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Review Article

Integrating Artificial Intelligence in Pavement Design for Smart and Sustainable Urban Infrastructure: A Review

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Abstract - *Resilient, sustainable, and efficient infrastructures are essential in smart cities, and pavements play a critical role in facilitating mobility and connectivity. Artificial Intelligence (AI) is emerging as a disruptive paradigm in the design and use of pavements; it is providing tools and processes, leveraging real data to facilitate decision-making and improve pavement performance. This review will provide an overview of AI in the domain of pavement engineering that explores the following aspects: Material characterization, design optimization, performance prediction, and maintenance planning. By synthesizing recent research studies, this review illustrates that using techniques such as machine learning, deep learning, and predictive modelling will enhance performance accuracy, increase cost effectiveness, and create adaptive design models that will foster smart city applications. Despite the potential for innovation through the application of AI in pavement engineering, some challenges must be resolved: Comprehensive and standardized datasets are needed, AI models must be more transparent and explainable, and AI applications must be integrated into existing design and management processes. The study concludes with an emphasis that AI has the potential to enable smart, sustainable mobility and that AI represents new technology, but will also be a novel way to optimize future urban infrastructure.*

Keywords *- AI, Deep Learning, Intelligent Transportation, Machine Learning, Pavement Design, Predictive Modelling, Smart Cities.*

1. Introduction

The field of transportation engineering is changing fast, with AI improving transport safety, efficiency, and sustainability with the application of smart traffic management, predictive maintenance, and autonomous systems. Some of the most significant innovations are AI being used to optimize traffic, predict maintenance requirements of the infrastructure, and autonomous vehicles, logistics, and personal mobility solutions.

This study deals with the cities all across the globe that are urbanizing at a very unpredictable rate, due to which there is a need for coming up with ways to effectively optimize resources, resolve all mobility challenges, while keeping in mind sustainable goals [1-4]. This out-of-proportion urbanization has led to a surge of smart cities, which are not only data-driven but also more sustainable, making this more efficient [5, 6]. The transportation infrastructure is the pillar of the growth of these smart cities. They improve connectivity, movement, and reduce the costs [7-11].

The most essential part of transportation systems is the pavements. They have a direct effect on safety, service quality, and sustainability, which in turn leads to better mobility [12, 13]. The life cycle costs (maintenance and repair costs) can be reduced with better thinking and designing. Poorly designed pavements can have severe impacts, such as high service life costs, a poorer transportation network, and higher fuel consumption. Various studies reveal that the already existing pavements have now reached their capacity due to multiple reasons, such as heavy vehicles, unexpected traffic volumes, and climatic conditions [14-16].

The previous methods used are more factual, and predictions are made on static assumptions; due to these reasons, making long-term predictions in real-world scenarios is challenging. While keeping these in mind, too, there is an urgent need to modify and diversify our already existing pavements. For instance, pavement performances play a significant role as they directly affect environmental sustainability, i.e., by managing the fuel consumption and emissions [17-19].

Embodied carbon and recyclability over the long term are influenced by the choice of materials. Preferably, pavements ought to be designed as active elements that can help the sustainability agenda of a city, not as passive elements. In order to realize these goals, there is a need to have strict analytical skills to handle big, complicated, and interconnected data. Artificial Intelligence (AI), defined as computational techniques enabling machines to perform data-driven learning and decision-making tasks, is increasingly applied in pavement systems and has become the leading device in the context of satisfying these requirements [20-22].

Generally, in civil and transportation engineering, AI has provided methods of challenging the conventional analytical paradigm that utilizes training data that covers a wide spectrum of factors, to non-standard statistical tools. Machine Learning (ML) is a subset of Artificial Intelligence involving data-based predictive algorithms that have the capability to go through large volumes of data, including traffic loads, climatic conditions, and properties of materials, to fruitfully study the trends and help in improving the forecasting. The effectiveness can be increased by using deep learning methods by modelling complex nonlinear relationships; on the other hand, these complexities are not captured by conventional methods. Also, by using maintenance plans, outages of systems are reduced, and the use of resources is maximized [23, 24]. In recent years, optimal use of asphalt and concrete mixtures using AI models has shown a significant increase in strength, economy, and environmental benefits [5].

Smart predictive technologies have the ability to anticipate such problems as cracking or rutting. Such a proactive approach allows agencies to shift the focus of responding to the damage to proactively intervene in order to enhance the functioning effectiveness [25].

The optimization methodologies are critical in determining the best design alternatives to use to design the roadway infrastructure based on the performance, cost, and environmental factors, thus falling in line with the idea of smart cities [26-28]. Through the application of AI to transportation systems, it is now possible to monitor the condition of the pavements in real-time and introduce some modifications to the construction design and ongoing enhancement of the maintenance procedures as the infrastructure develops [29, 30].

As a result, AI does not limit itself to the sphere of design, but it connects the engineering practice with the overall goals of smart cities. Compared to the conventional approaches, the AI-based pavement designs are more effective, predictive, and sustainable. They also contribute directly to smart mobility, in return enhancing the resilience and efficiency of resources in transportation systems. These systems also support sustainability goals by encouraging efficiency, adaptivity, and carbon-neutral structures.

The rapid and unsystematic method of urbanization in smart cities has caused a sudden need for more advanced transport systems, which are technologically advanced but also environmentally friendly. The backbone for more efficient mobility systems is pavements. Due to the usual way of designing, the standard pavements fail to manage traffic congestion and complex datasets effectively. To solve this problem, incorporating Artificial Intelligence (AI) in pavement designs can be beneficial. Using data-driven methodologies can enhance the structural integrity, better resource utilization, and selection, and in return enhance the performance models. Even after such great advancements, there is still a need for more data-driven and AI-targeted approaches to be utilized to their maximum capabilities.

The volume of literature available on the topic of Artificial Intelligence applications in the field of transportation and pavement engineering is growing, but the results of the studies are scattered and do not include comprehensive aspects such as traffic prediction, material characterization, or even maintenance schedules. The fact that the AI-based techniques contribute to the design of the pavements in the framework of the smart and sustainable urban infrastructure is not yet entirely comprehended. Further, the existing pavement design processes continue to use empirical or static designs that cannot accommodate dynamic traffic, the variability of the environment, and the massive infrastructure information. This provides a massive gap between the creation of the AI capabilities and the systematic implementation of AI in the pavement engineering endeavor. This has led to the necessity to have a consolidated review that will examine the application of AI in the material design, structural performance, prediction, and sustainability perspectives. In order to fill in the identified research gap, the given paper will offer a detailed discussion of how Artificial Intelligence in pavement design can be one of the key drivers that will ensure the development of smart and sustainable cities. They will be able to use such systems to leverage widespread data collections captured in real-time to promote efficiency, sustainability, and safety beyond the abilities of conventional methodologies on the basis that the major objectives of this review were to investigate in detail the smart city and pavement design.

Substantial research has been done on Artificial Intelligence in pavement engineering; the majority of the studies are focused on certain areas, including performance, maintenance management, or traffic analysis or prediction in isolation. An all-encompassing synthesis incorporating AI-based. pavement design, material appraisal, lifecycle performance. Sustainable city infrastructure goals, sustainable development, and assessment remain limited. Thus, this review will be a unification of current knowledge and a critical analysis of AI-driven strategies in an integrated intelligent and eco-friendly pavement. structure and establishing research gaps that are emerging for possible developments in the future.

