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REVIEW

Environmental Stewardship in Civil Infrastructure: A Comprehensive Review of AI Applications in Road and Bridge Engineering

Yi Su [1,2]

[1] College of Road and Bridge Engineering, Guizhou Communications Polytechnic University, Guiyang 551400, China

[2] Guizhou Key Laboratory of Intelligent Construction and Maintenance of Mountain Bridge and Tunnel, Guiyang 551400, China

ABSTRACT

The road and bridge infrastructure systems are also among the most resource-intensive systems in the built environment, which produce massive environmental impacts on their life cycles. Civil infrastructure environmental stewardship must therefore demand decision-making methods that are no longer limited to the static analysis of sustainability, but rather to the adaptive and data-driven management of long-lived resources. Recent innovations in artificial intelligence (AI) can provide transformative potential to facilitate this transition by making predictions, optimization, and continuous monitoring in the process of planning, design, construction, operation, maintenance, and end-of-life stages. The article is a comprehensive review of AI applications that promote environmental stewardship in road and bridge engineering. The review combines the state-of-the-art approaches, which involve AI in combination with the life-cycle assessment, digital twins, sensing systems, and asset management systems to minimize greenhouse gas emissions, energy consumption, material use, waste, and ecosystem disruption. The focus is specifically on the way AI advances environmentally responsible planning and design, low-impact construction delivery, predictive and network-level maintenance approaches, and circular end-of-life approaches. The review also explores cross-cutting issues to do with the quality of data, model transferability, interpretability, governance, and equity that impact the practical efficacy of AI-based stewardship. This article forms a systematic basis for future research and implementation by categorizing the current research on environmental impact

*CORRESPONDING AUTHOR:

Yi Su, College of Road and Bridge Engineering, Guizhou Communications Polytechnic University, Guiyang 551400, China; Guizhou Key Laboratory of Intelligent Construction and Maintenance of Mountain Bridge and Tunnel, Guiyang 551400, China; Email: zzzqh95831@163.com

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domains, life-cycle stages, and AI methods. The results show how AI can transform the infrastructure management system into a proactive, measurable, and robust environmental custodianship, as well as the requirement of interconnected systems, reliable models, and institutional preparedness.

Keywords: Artificial Intelligence; Environmental Stewardship; Road Infrastructure; Bridge Engineering; Life-Cycle Sustainability

1. Introduction

Modern societies are supported by civil infrastructure systems that define the mobility of people, economic productivity, and social connectivity [1]. Road and bridge networks are among these systems and some of the longest-lived and resource-intensive engineered assets on the planet. Their benefits in society can never be disputed, but their impact on the environment in terms of planning, design, construction, operation, maintenance, and end of their life is significant. The emission of greenhouse gases through the production of materials and construction, the use of energy in operation, effects on water and ecosystems, land use, noise, and waste generation all put road and bridge infrastructure at the center of environmental management in the built environment [2–4].

Environmental stewardship of civil infrastructure is not a process confined to adherence to environmental regulations or the attainment of sustainability objectives with a very limited set of definitions. It includes a life-cycle and holistic responsibility to reduce undesirable environmental effects, maximize resource efficiency, safeguard ecosystems, and increase long-term system stability, while still fulfilling functional and societal needs. In road and bridge engineering, this stewardship issue is especially complicated because the infrastructural networks are large, the service life of assets can be long, and one cannot be sure of the traffic demand and climate conditions in the future, and the environment, economy, and social performance goals are interconnected [5].

In the last 20 years, there has been a tremendous advancement in the attempt to measure environmental effects using tools like life cycle assessment (LCA), life cycle cost analysis (LCCA), as well as multi-criteria decision analysis. There have been rating systems and guidelines on sustainable infrastructure that have promoted sustainable practices. Nevertheless, these methods can be based on simplified assumptions, steady-state analyses, and small datasets that may limit their usefulness in capturing the dynamic and system-level dynamics of infrastructure-environment interactions. In addition, road and bridge engineering, more often than not, requires trade-offs between conflicting goals such as cost, safety, durability, user effects, and environmental performance, which cannot be addressed solely through conventional analytical tools [6–8].

Recent innovations in artificial intelligence are the sources of transformational opportunities to overcome these restrictions and reinvent the way in which environmental stewardship is practiced in civil infrastructure. The accelerated increase in the amount of data, such as remote sensing, unmanned aerial vehicles, Internet of Things (IoT) sensors, structural health monitoring systems, traffic detectors, and digital design platforms, has led to a data-rich environment that is ideally suited to AI-based analysis. Simultaneously, machine learning, deep learning, reinforcement learning, and hybrid physics-informed AI models have emerged and now offer much better predictive, optimization, pattern recognition, and decision support applications to complex engineering systems [9].

