks are characterized by extreme precipitation, floods, and accelerated road deterioration leading to challenges associated with maintenance. This scenario is experienced in Malaysia owing to its weather.

However, regardless of these challenges, the reviewed literature suggests that there is still a huge potential of adopting digital technologies in road maintenance in the future. With the current adoption of technologies such as AI, GIS, Computer Vision, IoT, and Digital Twins, it is obvious that the world is moving from simple data management to a much smarter and efficient system. Efforts towards better data management, interoperability, technical expertise, and standardization frameworks are therefore critical in the future.

Table 2. Summary of Digital Technologies in Road Maintenance Management

Technology	Main Applications	Key Benefits	Key Challenges	Example Studies
GIS	Condition assessment, maintenance prioritisation	Spatial analysis and maintenance cost optimisation	Data updating requirements	[15], [16], [19]
AI/ML	Deterioration prediction	Prediction accuracy up to R^2 = 0.949	Data dependency	[20], [22], [23]
Computer Vision	Defect detection	Detection accuracy up to 96.5%	Environmental sensitivity	[25], [27], [30]
DSS/PMS	Maintenance planning	Decision accuracy up to 95%	System integration	[35], [37], [47]
IoT	Real-time monitoring	Continuous monitoring with >99% accuracy	Infrastructure cost	[38], [48]
Digital Twin	Lifecycle management	Integrated monitoring and simulation	Early-stage implementation	[31], [32], [33]

4. CONCLUSION

The current literature review has analyzed the most recent applications of modern digital technologies in road maintenance management, specifically focusing on Artificial Intelligence (AI), Geographic Information Systems (GIS), Internet of Things (IoT), Digital Twins, Mobile Applications, Computer Vision, and Decision Support Systems (DSS). Overall, this research indicates that the implementation of such technologies revolutionized traditional maintenance approaches through introducing automated detection of the road defects, predictive maintenance management, real-time monitoring capabilities, and data analysis-based decision-making processes. The use of AI and computer vision techniques contributes to the more accurate and efficient detection of the road defects and deterioration, whereas GIS, IoT, and Digital Twin systems enable spatial analysis, monitoring, and asset management. Nevertheless, the identified research gaps point to several problems, which can include the quality of input data, integration complexity, high costs of implementation, interoperability challenges, and absence of any standard framework. Moreover, the studies in question typically focus on one technology at a time, making it difficult to evaluate the role of each solution in the overall road maintenance ecosystem. The results of this review are especially valuable for developing nations like Malaysia since tropical climate, aged road networks, and increasing maintenance needs necessitate smarter maintenance solutions. Thus, further research is needed to develop systems and platforms based on various technologies that incorporate the elements of sensing, monitoring, prediction, and decision-making to facilitate a smarter, efficient, and sustainable maintenance process. This review contributes to the existing body of knowledge by providing a multi-technology synthesis of digital road maintenance solutions, highlighting their applications, benefits, limitations, and future integration opportunities.

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