- To test AI applications in the characterization of materials, performance, performance prediction, and structural design in maintenance management.
- To define the benefits of AI-based approaches to enhance the cost-effectiveness, durability, and efficiency of pavement systems.
- To determine the existing constraints, such as data availability, integration, and model interpretability
- To suggest the future directions of integrating AI technologies in transportation and increasing urban mobility systems.

This is contrary to the current review studies that mainly concentrate on how Artificial Intelligence is being used. The meaning of work is a synthesis of AI-based design, evaluation of material performance, pavement design, lifecycle management, and smart city sustainability. Objectives of the paper also bring forth a comparative assessment and determine difficulties of implementation in the subsequent course of research, thus providing an integrated AI smart pavement infrastructure framework.

2. Literature Review

In civil and transportation engineering, AI is being recognized more and more as a disruptive technology and can enhance the approach to infrastructure design, operation, and management to predictive, data-driven, and optimization-based approaches [31, 32]. In the last ten years, extensive research on Artificial Intelligence used in transport infrastructure has been performed, that is, in the field of traffic control, infrastructure detection, pavement performance forecasting, material search, and maintenance scheduling. Findings of earlier research were mainly based on statistical and mechanistic modelling tools, but recent research papers are progressively subjecting complex and data-intensive engineering problems to machine learning, deep learning, and hybrid AI methods.

The increased interdisciplinary view of the application of AI has led to a variety of methodologies and approaches to implementation reported in the literature. Hence, to give a clear idea of the development, recent progress, and future of research of AI-based pavement engineering, it is critical to synthesize existing research literature, offering it in a clear manner. There is a possibility of improving the safety through the introduction of AI approaches, at the same time being efficient and implementing sustainable transportation systems as a part of the smart city development objectives [33]. Increasing attention has been paid to the recent studies on the same. This is predictive maintenance and intelligent pavement that is powered by AI real-time sensing systems inside management systems and data analytics. The literature reviewed is divided into two categories. They are described below:

2.1. AI in Transportation Engineering

Nowadays, artificial intelligence is integrated into the smart-city systems, with digital-twins systems, predictive maintenance systems, and sophisticated decision support systems, which are transforming the design, planning, and operation of transportation systems. To create smarter cities, create even smarter predictive maintenance regimes, and make automated transportation infrastructure safer, artificial intelligence is expected to trigger these changes. Smart systems, which are vehicles with an automated driverless mechanism, public transport optimization, and dynamically controlled traffic lights, have come to the forefront of the research community of transportation engineering.

2.1.1. Background and Evolution of AI in Civil and Transportation Engineering

Typically, engineering dilemmas in civil and transportation use of the Artificial Intelligence (AI) technology in civil and transportation engineering has been growing significantly in the last few decades. Engineering problems were solved through statistical models, optimization methods, and simulation-based approaches. Specifically, traffic flow prediction, pavement condition evaluation, and structural response were obtained through linear regression, time-series models, and finite element simulations. Although these methods have worked very well for small-scale, deterministic problems, they have been ineffective for complex, nonlinear, and large-scale datasets.

AI as a phenomenon came into the limelight in the late twentieth century with the introduction of rule-based models and expert systems. Such systems allowed for the analysis of data and the recreation of the human engineering decision-making process in the areas of structural diagnostics, construction management, and traffic discipline. The previous works in AI in transportation mainly focused on traffic predictions, planning of routes, and managing signals, which were completely dependent on pattern recognition and heuristic techniques.

In the early 2000s, there was a significant shift in the field of civil engineering. It was the adoption of AI, data-driven machine learning, and deep learning approaches. The evolutions allowed our engineers to develop more complex modelling relationships without relying on those traditional mathematical equations. For example, to estimate the wear and tear of pavements, traffic congestion, and to examine the condition of bridges, neural networks and support vector machines are used to achieve higher accuracies. The utilization of AI in civil and transportation engineering has changed in recent years with the proliferation of the Internet of Things (IoT) devices, real-time sensors, and big data analytics. The recent implementation relies on Machine learning and Deep learning algorithms for city planning, traffic flow optimization, and maintenance. Newer tools aid in improving the speed, accuracy, and efficiency of programs.

2.1.2. Incorporating AI in Civil and Transportation Engineering

In the field of civil and transportation engineering, the evaluation of AI models is extremely important to ensure their utility in real-world scenarios. Assessment performance measures can be:

- Accuracy: This measure is used to indicate the fraction of accurate predictions when compared to the overall number of predictions. It is relevant to activities like predicting traffic patterns and evaluating the state of structures.
- Root Mean Square Error (RMSE): This is a measure that is used to estimate the difference between the predicted and the observed values of continuous data. RMSE is widely used in artificial intelligence applications in the traffic flow prediction field, in the pavement performance assessment field, and in the load response modelling field.
- F1-Score: Important evaluation metrics for problems involving classification that may require the handling of class imbalance. For example, detecting anomalies in structural inspections or initiating a traffic incident investigation.
- Efficiency: Efficiency considers the computational cost and the time required to run the AI algorithms. The efficiency of an AI model is especially relevant in applications related to automated real-time traffic monitoring.
- Robustness: The robustness of an AI model considers the stability of the model against noise, missing data, or variations in the operating environment, and is particularly important in assessing infrastructure that is monitored under dynamic conditions or predictive maintenance projects.
- Several AI methods have been applied in the civil and transportation domains:
    - Machine Learning (ML): ML algorithms use historical and real-time datasets to develop accurate predictions for traffic flow, congestion, and infrastructure deterioration [34].
    - Deep Learning (DL): DL utilizes multilayered neural networks to extract complex feature representations from large-scale, high-dimensional datasets, which have supported applications such as automated traffic monitoring, image-based structural inspection, and anomaly detection [35, 36].
    - Artificial Neural Networks (ANN): ANNs are specifically used for modelling nonlinear relationships in fields of transportation infrastructure [37].
    - Support Vector Machines (SVM): SVM, along with different classification metrics, are usually used together for regression tasks, which require higher levels of accuracy [38].
    - Genetic Algorithms (GAs): GAs solve traffic signal control, route planning, and multi-objective infrastructure design [39].
    - Random Forests: Utilize Random Forests for predictive modelling and feature selection in traffic and asset management [40].

2.1.3. Applications in Transportation Engineering

AI has been successfully used in numerous domains, including the transportation sector. In this sector, the major concern for the use of AI is traffic flow management. AI deploys various strategies to increase vehicle movement, minimize traffic congestion, and increase efficiency.

- ML and DL models have been employed to improve signal timing to decrease congestion, which ultimately improves safety for drivers on the road [41].
- Asset Management: Predictive models assist with scheduling maintenance, distribution of resources, and extend the life of bridges, pavements, and tunnels [42].
- Sustainability: AI has helped with decreasing energy, emissions, and waste of materials in transportation operations [43].

IoT and Smart Cities with IoT: The incorporation of IoT has helped enhance mobility in cities, more flexible control systems, and real-time monitoring [44]. Various uses of AI in the transportation engineering field are stated in Figure 1.