The field of road and bridge engineering has already seen AI have some potential in areas like automated state evaluation, traffic forecasting, construction productivity modeling, and optimization of asset management. More and more such applications are being associated with environmental goals, such as the minimization of embodied carbon by optimization of materials, cost reduction of construction by intelligent scheduling, reduction of operational emissions through enhanced traffic flow, and an increase in the service life of the assets to prevent unplanned and expensive rehabilitation. With the addition of life-cycle thinking and digital twins, AI can transform environmental stewardship into a more proactive, adaptive, and continuously optimized management approach than the rather retrospective evaluation approach it is [10,11].

In spite of this increased interest, the literature that exists on the application of AI in road and bridge engineering is still patchy in regard to environmental stewardship. Most studies are specifically dedicated to independent tasks—predicting pavement deterioration or optimization of construction logistics without directly presenting results in relation to environmental performance or stewardship goals. On the other hand, studies focused on sustainability tend to use AI as an auxiliary analytical tool and do not systematically investigate the role of various AI approaches in various life-cycle phases and in various environmental impact categories. Consequently, a synthesis, which links AI methods, phases of infrastructure life-cycles, and environmental stewardship objectives within one framework, is deficient [12].

Additionally, critical issues are yet to be solved. These are data quality and representativeness, regional and asset type transference of AI models, explanativeness and credibility of AI-based recommendations, and linking of environmental metrics to conventional engineering performance measures. Higher governance and ethical factors can also be noted, e.g., transparency in AI-assisted decisions, consistency with regulatory frameworks, and that environmental gains are fairly distributed within communities [13].

It is in this context that it is time and need to conduct a thorough examination of how AI can be applied in the field of environmental stewardship in road and bridge engineering. This kind of review can help to explain the state of the art, determine the best practices and constraints, and draw out research gaps that need to be filled in order to make it possible to adopt it on a large scale and in the real world. Notably, it can also aid in changing the discourse of considering AI as a collection of discrete technical instruments into realizing it as an empowering technology for environmentally responsible infrastructure systems [10,12,14].

This review has threefold objectives. First, it will attempt to methodically assess the application of AI methods throughout the life cycle of road and bridge infrastructure, such as planning and design, construction, operation, maintenance, rehabilitation, and end-of-life, with special attention paid to the results of environmental stewardship. Second, it aims to classify and group such applications based on areas of environmental impact, scopes of decisions (asset-level versus network-level), and AI methodologies types used. Third, it determines the main challenges, gaps in knowledge, and research avenues in the future concerning data integration, robustness of models, governance, and the integration of AI with life-cycle sustainability assessment models [15–17]. To frame the review, **Figure 1** presents a life-cycle stewardship concept in which AI functions as a cross-cutting enabler linking assessment, optimization, monitoring, and adaptive decision-making.

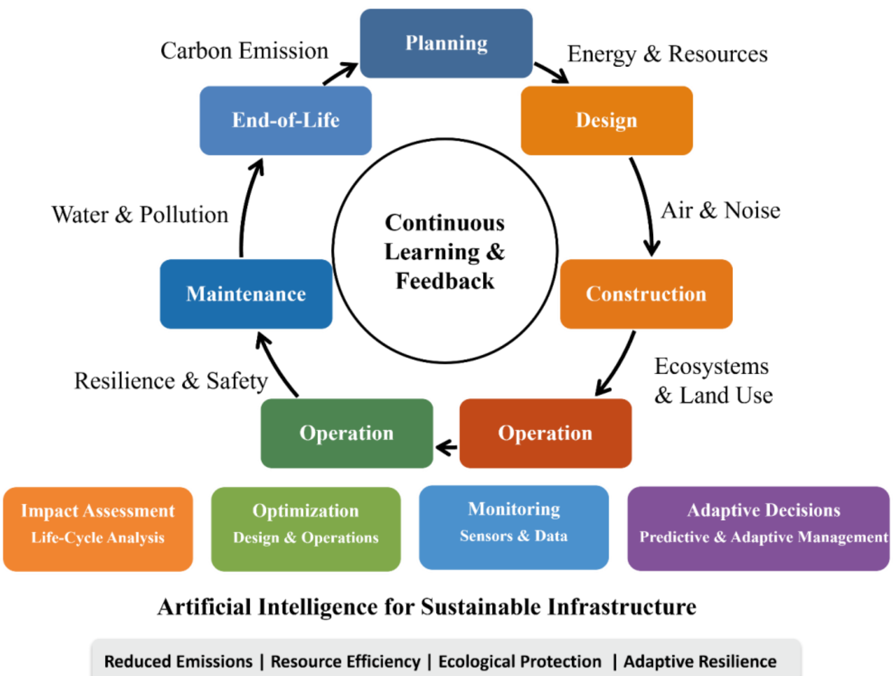

Figure 1. Conceptual framework for AI-enabled environmental stewardship in road and bridge infrastructure across life-cycle stages, impact domains, and decision feedback loops.

This review includes both pavements and bridges, which include concrete, steel, and composite systems, and also covers infrastructure on the project level, corridor level, and network level. Such environmental dimensions are, but not restricted to, greenhouse gas emissions, energy consumption, material consumption and circularity, water quality, air quality, noise, land use, and ecosystem-impacts. Although the review focuses on the methodological developments and uses of AI, institutional and policy contexts that shape the use of AI-enabled stewardship strategies are also addressed [18].