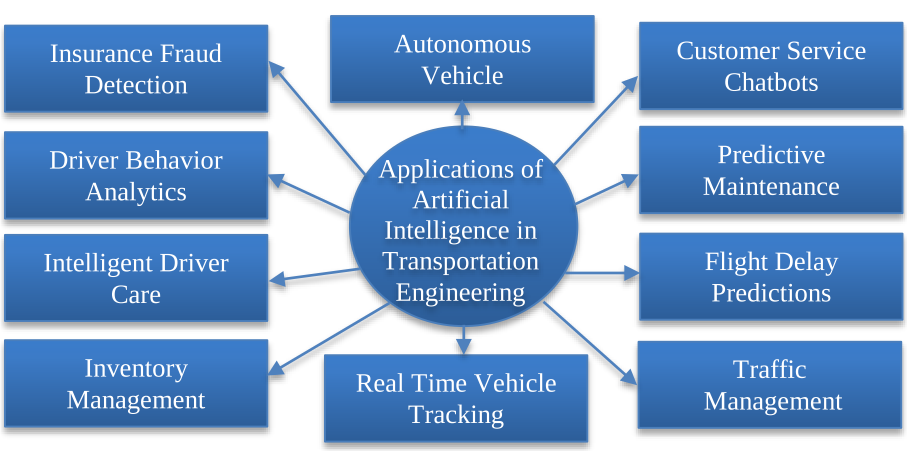

Fig. 1 Applications of artificial intelligence in transportation engineering

From the literature search, one of the many conclusions that has been made is that using AI in the development of a smarter and more intelligent transportation system is going to be really helpful. The usage of AI aids in creating a more robust infrastructure. It works on the concept of combining systems that are scalable predictive analytics, optimizing techniques, and real-time decision-making processes [45].

2.1.4. Challenges and Limitations

Although there has been significant growth and advancements in applying AI in transportation engineering, there have been numerous obstacles on the way to the adoption of this method. The major constraints during the adoption are the quality and availability of data [46]. Most of the AI models require huge high-resolution datasets for training to make more accurate predictions. But in infrastructure and traffic data, available information is mostly minimal, irregular, incomplete, and inconsistent. Decision-making is heavily compromised due to the low quality of data, as this can lead to biased predictions. Further challenges are scalability and computational efficiency, especially in real-world applications of deep learning, which require high memory and processing. Another critical obstacle is the explainability of AI systems, more specifically, deep neural networks [47]. Many AI tools, such as “black-box AI models”, make predictions without disclosing the rationale.

Such transparency is harmful to the reduction of risks and the inability to adhere to the regulatory norms [48]. Furthermore, AI systems should be able to adapt to the changing urban environment, which has changing traffic flow patterns, constant construction, and infrastructural changes. The models that have been trained on fixed historical data will perhaps not be able to perform generalization effectively under such dynamic conditions, which require re-training or constant adaptation with real-time changes [36].

The resolutions to the challenges will be based on a solid data collection infrastructure, the effective design of algorithms, explainable AI, and adaptive modelling models to attain credible, sensible, and sustainable use of AI in civil and transportation engineering.

Table 1. Comparative analysis of AI applications in various studies

Study Focus	AI Technique	Application	Advantage	Limitation
Pavement performance	ANN	Prediction	High accuracy	Data dependent
Distress detection	CNN	Image analysis	Automation	Large datasets
Maintenance planning	RF	Decision support	Robust	Interpretability
Traffic interaction	ML models	Optimization	Adaptive	Calibration need

2.1.5. Trends and Future Directions

Application of AI in civil and transportation engineering is developing rapidly due to the improvement of the availability of data, computing power, and sensors. The development of Autonomous Vehicles (AVs) and the network of connected mobility is one of the major trends where AI algorithms are specialized to ensure the safety and efficiency of transportation networks in urban domains [49]. The other promising area of use is digital twins.

Virtual replicas of urban infrastructure may provide an AI with the ability to simulate, monitor, and predict the behavior of bridges, pavements, and utilities under various loads and environmental conditions, facilitating better maintenance and informing urban planning [50].

Multi-agent systems and reinforcement learning offer great potential for smart city management, which can enable many AI agents to coordinate in managing traffic, reducing energy consumption, managing emergency response, and updating and responding to changing conditions in real-time in complex urban environments [51].

In conclusion, AI is also being adopted in transportation systems for climate resilience and disaster response. For example, predictive models may be used to predict and evaluate climate impacts related to extreme weather, vulnerability assessments related to critical transport infrastructure, and recommendations related to evacuation planning in the interest of safety and sustainability. The AI in civil and transportation engineering is most likely to depend on adaptive, autonomous predictive systems. These systems continue to run efficiently in real time and operate smoothly with smart city rules and regulations, while contributing to the development of more resilient and sustainable infrastructure [52]. Figure 2 illustrates the different challenges in the literature, how they can be overcome by using AI, its outputs, and the future scope.

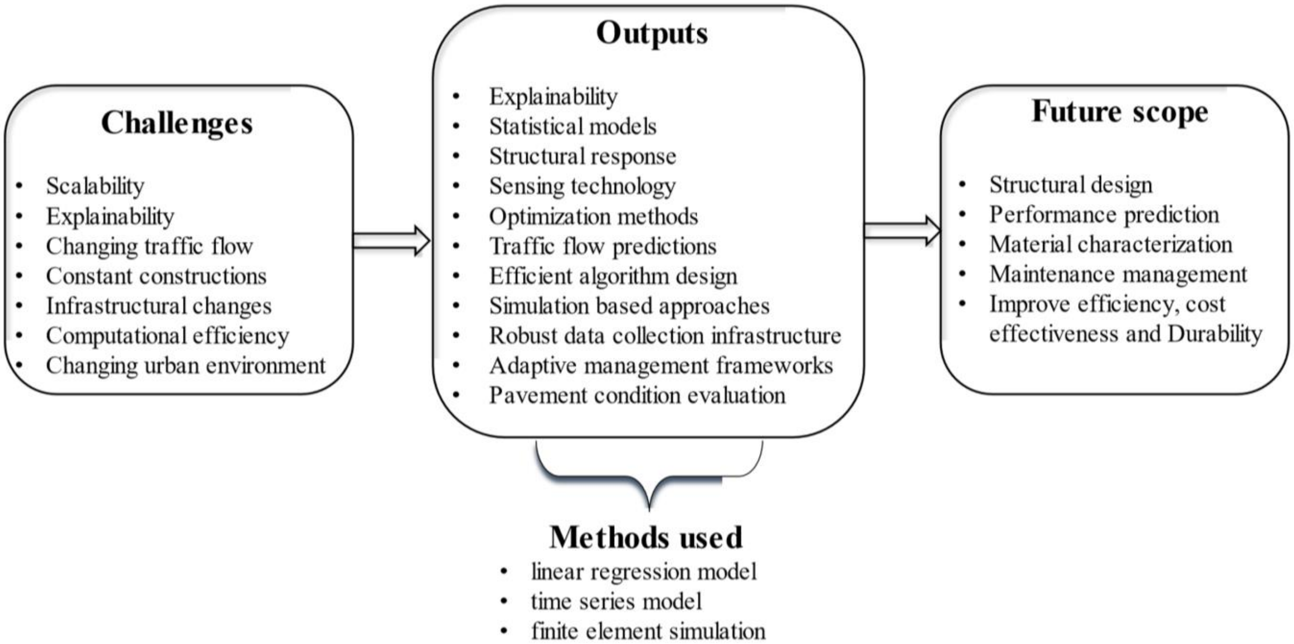

Fig. 2 Overview of challenges, outputs, and future scope of AI-driven pavement design

2.2. AI in Pavement Design: Review of Applications

The use of artificial intelligence in pavement design has developed at a very fast rate during the last decade, providing more precise, efficient, and sustainable practices [53]. The AI has been used in material characterization, structural design, predicting performance, maintenance planning, and sustainability assessment using approaches like Machine Learning (ML), Deep Learning (DL), Artificial Neural Networks (ANNs), Support Vector Machines (SVMs), and Genetic Algorithms (GAs) [54].

2.2.1. Pavement Material Characterization

Material characterization is one of the essential elements of pavement design because it forecasts the mechanical traits of asphalt, aggregates, and soil constituents. The traditional method of laboratory testing of these materials is costly and time-consuming. Recently, AI models, especially ML and ANN, have been used to predict the resilient modulus, soil strength, and the properties of asphalt mix, all utilizing historical databases instead of a full laboratory testing process [55]. For instance, neural networks can model complex nonlinear relationships between soil composition, compaction, and strength, therefore significantly reducing testing. ML models have also been used to develop sustainable material mixes that optimize recycled aggregates or waste plastics into asphalt while achieving acceptable mechanical performance and reduced environmental impact. Overall, the characterization of pavement materials can significantly benefit from AI by accurately predicting mechanical behavior, providing the opportunity for informed decision-making for both material selection and its design formulation [54].

2.2.2. Pavement Structural Design

The use of AI to assist in the structural design of pavement layers, which can include subgrade, base, and surface layers, continues to grow. Structural performance is increasingly evaluated, optimized, and estimated to support load-bearing capacity and durability. For example, ANN and SVM models may be used to estimate structural response based on different traffic loads and environmental scenarios. Genetic Algorithms (GAs) and other heuristic techniques are well-suited for solving multi-objective problems, as they aim to optimize a selected objective while considering overall structural performance, subject to limits on cost and materials, sustainability of materials, and other variables [56]. Methods such as the Genetic Algorithm (GA) can be used to calculate optimum asphalt layer thicknesses and reduce the maximum strains and stresses in the pavement structural system. The paradigms of designing can be changed by AI-based optimization, in which the design is not entirely empirical, which is more reliable in the conditions of complex loading [57].

2.2.3. Predicting Performance & Service Life

Proactive infrastructure management is considered for service life and performance prediction. The rutting, fatigue, and general distress patterns are predicted using artificial intelligence models. Time-series data can also be trained using deep learning to predict the future occurrence of pavement distress with time-dependent traffic and climatic conditions on Long Short-Term Memory (LSTM) networks. To predict the rut depth or fatigue cracking using the historical records of the performance and the traffic loading, random forest and ANN models can also be used [58]. The use of these predictive tools allows the pavement managers and agencies to recognize the vulnerable segments at an early stage, as well as to adopt specific approaches to distress reduction and prolonging the asset life cycle. Moreover, performance prediction enables scenario testing that takes into consideration the different rates of growth in traffic or climate change projections, thus guiding the design [59].

2.2.4. Maintenance, Sustainability & Smart City Integration

Artificial Intelligence (AI) has realized a significant breakthrough in the fields of predictive maintenance and Pavement Management System (PMS) to promote the sustainability goals and support intelligent city projects. Deep learning models based on the convolutional computer vision process the images taken by unmanned aerial vehicles or ground platforms to estimate the values of the Pavement Condition Index (PCI), thus reducing the need to conduct the labor-intensive manual surveys to assess the PCI [60]. Together with machine learning algorithms, embedded sensor networks can be used to measure structural stress, crack propagation, and moisture content accuracy, providing advanced prognostic measures of impending maintenance operations. The Support Vector Machines (SVM) and the Random Forest classifiers are used to help differentiate the typologies of distress and correctly predict the level of distress and rate of degradation, thus guiding the agencies on the best way to use the remaining maintenance budgets and also which ones to prioritize in order to affect the least traffic disruption [61, 62].

In addition to the normal maintenance, AI may be used in choosing sustainable materials during pavement design, considering the costs per life cycle, the carbon footprint, and energy use during the lifespan of the pavement. Machine learning predictive algorithms can determine low-carbon material substitutes and other eco-friendly approaches in the design or implementation of pavement repair during machine learning infrastructure renovation or the development of new roads [63]. The Internet of Things (IoT) device integration and digital twin technologies encourage constant monitoring; the simulations, which are informed by real-time traffic and environment-related data, can be used to show pavement performance and make the maintenance decision-making more efficient to maximize the service life [64, 65]. Figure 3. Highlights the Implementation of AI in Assessing Factors Affecting Road Pavement.

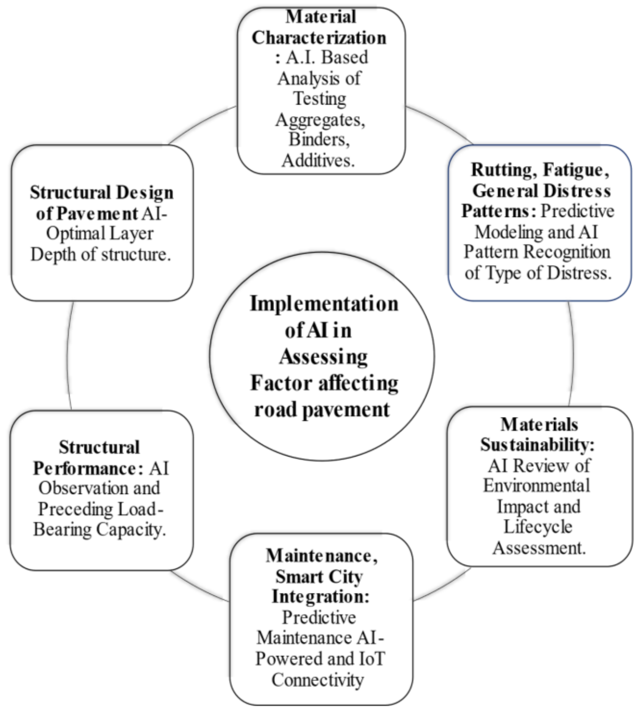

Fig. 3 Implementation of AI in assessing factor affecting road pavement

The reviewed articles show that there has been a considerable advance in the field of deploying Artificial Intelligence to transportation and pavement engineering, but the changes in 1) data availability, 2) modelling strategies, and 3) scaffolds allow concluding that there is a necessity to integrate the concepts of AI application throughout the entire Pavement design cycle. This is the fundamental point of the research synthesis that builds up the information on research trends, limitations, and marketing opportunities that it will explore in the next sections.