The rest of this paper is presented in the following ways. Section 2 presents the conceptual bases of environmental stewardship in road and bridge engineering and assessment frameworks that are frequently applied, and data ecosystems that are utilized in AI applications. Section 3 examines AI-based strategies to consider environmentally responsible planning and design. Section 4 is devoted to the AI use in the construction process and delivery of projects to minimize the environmental load. Section 5 focuses on the AI-empowered policies related to sustainable operation, maintenance, rehabilitation, and the end-of-life. Lastly, Section 6 summarizes the major findings, reflects upon their implications to researchers and practitioners, and identifies the future directions in the direction of AI-enabled, environmentally responsible civil infrastructure systems [19].

2. Environmental Stewardship Frameworks and Assessment Methods for Roads and Bridges

The idea of environmental stewardship in road and bridge engineering is based on the understanding that the infrastructure systems have long-term and multidimensional impacts on both the natural environment and the human environment. In contrast to traditional project-level environmental management, stewardship focuses on life-cycle accountability, systems thinking, and the ongoing alignment of the engineering choices to the performance targets of environmental performance. The section provides the conceptual basis of environmental stewardship of civil infrastructure and examines the main assessment frameworks and indicators applied to measure environmental effects, as well as discusses the data environments that can be used to apply artificial intelligence throughout the infrastructure life cycle [5,20,21].

2.1. Conceptual Foundations of Environmental Stewardship in Civil Infrastructure

Environmental stewardship in the road and bridge engineering context is far more than the conventional understanding of sustainability, which is, in most cases, viewed as a means of balancing the environmental, economic, and social aspects at any given moment in time. Stewardship refers to a proactive process of maintaining infrastructure assets in a manner that reduces cumulative environmental degradation and maintains or increases system functionality throughout longer service lives. This point of view applies specifically to roads and bridges that are usually in service for several decades and have numerous stages of maintenance, renovation, and adaptation [5,22].

One of the conceptual characteristics of stewardship is the implementation of life-cycle thinking. Environmental effects on infrastructure assets do not just occur during the construction process but are experienced during the extraction and processing of materials, transportation, construction, operation, maintenance, and even during the decommissioning or reuse of the infrastructure assets. The fact that decisions in early stages of planning and design may bind environmental impacts over decades highlights the need to have stewardship considerations in the initial stages. Moreover, stewardship has to think in systems terms, taking into consideration relationships between infrastructure assets, users, and environments. As an example, the design of pavements has not only material-related emissions but also impacts on vehicle fuel use and noise emissions during use, whereas bridge maintenance strategies can also have an impact on the traffic flows and air quality effects at the network level [23].

The other notable feature of environmental stewardship is that it is closely associated with resilience and adaptability. Climate change, changing mobility patterns, and technological changes bring major uncertainty to the long-term infrastructure performance. The management systems that are stewardship-oriented are aimed at foresight of any such uncertainties and are designed to accommodate them by preferring innovative, long-lasting, versatile, and resource-effective solutions that minimize the chances of failures or premature replacements with environmental implications of high cost. In this context, AI is becoming seen as a facilitating technology that will assist in adaptive decision-making by helping to derive actionable insights on complex and constantly changing datasets [24,25].

2.2. Environmental Impact Categories and Performance Indicators

Environmental stewardship is an acquired process that demands the ability to identify, quantify, and compare the environmental impacts of road and bridge infrastructure. These effects lie within a wide range of categories and also work through various spatial and temporal scales. The most outstanding issues include greenhouse gas emissions and embodied carbon, which are mainly attributed to the manufacturing of construction products like cement, steel, and asphalt products, and the use of construction machinery and the consumption of energy in the form of traffic. Since transportation infrastructure is a significant portion of the world's emissions, the carbon intensity decrease nowadays has become a primary goal in the modern road and bridge construction business [26,27]. The multiple categories of impacts involved in road and bridge engineering environmental stewardship need to have regular indicators to assess and compare. **Table 1** summarizes the critical stewardship dimensions, indicators that represent them, and the stages of the life-cycle where the impacts generally build up.

Table 1. Environmental stewardship dimensions and representative impact categories and indicators for road and bridge infrastructure across the life cycle.