Table 2. Summary of recent studies on AI applications in pavement engineering

Author & Year	AI Technique	Application Area	Key Contribution	Limitation
Kang et al. (2025)	Machine Learning	Performance Prediction	Improved distress prediction accuracy	Requires large datasets
Xu & Zhang (2022)	ANN	Pavement Management	Automated condition assessment	Limited field validation
Marcelino et al. (2021)	ML Models	Service Life Prediction	Reliable deterioration modelling	Data dependency
Ramadan et al. (2024)	Hybrid AI	Pavement Design	Integrated decision framework	Computational complexity
Zhao & Wang (2025)	Deep Learning	Overlay Decision	Data-driven optimization	Interpretability issues

Comparison of research reveals that the existence of studies shows that Artificial Intelligence methods, including Artificial Neural Networks, Support Vector Machine, Random Forest, and deep learning methods, have proved to have better prediction ability in contrast to the traditional empirical models and mechanistic diagrams of pavement engineering. While the accuracy of machine learning models is better. performance forecasting and maintenance control, they mostly rely on the quality of data availability and the model conditions of training. Furthermore, research that places more emphasis on individual applications like material characterization, prediction, or maintenance of distress. Two tend to be independent of one another, and these are normally called optimization and building of decision support systems. Therefore, it is observed that AI frameworks must be unified and be able to sustain the entire lifecycle of the pavement. The current trends in research show that there is a shift in research. Independent Artificial Intelligence models against data-driven IoT-based systems monitoring smart infrastructure, predictive maintenance strategies, and real-time monitoring. Sustainability is also in terms of increased focus on pavement management in line with smart city initiatives. Nonetheless, a number of limitations still exist, among which are the absence of uniform datasets, scale validation, problems of model interpretability, and problems of interoperability between digital infrastructural platforms. These constraints restrict the large-scale implementation of AI-driven pavement systems despite promising laboratory and simulation-based outcomes.

Table 3. Comparative analysis of AI applications in pavement engineering

AI Technique	Application Area	Key Advantage	Limitation
ANN	Performance prediction	High accuracy	Requires large datasets
SVM	Distress detection	Robust modeling	Computational effort
Random Forest	Maintenance planning	Handles nonlinear data	Interpretability issues
Deep Learning	Image-based monitoring	Automation	Data intensive

3. Methodology

The review of the goal-oriented method investigates the incorporation of AI in pavement designs and how it is helping in developing the smart and more sustainable urban infrastructure. The main aim was to help create greener and smarter urban infrastructure in response to rapid urbanization. To fulfil this goal, an in-depth literature search was carried out with the help of various platforms like Scopus, Google Scholar, and Web of Science. Special emphasis was placed on peer-to-peer studies, journals, conference proceedings, and reports that specifically dealt with the amalgamation of AI in civil and transportation engineering. The literature search was eased out by utilizing a well-defined set of keywords, which included: “Artificial Intelligence”,” Machine Learning”, “Deep learning”, “Pavement designs”, “Smart cities”, “Road infrastructure”, and “Transportation Engineering” [59]. A good combination of keywords and Boolean operators was used to refine the search, making sure the result of the search included the AI-driven methods to enhance and tackle the challenges faced in pavement engineering [66]. Although the current study uses a narrative review method, in comparison with traditional narrative reviews, the systematic categorization of AI applications according to pavement design functions and sustainability outcomes is presented to accentuate the convergence of the research and the opportunities of its further implementation.

Additionally, the reference lists of relevant articles were examined to identify other related studies. Major scientific databases such as Scopus, Web of Science, and Google Scholar were searched in order to have a wide area in searching peer-reviewed journal articles and conference proceedings. The search mainly focused on 2015-25 publications to represent the latest developments in the field of Artificial Intelligence applications in pavement engineering, although any base publications published prior to this time were not ignored due to continuity in the concepts. Several combinations of Boolean searches, including: Artificial Intelligence AND Pavement Design, Machine Learning AND Pavement Performance, AI in Transportation infrastructure, and Smart Cities AND Pavement Management, were used. The reviewed literature was filtered in terms of relevance, methodology contribution, and engineering relevance according to preset inclusion and exclusion criteria in the Literature Review Methodology. The current review will be based on the structured literature survey methodology to locate the appropriate studies regarding the topic of the use of Artificial Intelligence in pavement engineering and smart infrastructure. Literature retrieval was done by the use of scientific databases like Scopus, Web of Science, and Google Scholar. Such keywords as Artificial Intelligence, Machine Learning, Pavement Design, Smart Infrastructure, and Sustainable Transportation were used. The studies published not earlier than 2015 were mostly thought to be relevant in order to capture the current developments. The articles were chosen according to their suitability to the topic of AI-based pavement analysis, performance prediction, maintenance optimization, and sustainability integration, and irrelevant studies, as well as duplicates, were eliminated.

3.1. Selection Criteria of Literature

The systematic selection of literature was also taken into consideration through inclusion and exclusion criteria to ensure that there was a comprehensive coverage of the topic. The articles were deemed eligible in case they (i) included a topic that was focused on either the Artificial Intelligence or machine learning applications in pavement engineering or transportation infrastructure, (ii) addressed the issues of characterizing materials, structural design, performance, maintenance, or sustainability. It avoided research that was not primarily in the area of pavement systems, lacked methodological clarity, and research that mentioned the development of theoretical AI, and did not put it into engineering applications. There was a priority given to recent publications to reflect on up-to-date developments, whereas seminal research papers were not discarded in order to have a base of knowledge.

This review examined a wide range of AI methods: supervised and unsupervised machine learning algorithms, deep learning algorithms, reinforcement learning methods, and hybrid predictive models [67, 68]. All searches were carefully appraised and arranged into the needed systems, which guaranteed the desired components of designing a pavement:

- Materials- such as mixture design, materials characterization, and new material composites.
- Structural Design- such as optimization of layer thickness, geometric design, and load distribution.
- Performance- such as being able to predict the failure of distress (e.g., deterioration, cracking, fatigue, and rutting), etc.
- Maintenance and Sustainability- such as predictive maintenance, life-cycle, and minimization of environmental impacts. In an effort to eliminate bias in one of the areas of research, this classification was employed to cover the critical areas of Artificial Intelligence application in pavement engineering in the same proportions. Figure 4. Represents AI Applications in Pavement Design

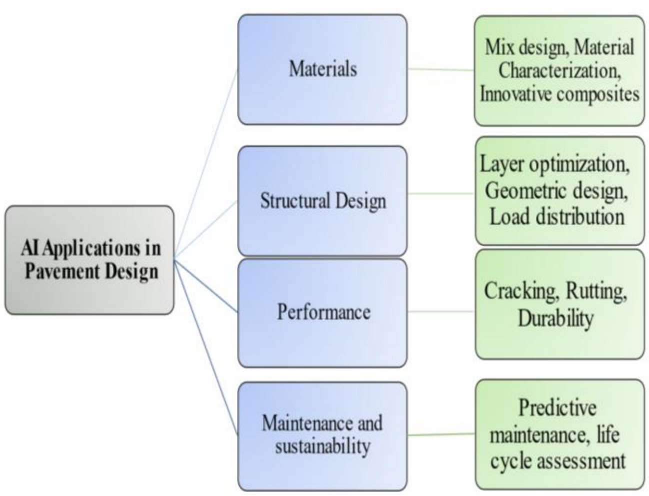

Fig. 4 AI Applications in Pavement Design

The reviewed framework defines an organized, methodical concept of the applications of AI techniques in pavement design, in order to depict the trend of growth and create a framework to establish opportunities to utilize AI in structural planning of infrastructure in smart cities of the future [69, 70].

4. Conclusion

This review critically examined the role of Artificial Intelligence in transforming pavement engineering from conventional empirical practices toward data-driven, predictive, and sustainable infrastructure systems. Before full computer vision can be implemented, predictive maintenance will be more and more reliant upon large sensor networks and material optimization, with advanced machine learning algorithms, before full autonomy, as far as assessing conditions on a machine is concerned, is achieved. The deep learning techniques will be used as the basis of the hybrid models that will be applied to the decision-making process, but at the same time, they will include the already known engineering principles. The information that is sent by connected cars and Internet-of-Things (IoT) devices will keep on adding to the real-time monitoring, thus increasing the level of analytics. Lifecycle management also involves adding the necessary adjustments to incorporate climate change to develop truly smart and resilient smart city transportation networks.

4.1. Transformation through AI Integration and the Importance of AI in Smart City Initiatives

AI Incorporation can be interpreted as the next stage of the evolution of the old methods of designing a pavement. It is a way to simplify the process of data modelling and make the decision process more advanced, and consequently enhance the predictive effectiveness. Additionally, artificial intelligence makes it possible to identify the pavement distress directly or any other factors that may affect the choice of materials and their optimization. These attributes complement design processes and entrench central principles of safety, reliability, and long-life span qualities inherent in modern-day pavement systems.

4.2. Life Cycle Management, Lifecycle, and Predictive Maintenance for Sustainability

Predictive maintenance, as well as lifecycle management, provides a potentially fruitful direction of sustainability as informed by AI. Artificial intelligence-based systems have the capacity to significantly increase efficiency and sustainability in infrastructural systems. Predictive maintenance based on an artificial intelligence model can use big data obtained through sensors, drones, and ground-condition measuring devices to predict the impending failure early enough, thus allowing one to choose the most effective maintenance timeframes. This means that there can be better control of maintenance budgets, less redundancy in interventions, nulling of operational disruption, and increasing the service life of pavements.

4.3. Discussion

The integration of Artificial Intelligence (AI) into the smart city programs is gradually transforming the patterns of planning, administration, and supervision of the city infrastructure. Findings of this research show that AI-based solutions, such as predictive analytics, intelligent transportation systems, and automated population service, enhance operational effectiveness significantly and allow enhancing the citizen-centered nature of service delivery. However, AI adoption simultaneously introduces the issues of data quality, interoperability, cybersecurity, and ethical concerns, and urban administrations should take active steps to address them. Also, the discussion highlights the importance of resilient digital infrastructure and high institutional readiness for the success of AI-driven changes.

Despite the powerful potential of AI in the optimization of resources and the improvement of the quality of life, to achieve the long-term effects, inclusive governance systems and long-term capacity-building of stakeholders are necessary. Overall, AI has become a key facilitator of building resilient, effective, and future-proofed smart cities. Although its potential is achievable, it is quite clear that it is the responsible and well-thought-out utilization of AI that can unlock its potential.

The current research highlights the fact that effective life cycle management is the central aspect of long-term sustainability in infrastructure systems. Early identification of performance downturn can be done as a result of combining life cycle assessment and predictive maintenance, which, respectively, helps to reduce unexpected failures and decrease the cost of resources. The analysis also indicates that machine learning based predictor models or data-driven methods can significantly enhance the quality of maintenance planning. Besides extending the lifespan of assets, these methods also enable effective decisions made by the stakeholders at low costs. Furthermore, adherence of the maintenance strategies to sustainability plans helps to reduce the environmental effects by maximizing the utilization of materials, energy usage, and the frequency of the intervention. The study highlights a holistic life cycle viewpoint as a strategy to increase the resilience of a system towards future uncertainties, such as larger loads and stresses brought about by climate. Overall, the paper proves that combining life-cycle thinking and predictive maintenance technology provides an efficient framework for sustainable infrastructure management.

4.4. Future Scope

In the future, the work can be done in hybrid-AI-IoT systems and Intelligent, future-ready pavement systems, which are explained as follows:

4.4.1. Future Considerations of Hybrid-AI-IoT Systems

It has been suggested in future speculation of Hybrid-AI-IoT systems that future innovation will require hybrid designs through a combination of AI-based designs and IoT-compatible devices in a single design. These interacting systems provide real-time sensing, communication, and dynamic response functionalities, hence rendering climate-responsive environmental resilience in pavements. A hybrid AI IoT system can also provide machine learning based decision support planning, which integrates sensor data in order to maximize fault-detection rates and performance modelling.

4.4.2. Intelligent, Future-Ready Pavement Systems

Future-ready and smart pavement systems eventually strive to achieve system-level interconnectivity of AI, IoT, and digital infrastructure management systems. This technological development is meant to allow intelligent, learning, and adaptive pavement systems to undergo real-time performance enhancement. The latter goal is a more generalized gradual movement to data-driven, resilient, and sustainable infrastructure, thus leading to the formation of AI-based smart cities based on ubiquitous sensing systems, real-time performance measurement, and dynamic pattern sensors.

References

[1] Dan Chong, and Yuhong Wang, "Impacts of Flexible Pavement Design and Management Decisions on Life Cycle Energy Consumption and Carbon Footprint," *The International Journal of Life Cycle Assessment*, vol. 22, no. 6, pp. 952-971, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[2] U. Siva Rama Krishna, and Ch. Naga Satish Kumar, "A Case Study on Maintenance of Bituminous Concrete Pavement Considering Life Cycle Cost Analysis and Carbon Footprint Estimation," *International Journal of Construction Management*, vol. 22, no. 9, pp. 1756-1764, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[3] Saurabh Kulkarni, and Mahadeo Ranadive, "Optimizing Perpetual Pavement Design in India: Stabilized Soil and Polymer-Modified Bitumen Approach for Cost and Carbon Efficiency," *Multiscale and Multidisciplinary Modeling, Experiments and Design*, vol. 7, no. 2, pp. 1185-1196, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[4] Brundaban Beriha, and Umesh Chandra Sahoo, "Design of Long-Life Pavements for India," *Recent Developments in Sustainable Infrastructure: Select Proceedings of ICRDSI*, vol. 75, pp. 1061-1070, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[5] B.A. Priyanka, Goutham Sarang, and A.U. Ravi Shankar, "Evaluation of Superpave Mixtures for Perpetual Asphalt Pavements," *Road Materials and Pavement Design*, vol. 20, no. 8, pp. 1952-1965, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[6] S. Gireesh Kumar et al., “Design of a Bituminous Mixture for Perpetual Pavement,” *IOP Conference Series: Materials Science and Engineering, International Conference on Recent Advances in Materials, Mechanical and Civil Engineering*, Hyderabad, India, vol. 330, no. 1, pp. 1-7, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[7] You Huang Sheng Li, and Zhao-hui Liu, “Experimental Evaluation of Asphalt Material for Interlayer in Rigid-Flexible Composite Pavement,” *Construction and Building Materials*, vol. 102, pp. 699-705, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[8] A.R. Parry et al., “Design and Performance of Flexible Composite Road Pavements,” *Proceedings of the Institution of Civil Engineers - Transport*, vol. 135, no. 1, pp. 9-16, 1999. [CrossRef] [Google Scholar] [Publisher Link]

[9] Jun Cai et al., “Comprehensive Service Properties Evaluation of Composite Grouting Materials with High-Performance Cement Paste for Semi-Flexible Pavement,” *Construction and Building Materials*, vol. 153, pp. 544-556, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[10] Xiaoyu Liu et al., “Influence of the Composite Interface on the Mechanical Properties of Semi-Flexible Pavement Materials,” *Construction and Building Materials*, vol. 397, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[11] Thomas Bennert, and Ali Maher, “Evaluation of Current State of Flexible Overlay Design for Rigid and Composite Pavements in the United States,” *Transportation Research Record: Journal of the Transportation Research Board*, vol. 1991, no. 1, pp. 97-108, 2007. [CrossRef] [Google Scholar] [Publisher Link]