Stewardship Dimension	Impact Category	Representative Indicators	Typical Life-Cycle Stages
Climate change	Greenhouse gas emissions	Embodied carbon (kg CO_2), operational emissions (kg CO_2/year)	Design, construction, operation
Energy efficiency	Energy consumption	Fuel use, electricity demand, vehicle energy intensity	Construction, operation
Materials and resources	Resource use and circularity	Material quantities, recycled content, reuse rate	Design, construction, end-of-life
Water environment	Water quality and quantity	Runoff pollutant load, sediment yield, water use	Construction, operation
Air and noise	Local environmental quality	NO_x, $PM_{2.5}$, noise levels	Construction, operation
Ecosystems and land use	Biodiversity and habitat	Land take, habitat fragmentation	Planning, construction

The issue of energy consumption is a closely related category of impact, as it includes direct construction energy and energy consumption in maintenance, as well as indirect energy consumption in terms of the interaction of vehicles and infrastructures. The roughness of the pavement, structural deflection, and strategies of managing the traffic may all affect the fuel consumption of the vehicles and consequently operational emissions. Another important impact caused by water is the effects on roads, whereby the runoff would carry sediments, heavy metals, hydrocarbons, and deicing chemicals to the receiving water bodies. Construction and renovation of bridges can also have further impact on the aquatic ecosystems by in-water development, as well as the change of flow regimes [28,29].

Another dimension of environmental stewardship of great importance is material consumption, waste, and circularity. High volumes of raw materials are used in creating roads and bridges, and their maintenance produces huge amounts of waste. There has consequently been a growing interest in the use of recycled and reclaimed materials, durable design, and end-of-life methods, which can reuse materials instead of disposing of them. Another category of impacts is air pollutants, including nitrogen oxides (NO_2 and NO_3) and particulate matter, which are caused by traffic and construction work, land-use transformation, and biodiversity and habitat connectivity [30,31].

In order to deal with these various effects, various performance indicators have been formulated, such as carbon intensity per functional unit, use of energy per lane-kilometer or vehicle-kilometer traveled, loadings of pollutants in the runoff, garbage diversion rates, and measures of ecological disturbance. Although these metrics could give valuable insights, they tend to be interdependent and can have trade-offs, hence integrative assessment methods that would be able to assist in making balanced decisions.

2.3. Assessment and Decision-Support Frameworks

Life cycle assessment has become a keystone approach to the quantification of the environmental effects of road and bridge structures. LCA offers a systematic framework of design alternatives comparison and hotspots of impacts through the consideration of material and energy flows at all life-cycle phases. Attributional and consequential LCA have been used in infrastructure settings and the method used affects the management of the system boundaries, functional units, and time impacts. Although it has its strong sides, standard LCA may be a data-intensive and computationally expensive method, especially when used on a large network, or when uncertainty and variability are explicitly incorporated [32].

Life cycle cost analysis and more comprehensive life-cycle sustainability assessment models are the complements to LCA that combine the economic and, in certain instances, the social aspects with environmental performance. The principles of stewardship have been further operationalized in terms of rating systems and guidelines of sustainable infrastructure, which offer systematic criteria and benchmarks. These tools are, however, usually based on fixed scoring systems, and they might be unable to reflect dynamic interactions, e.g., alterations in traffic demand or weather conditions over time [33].

Multi-criteria decision analysis has hence been extensively embraced to facilitate infrastructure decision-making on competing objectives. MCDA allows explicitly relating the trade-offs between the cost, performance, risk, and environmental impacts, yet its usefulness is sensitive to the quality of the input data and the transparency of the weighting schemes. In this respect, AI can improve assessment and decision-support systems by increasing the speed of simulations, discovering multifaceted relationships between variables, and facilitating the analysis based on scenarios in the face of uncertainty. The effects on the environment come in an interrelated way that cuts across material production, construction activities, and operational impacts [16,34–36]. **Figure 2** summarizes these pathways and demonstrates how this assessment framework relates to decision-making, where AI can be used to estimate faster and do additional scenario exploration.

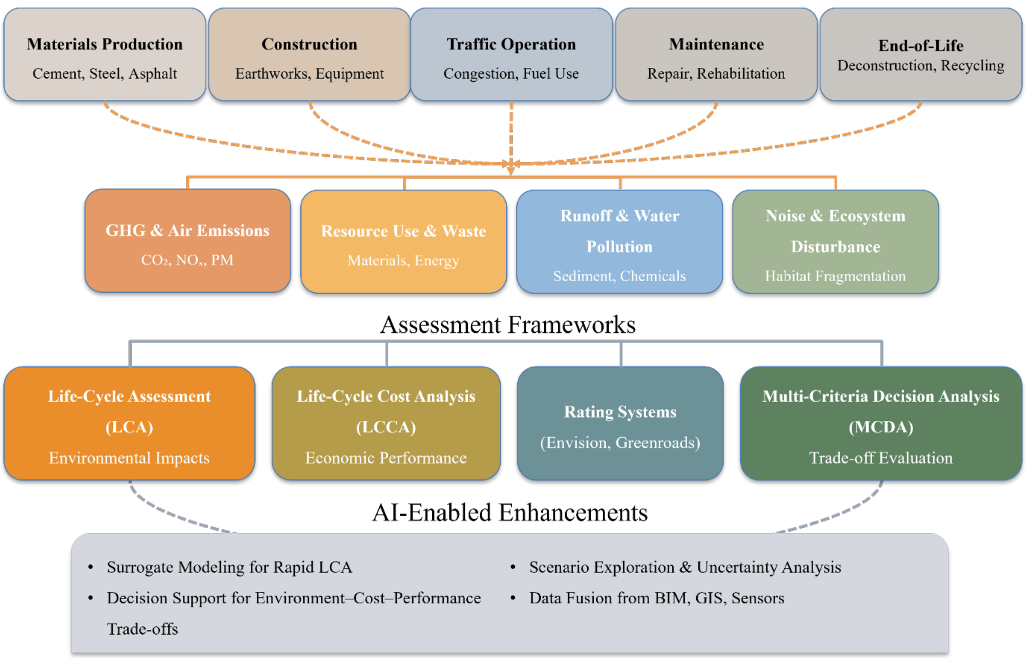

Figure 2. Environmental impact pathways in road and bridge infrastructure and their linkage to assessment frameworks (e.g., LCA/LCC/MCDA), highlighting points where AI accelerates estimation and supports uncertainty-aware decisions.

2.4. Data Ecosystems Supporting AI-Enabled Stewardship

The presence and quality of data are the cornerstones of the implementation of AI to environmental stewardship in the road and bridge engineering field. The data sources on infrastructure systems have been growing at a very fast rate in recent years. Satellite imagery and unmanned aerial vehicles are remote sensing technologies that enable the delivery of information with high resolution to determine the use of the land, construction work, and environmental factors. Ground sensing and monitoring systems measure structural response, vehicle movement, pavement conditions, and other environmental conditions including temperature, moisture, and even pollutant levels [37].

Similarly, the growing use of building information modeling, geographic information systems, and asset management systems has helped to combine geometric, material, operational, and historical information across the infrastructure life cycles. These digital environments are the basis of AI-driven analysis and decision support when integrated with external datasets responding to climatic, hydrologic, and socio-economic conditions.

Though these advances have taken place, there are still major challenges. The infrastructure datasets are commonplace in being heterogeneous, incomplete, and gathered at varying spatial and temporal levels. An old system might be incompatible with other systems, and data sharing can be obstructed by the problem of data governance connected to the ownership, privacy, and cybersecurity. Overcoming these obstacles is a precondition of achieving the full potential of AI in assisting environmental stewardship [38].

2.5. Role of AI within Environmental Stewardship Workflows

In a stewardship-based infrastructure management, AI may be considered as a cross-cutting capability, that is, it improves, but does not substitute, current assessment and decision-making processes. The stewardship workflows with the help of AI are supported by separate methodological families, which vary in the requirements of data, understandability, and decision domains. **Table 2** provides a general description of common families of AI techniques, their general functions, and the manner in which they advance environmental stewardship goals. Surrogacy Machine learning models can also be used to replace computationally costly simulations, so that the environmental impacts of the planning and design can be quickly evaluated. Pattern recognition and anomaly detection methods would help in the round-the-clock observation of construction and operational processes to enable the timely detection of environmentally damaging situations. The exploration of strategies that are cost-effective and involve both environmental performance and safety, as well as serviceability at the asset and network level, can be facilitated through optimization and reinforcement learning techniques [4,10,12].

More importantly, transparency, interpretability, and accountability are also questioned in the context of the integration of AI in the stewardship workflows. Civil infrastructure decisions on the environment are frequently regulatory and social in nature, and require explainable, accurate, and reliable AI systems. In this regard, the issue of AI as a kind of environmental stewardship should be perceived as a part of a more comprehensive socio-technical framework encompassing engineering judgment, institutional structures, and societal values.

Table 2. Overview of AI technique families, typical functions, data sources, and stewardship contributions in road and bridge engineering.

AI Technique	Typical Functions	Data Sources	Stewardship Contributions
Supervised machine learning	Prediction, regression, classification	Inspection data, material properties, traffic data	Impact prediction, performance forecasting
Deep learning	Image and signal interpretation	UAV imagery, video, sensor signals	Automated condition and impact detection
Reinforcement learning	Sequential decision-making	Asset states, network performance	Optimized maintenance and operation strategies
Optimization algorithms	Multi-objective optimization	Design variables, constraints	Low-carbon and resource-efficient solutions
Hybrid physics–AI models	Data-enhanced simulation	Mechanistic models and monitoring data	Improved robustness and interpretability

To conclude, the conceptual frameworks, assessment methods, and data infrastructures assist in environmental stewardship in road and bridge engineering in a variety of ways. AI provides strong means to improve such aspects, although its potential will be achieved through consideration of life-cycle thinking, strong data ecosystems, and transparent decision-making. The subsequent paragraphs expand on the idea by looking at the application of AI at certain life-cycle phases to support the goals of environmental stewardship [39].