[12] Alexa Raffaniello et al., “Traffic and Climate Impacts on Rutting and Thermal Cracking in Flexible and Composite Pavements,” *Infrastructures*, vol. 7, no. 8, pp. 1-19, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[13] I.L. Al-Qadi et al., “Asphalt Portland Cement Concrete Composite: Laboratory Evaluation,” *Journal of Transportation Engineering*, vol. 120, no. 1, pp. 94-108, 1994. [CrossRef] [Google Scholar] [Publisher Link]

[14] David Webb, and Bilal M. Ayyub, “Sustainability Quantification and Valuation. II: Probabilistic Framework and Metrics for Sustainable Construction,” *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering*, vol. 3, no. 3, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[15] Jinli Jiang et al., “A Quantified Methodology for Evaluating Engineering Sustainability: Ecological Footprint Measurement Modeling,” *Buildings*, vol. 14, no. 11, pp. 1-30, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[16] Jingnan Zhao, and Hao Wang, “Machine Learning based Pavement Performance Prediction for Data-Driven Decision of Asphalt Pavement Overlay,” *Structure and Infrastructure Engineering*, vol. 21, no. 6, pp. 940-955, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[17] Mohammad Fahad, and Nurullah Bektas, “Data-Driven Pavement Performance: Machine Learning-based Predictive Models,” *Applied Sciences*, vol. 15, no. 7, pp. 1-26, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[18] Hoang Long Nguyen, and Van Quan Tran, “Data-Driven Approach for Investigating and Predicting Rutting Depth of Asphalt Concrete Containing Reclaimed Asphalt Pavement,” *Construction and Building Materials*, vol. 377, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[19] Rita Justo-Silva, Adelino Ferreira, and Gerardo Flintsch, “Review on Machine Learning Techniques for Developing Pavement Performance Prediction Models,” *Sustainability*, vol. 13, no. 9, pp. 1-27, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[20] Mohammad Z. Bashar, and Cristina Torres-Machi, “Performance of Machine Learning Algorithms in Predicting the Pavement International Roughness Index,” *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2675, no. 5, pp. 226-237, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[21] Mohammadsadegh Fahmani, Amir Golroo, and Mohammad Sedighian-Fard, “Deep Learning-based Predictive Models for Pavement Patching and Manholes Evaluation,” *International Journal of Pavement Engineering*, vol. 25, no. 1, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[22] L. Yao et al., “A Multi-Agent Reinforcement Learning Model for Maintenance Optimization of Interdependent Highway Pavement Networks,” *Computer-Aided Civil and Infrastructure Engineering*, vol. 39, no. 19, pp. 2951-2970, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[23] Moein Latifi et al., “A Deep Reinforcement Learning Model for Predictive Maintenance Planning of Road Assets: Integrating LCA and LCCA,” *arXiv Preprint*, pp. 1-26, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[24] Jianqi Kang et al., “Artificial Intelligence Techniques for Pavement Performance Prediction: A Systematic Review,” *Road Materials and Pavement Design*, vol. 26, no. 3, pp. 497-522, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[25] Febri Zukhruf et al., “Reinforcement Learning-Based Model for Road Network Maintenance and Rehabilitation Programming Considering Flood Occurrences,” *International Journal of Pavement Engineering*, vol. 26, no. 1, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[26] Yang Xu, and Zhanmin Zhang, “Review of Applications of Artificial Intelligence Algorithms in Pavement Management,” *Journal of Transportation Engineering, Part B: Pavements*, vol. 148, no. 3, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[27] Pedro Marcelino et al., “Machine Learning Approach for Pavement Performance Prediction,” *International Journal of Pavement Engineering*, vol. 22, no. 3, pp. 341-354, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[28] Saúl Cano-Ortiz, Pablo Pascual-Muñoz, and Daniel Castro-Fresno, “Machine Learning Algorithms for Monitoring Pavement Performance,” *Automation in Construction*, vol. 139, pp. 1-16, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[29] Wanen Feng et al., "Vertical Planning and Optimization Strategies of Green Measures in Urban Flood Control: Combining Automated Land Use Segmentation with Integrated Hydrodynamic Calculations," *Water Research*, vol. 287, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[30] Qi Yang, Wei Tian, and Xiaomin Dai, "Machine Learning-based Highway Pavement Performance Prediction in Xinjiang," *Infrastructures*, vol. 10, no. 7, pp. 1-19, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[31] Ali Bahadori-Jahromi et al., "The Role of Artificial Intelligence and Machine Learning in Advancing Civil Engineering: A Comprehensive Review," *Applied Sciences*, vol. 15, no. 19, pp. 1-52, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[32] Taba Nyokum, and Yamem Tamut, "Artificial Intelligence in Civil Engineering: Emerging Applications and Opportunities," *Frontiers in Built Environment*, vol. 11, pp. 1-8, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[33] Youqin Huang, Jiayong Li, and Jiyang Fu, "Review on Application of Artificial Intelligence in Civil Engineering," *Computer Modeling in Engineering and Sciences*, vol. 121, no. 3, pp. 845-875, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[34] Dimitrios Sargiotis, "Advancing Civil Engineering with AI and Machine Learning: From Structural Health to Sustainable Development," *International Journal of Architecture and Planning*, vol. 4, no. 2, pp. 54-81, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[35] Can Li et al., "A Bibliometric Analysis and Review on Reinforcement Learning for Transportation Applications," *Transportmetrica B: Transport Dynamics*, vol. 11, no. 1, pp. 1-40, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[36] Saeed Nosratabadi et al., "State of the Art Survey of Deep Learning and Machine Learning Models for Smart Cities and Urban Sustainability," *International Conference on Global Research and Education*, Balatonfüred, Hungary, vol. 1, pp. 228-238, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[37] Lauren McMillan, and Liz Varga, "A Review of the Use of Artificial Intelligence Methods in Infrastructure Systems," *Engineering Applications of Artificial Intelligence*, vol. 116, pp. 1-21, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[38] Bhattraradej Boonsap Witchayangkoon et al., "A Deliberation on Modern AI-Driven Research within Civil Engineering," *International Transaction Journal of Engineering, Management, and Applied Sciences and Technologies*, vol. 16, no. 1, pp. 1-21, 2025. [Google Scholar] [Publisher Link]