3. AI for Environmentally Responsible Planning and Design

The environmental performance of the road and bridge infrastructure is largely influenced by planning and design choices over the long term. Decisions made during these preliminary phases define alignment, form, type, and quantity of materials, and design life, and, as a result, shape environmental effects that continue through the construction, operation, maintenance, and end-of-life stages [40]. Since such decisions are frequently made in circumstances of uncertainty and with little time to analyse them in greater depth, there have been difficulties in traditional methods in integrating the goals of environmental stewardship into normal engineering. The recent developments in artificial intelligence open up new possibilities of helping in environmentally responsible planning and design through the possibility to explore alternative options based on data, quickly evaluate the impact of the selected options, and optimize multiple and competing goals systematically. Since decision levers and environmental impacts are different at different life-cycle stages, a systematic mapping can be used to explain the areas in which AI can produce the most stewardship advantages [41,42]. In **Table 3**, the main environmental advantages of representative AI applications have been identified and attached to each stage of the life-cycle.

Table 3. Mapping of AI applications to infrastructure life-cycle stages and primary environmental stewardship benefits for roads and bridges.

Life-Cycle Stage	Representative AI Applications	Primary Environmental Benefits
Planning	Corridor optimization, spatial impact screening	Reduced land-use and ecosystem disturbance
Design	Low-carbon material optimization, durability modeling	Lower embodied emissions, longer service life
Construction	Equipment scheduling, logistics optimization	Reduced fuel use, emissions, and waste
Operation	Traffic prediction and control	Lower congestion-related emissions
Maintenance	Predictive deterioration modeling	Reduced material use and intervention frequency
End-of-life	Deconstruction planning, material reuse	Enhanced circularity, waste reduction

3.1. AI-Assisted Corridor Planning and Alignment Optimization

During the planning phase, land use, ecosystems, and emissions over a long duration are seriously threatened by the choice of road corridors and bridge sites. Corridor planning, Interactive Geospatial analysis using AI has progressively been utilized to aid the planning of corridors with high and heterogeneous data, such as topography, land cover, protected habitats, hydrology, population distribution, and existing infrastructure. Machine learning models are able to discover spatial patterns and sensitivities that are hard to represent in traditional rule-based methods and allow planners to cull alignment options with regard to environmental constraints and cumulative effects [43].

AI-inspired optimization algorithms have been applied further to formulate and screen alignment options to reconcile engineering and construction costs against environmental disruption. The planning tools based on AI enable making environmental custodianship factors first-order design drivers and not post hoc controls by integrating environmental requirements, including earthwork volumes, habitat fragmentation, and proximity to sensitive receptors, directly into objective functions. This would be especially useful on regional and corridor scales, whose environmental impact of alignment choices is far-reaching beyond the scope of single projects [44].

3.2. Low-Carbon Structural and Pavement Design

The design of structures and pavements is a significant opportunity to decrease the embodied carbon and resource usage in road and bridge infrastructure. The AI has been used more widely to simulate complex relationships in design variables, material properties, structural performance, and environmental impacts. Machine learning analysis of large datasets of structural configuration and material choices in bridge engineering has been utilized to predict metrics of performance (load capacity, durability, service) immediately, without having to search and identify low-material-intensity solutions, without compromising safety or functionality [45].

The use of AI-based generative design and topology optimization methods has also broadened the design space already by generating structurally efficient shapes that use a minimum of materials. These methods, combined with environmental indicators like embodied carbon or energy intensity, enable designers to clearly aim at environmentally efficient structural systems. AI-based optimization of mix designs has been used in pavement engineering to optimize the contents of recycled materials and alternative binders, and methods of construction, to support the implementation of low-carbon and circular materials approaches without compromising the performance standards [46,47].

Similarly, AI applications have been used to design concrete mixtures and curing techniques to simulate the blend of additional cementitious substances, curing environment, strength progress, and durability. These strategies will make it easier to use alternative materials that have a smaller ecological footprint to achieve more sustainable bridge and pavement systems by minimizing the use of trial-and-error testing.

3.3. Integration of AI with Life-Cycle Environmental Assessment in Design

Another consistent issue with the environmentally responsible design is the implementation of the life-cycle environmental assessment in the early design. Traditional LCA processes tend to be prohibitively time-consuming and data-intensive to be used in an iterative fashion in the planning and preliminary design. Surrogate models of AI have a potential solution by estimating life-cycle environmental effects according to the main design parameters and materials. These models make it possible to assess the alternatives quickly and make sensitivity analysis that helps to see the drivers of environmental performance [48].

With the integration of AI-powered LCA tools into digital design systems, i.e., building information modeling and parametric design systems, it is possible to provide environmental feedback in near real-time as design parameters vary. This has empowered designers to take into account environmental impact as well as structures and economic standards that promote a more holistic approach to stewardship. Furthermore, AI solutions can be used to help in uncertainty analysis, as it learns based on past data and predict a diversity of future environments, such as changes in the traffic demand, maintenance planning, and weather conditions [49,50].

3.4. Design for Durability, Adaptability, and Circularity

Planning and design Environmental stewardship is closely associated with the capability of the infrastructure assets to provide long service life with minimum intervention. Durability models based on AI have been used to model the deterioration processes of materials like fatigue, corrosion, and material degradation, which enables designers to assess the long-term effects of various design decisions. ANI-based design solutions may prefer solutions that minimize the number of resource-intensive repairs and other environmental effects by accounting for maintenance requirements and the likelihood of a solution failing [51].

Circularity and flexibility have also become relevant areas of design. It is possible to use AI tools to analyze design strategies that can be used in the future to adjust to shifting requirements or climate environments, e.g., modular construction or higher structural redundancy. Moreover, AI-assisted tracking of materials and information in the design process can provide the basis of end-of-life reuse and recycling since the components and materials could be traced. These abilities make design choices consistent with the wider goals of the circular economy, and not limited only to first-time construction [52].

3.5. Governance, Transparency, and Equity in AI-Driven Design Decisions

Although AI can provide potent tools to improve environmental performance across the planning and design processes, there are specific issues of governance that can arise due to its application. The AI-driven analyses should not be arbitrary in design decisions, especially in cases of environmental compliance, population investment, and community results. This can sabotage the application of the black-box models that make recommendations without providing any explanation, since they would not be trusted and adopted in regulating and professional areas.

Equity is also being considered as an aspect of environmental stewardship. Planning tools that are in AI should take into consideration the distribution of environmental impacts and benefits to various communities without creating a situation where vulnerable communities are overburdened. It is then crucial to make sure that AI models are trained on representative data and their assumptions are publicly shared. In this wider system of governance, AI must be perceived as an aiding, not a substituting, tool to professional judgment and stakeholder engagement [53].

To conclude, AI in planning and design has tremendous potential to entrench the environmental stewardship concepts at the earliest and most impactful phases of road and bridge design. With the ability to explore the options in a holistic way, evaluate the environmental effects quickly, and clearly address the lifecycle and circularity, AI-based solutions can assist in changing the approach of infrastructure design to more sustainable and responsible results. The next part of this paper looks at the extension of these principles to the construction phase, where AI can further put environmental strains off its shoulders with smart implementation and monitoring policies.

4. AI in Construction and Delivery for Reduced Environmental Burden

Construction and delivery of road and bridge projects is a stage of focused environmental influence, with high consumption of materials, significant amounts of energy, emissions from construction machines, and local disruptions of the community and the ecosystem. Although this stage is not very long compared to the operational life of infrastructure objects, its impact on the environment is large and, in most cases, very noticeable. Consciousness of the environment during construction thus aims at reducing emissions, wastes, and environmental disturbance without compromising on the safety, quality, and schedule performance. The use of artificial intelligence has become a potent facilitator of these goals because it assists in data-driven planning, real-time monitoring, and adaptive control of the construction process [54].

4.1. Optimization of Construction Energy Use and Emissions

The construction works depend on diesel-fueled machines and thus emit a lot of greenhouse gases and air pollution. The conventional methods of construction planning often focus on cost and schedule performance with very little or no regard for the environmental performance. The intelligence of the AI-based optimization methods has started to fill this gap by simulating the interaction between equipment choice, sequence of tasks, productivity, and energy usage. By utilizing machine learning models that have been trained using historical project data, it is possible to predict fuel consumption and emissions in alternative construction situations to allow the contractors and agencies to determine alternative low-impact strategies to use during the planning process [55].

The AI-based scheduling and dispatch systems can dynamically optimize the use of equipment during execution in order to minimize idle time and inefficient operation. These systems facilitate real-time decision-making by combining data on telematics, GPS, and onsite sensors to ensure productivity goals are met in a way that does not negatively impact environmental stewardship. The growing number of electric and hybrid construction machines also broadens the scope of AI in the management of the energy source and the charging habits, which will lead to the minimization of emissions and noise [56].

4.2. AI-Enabled Materials Sourcing, Transportation, and Logistics

The environmental impacts of construction, attributed to materials production and transportation, are large. The use of AI in logistics and supply chain management has been promising in ensuring these effects are minimized by using AI to optimize sourcing plans, transportation paths, and delivery timetables. Trade-offs between the cost of materials, embodied carbon, supplier reliability, and the distance between suppliers and customers can be assessed with machine learning and optimization algorithms, and could be used to make more informed procurement choices based on environmental concerns [57].

Transportation optimization is especially applicable to the large-scale road and bridge projects in which the material deliveries are frequent. Routing algorithms based on AIs can reduce the distance traveled, prevent congestion, and deliveries to mitigate emissions and disruption. Moreover, computer vision and sensor-based AI systems are also employed to measure the quality of various materials onsite, such as the recycled aggregates and reclaimed asphalt grading. These technologies will ensure that more people embrace circular construction by enhancing the trust in the functionality of substitute materials.

4.3. Waste Reduction and Circular Construction Practices

Construction waste is a liability to the environment as well as a loss of resource exploitation. In road and bridge construction, AI has been used to enhance the estimation of waste, segregation, and reuse. Waste generation forecasting: Predictive models allow the generation of waste through design and construction parameters in order to plan to reuse and recycle the material. These models enhance the more precise cut and fill balancing of earthworks and lessen the requirement of off-site disposal and importation of virgin materials.