[39] Samir Ali Amin, and Ahmed Sady Salman AL-Kubaisi, "Importance of Artificial Intelligence in the Engineering Applications: A Review," *Al Rafidain Journal of Engineering Sciences*, vol. 3, no. 1, pp. 431-449, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[40] Mahmmoud Al-Subieh, "Evaluation of Textured Concrete as an Alternative for Stone as a Cladding Material," *Journal of Civil Engineering and Architecture*, vol. 18, pp. 199-205, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[41] Mohammad Saleh Dashti et al., "Integrated BIM-based Simulation for Automated Time-Space Conflict Management in Construction Projects," *Automation in Construction*, vol. 132, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[42] Rituraj Jain et al., "Data-Driven Civil Engineering: Applications of Artificial Intelligence, Machine Learning, and Deep Learning," *Turkish Journal of Engineering*, vol. 9, no. 2, pp. 354-377, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[43] Md Eshrat E. Alahi et al., "Integration of IoT-Enabled Technologies and Artificial Intelligence (AI) for Smart City Scenario: Recent Advancements and Future Trends," *Sensors*, vol. 23, no. 11, pp. 1-36, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[44] Taner Cokyasar, and Jeffrey Larson, "Optimal Assignment for the Single-Household Shared Autonomous Vehicle Problem," *Transportation Research Part B: Methodological*, vol. 141, pp. 98-115, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[45] Alaa Al Hawarneh, Salaheddine Bendak, and Firas Ghanim, "Dynamic Facilities Planning Model for Large Scale Construction Projects," *Automation in Construction*, vol. 98, pp. 72-89, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[46] Lele Zheng et al., "Deep Learning-based Intelligent Detection of Pavement Distress," *Automation in Construction*, vol. 168, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[47] Gargi Joshi, Rahee Walambe, and Ketan Kotecha, "A Review on Explainability in Multimodal Deep Neural Nets," *IEEE Access*, vol. 9, pp. 59800-59821, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[48] Patricia Gomes Rêgo de Almeida, Carlos Denner dos Santos, and Josivania Silva Farias, "Artificial Intelligence Regulation: A Framework for Governance," *Ethics and Information Technology*, vol. 23, no. 3, pp. 505-525, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[49] Hafiz Usman Ahmed et al., "Technology Developments and Impacts of Connected and Autonomous Vehicles: An Overview," *Smart Cities*, vol. 5, no. 1, pp. 382-404, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[50] Michael Batty, "Digital Twins," *Environment and Planning B: Urban Analytics and City Science*, vol. 45, no. 5, pp. 817-820, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[51] Spiros Kapetanakis, and Daniel Kudenko, "Reinforcement Learning of Coordination in Heterogeneous Cooperative Multi-Agent Systems," *Adaptive Agents and Multi-Agent Systems II. Adaptation and Multi-Agent Learning*, Leeds, United Kingdom, vol. 1, pp. 119-131, 2005. [CrossRef] [Google Scholar] [Publisher Link]

[52] Gaurav Tamrakar, and A. Surendar, "AI-Driven Big Data Framework for Climate-Resilient Transportation Infrastructure," *Journal of Smart Infrastructure and Environmental Sustainability*, vol. 2, no. 1, pp. 38-44, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[53] Sten Sundin, and Corinne Braban-Ledoux, "Artificial Intelligence-based Decision Support Technologies in Pavement Management," *Computer-Aided Civil and Infrastructure Engineering*, vol. 16, no. 2, pp. 143-157, 2001. [CrossRef] [Google Scholar] [Publisher Link]

[54] Kai Guo et al., "Artificial Intelligence and Machine Learning in Design of Mechanical Materials," *Materials Horizons*, vol. 8, no. 4, pp. 1153-1172, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[55] Gerardo W. Flintsch et al., "*Asphalt Materials Characterization in Support of Implementation of the Proposed Mechanistic-Empirical Pavement Design Guide*," Virginia Center for Transportation Innovation and Research, Technical Reports, Civil and Environmental Engineering: Technical Reports (VTTI), pp. 1-45, 2007. [Google Scholar] [Publisher Link]

[56] Yong Deng, "*Artificial Intelligence-based Inverse Analysis of Flexible Pavement Deteriorations under Moving Loads*," Dissertations & Theses, Texas A&M University, pp. 1-12, 2020. [Google Scholar] [Publisher Link]

[57] Gonzalo R. Rada, "*Pavement Structural Evaluation at the Network Level: Final Report*," Federal Highway Administration Research and Technology: Coordinating, Developing, and Delivering Highway Transportation Innovations, 2016. [Google Scholar] [Publisher Link]

[58] Orhan Kaya et al., "Statistics and Artificial Intelligence-based Pavement Performance and Remaining Service Life Prediction Models for Flexible and Composite Pavement Systems," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2674, no. 10, pp. 448-460, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[59] Fang Liu et al., "Effective Keyword Search in Relational Databases," *SIGMOD '06: Proceedings of the 2006 ACM SIGMOD International Conference on Management of Data*, Chicago, IL, USA, pp. 563-574, 2006. [CrossRef] [Google Scholar] [Publisher Link]

[60] Ibeawuchi Matthew Ebika et al., "Utilizing Machine Learning for Predictive Maintenance of Climate-Resilient Highways through Integration of Advanced Asphalt Binders and Permeable Pavement Systems with IoT Technology," *International Journal of Innovative Science and Research Technology (IJISRT)*, vol. 9, no. 11, pp. 69-89, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[61] Mohammed Ali Younus Alqasi, Youssif Ahmed Mohamed Alkelanie, and Ahmed Jamah Ahmed Alnagrat, "Intelligent Infrastructure for Urban Transportation: The Role of Artificial Intelligence in Predictive Maintenance," *Brilliance: Research of Artificial Intelligence*, vol. 4, no. 2, pp. 625-637, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[62] Tiago Tamagusko, Matheus Gomes Correia, and Adelino Ferreira, "Machine Learning Applications in Road Pavement Management: A Review, Challenges and Future Directions," *Infrastructures*, vol. 9, no. 12, pp. 1-32, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[63] Moncef L. Nehdi, *Artificial Intelligence Applications for Sustainable Construction*, 1st ed., Elsevier, 2024. [Google Scholar] [Publisher Link]

[64] Muhammad Nasir Amin et al., "Low-Carbon Embodied Alkali-Activated Materials for Sustainable Construction: A Comparative Study of Single and Ensemble Learners," *Reviews on Advanced Materials Science*, vol. 63, no. 1, pp. 1-15, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[65] M. Abdellatief et al., "Carbon Footprint Reduction and Performance Optimization of Sustainable Free Cement Concrete with Eggshell Powder and Rice Husk Ash using Machine Learning," *International Journal of Sustainable Development and Science*, vol. 7, no. 1, pp. 195-213, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[66] Jérôme Dinet, Monik Favart, and Jean-Michel Passerault, "Searching for Information in an Online Public Access Catalogue (OPAC): The Impacts of Information Search Expertise on the Use of Boolean Operators," *Journal of Computer Assisted Learning*, vol. 20, no. 5, pp. 338-346, 2004. [CrossRef] [Google Scholar] [Publisher Link]

[67] Mohamed Alloghani et al., *A Systematic Review on Supervised and Unsupervised Machine Learning Algorithms for Data Science*, Supervised and Unsupervised Learning for Data Science, Springer, Cham, pp. 3-21, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[68] Hind Alaskar, and TanzilaSaba Saba, "Machine Learning and Deep Learning: A Comparative Review," *Proceedings of Integrated Intelligence Enable Networks and Computing: IIENC*, pp. 143-150, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[69] Sai Krishna Chaitanya Tulli, "Technologies that Support Pavement Management Decisions through the Use of Artificial Intelligence," *International Journal of Modern Computing*, vol. 5, no. 1, pp. 44-60, 2022. [Google Scholar] [Publisher Link]

[70] Saadeddine Ramadan et al., "Incorporating Artificial Intelligence Applications in Flexible Pavements: A Comprehensive Overview," *International Journal of Pavement Research and Technology*, pp. 1-26, 2024. [CrossRef] [Google Scholar] [Publisher Link]