In situ, computer vision systems based on AI have been used to track the movement of materials and detect waste minimization options. The automatic sorting of waste streams contributes to the more effective separation and reuse of waste, whereas the behavioral changes within construction crews can be supported with the help of real-time feedback. When incorporated into the construction management systems as capabilities, AI helps in transforming linear material practices into circular practices when delivering the project [58].

4.4. Environmental Monitoring, Compliance, and Impact Mitigation

Unless well managed, construction activities have a negative impact on air quality, water resources, noise levels, and adjacent habitats. The use of periodic inspection and manual reporting has always been used as a means of environmental monitoring, and this method might not be effective in detecting problems early enough. The AI-enhanced surveillance systems are more proactive because they constantly examine the data provided by sensors, cameras, and remote sensing modes [59].

Machine learning will be able to identify irregularities in turbidity, dust levels, or noise levels, and give early alerts to take timely corrective measures. AI methods based on images of drones or fixed cameras can detect erosion, sediment transportation, and intrusion into restricted regions. These potentials can enhance adherence to environmental laws and minimize the chances of accidents that have environmental and reputational implications [60].

4.5. Digital Twins and Construction-Phase Stewardship

The idea of digital twins has become more popular as the tool of incorporating design, construction, and environmental data into one form of expression of infrastructure projects. AI-based digital twins can be used during construction to integrate real-time data on the progress, resource consumption, and the situation on the ground to aid in the making of informed decisions. Digital twins offer a clear platform of stewardship-driven project management by connecting construction activities to environmental performance metrics such as the quantity of emissions or the quality of water [61].

By ensuring constant monitoring of environmental effects in comparison with the project targets and regulatory obligations, such systems enable this. Another benefit that they provide in terms of post-construction learning is that they generate comprehensive documentation of construction processes and consequences that could be used in future projects and enhance the precision of AI models. With the advanced digital twin technologies, their application together with AI is set to dominate in realizing the concept of environmental stewardship when delivering infrastructure [62].

4.6. Challenges and Opportunities in AI-Driven Construction Stewardship

Although the advantages of using AI as an environmental steward in construction are proven, the realization of this industry suffers from a number of challenges. The integration of data between and among equipment, contractor, and regulatory systems is still complicated, and the accuracy of AI predictions is based on access to quality context-specific data. Implementation can also be limited by organizational barriers such as resistance to change and lack of technical capacity [63].

However, the construction phase presents a special occasion to implement the stewardship objectives into concrete positive changes in the environment through smart implementation. With the future advancement of more automated data collection and increased availability of AI tools, the possibilities of environmentally optimized construction practices are bound to increase. The second section builds on this debate with the operation, maintenance, and end-of-life phases, in which long-term performance of environmental assets and networks can be assisted by the AI on both assets and networks.

5. AI for Sustainable Operation, Maintenance, Rehabilitation, and End-of-Life

The operation life cycle provides a higher number of years and a cumulative environmental impact of road and bridge infrastructure. Environmental impacts during this stage are not only caused by the daily maintenance and rehabilitation activities but also through the traffic operations, congestion, and user behavior that is partially caused by the condition and management strategies of the infrastructure. Operation and maintenance environmental stewardship thus necessitates a long-term, system perspective that provides balance between asset performance, user impact, resource efficiency, and resilience to changing demands and climatic changes. Artificial intelligence is at the heart of facilitating such a view through supporting continuous eyeing, foreseeable analytics, and optimized selection through infrastructure systems [64].

5.1. AI-Enabled Condition Assessment and Predictive Maintenance

The correct and timely monitoring of the pavement and bridge conditions is the basis of environmentally responsible management of assets. The conventional types of inspection are usually manual, intermittent, and subjective in nature, and this may result in slow interventions and economically expensive repairs. Computer vision-driven AI-based condition assessment, especially with sensor data, has greatly improved the possibility to detect and measure the distress mechanisms of cracking, spalling, corrosion, and deformation.

With the help of machine learning models, it is possible to predict deterioration patterns and remaining life estimates with greater precision by learning trends on large sets of images and sensor measurements. These predictions allow the maintenance interventions to be planned at the most optimum time within the environment without causing premature rehabilitation and also without causing extreme deterioration that would necessitate costly remedies. With this, predictive maintenance with the help of AI leads to a direct impact on environmental stewardship by increasing the asset life and decreasing materials use and emissions in the long term [65].

5.2. Network-Level Optimization of Maintenance and Rehabilitation Strategies

Although the asset level interventions have significant roles to play, the performance of road and bridge systems in the environment is eventually settled on the network level. The choice on when and where to spend maintenance and rehabilitation resources has not only an agency emissions and cost impact, but also user impacts like congestion, detours, and related vehicle emissions. AI-based optimization models have also been used more to help in network-level planning to assess huge sets of intervention strategies within budgetary, performance, and environmental limits.

Reinforcement learning and more advanced optimization methods enable infrastructure managers to investigate adaptive maintenance policies that can reduce the environmental impact of the life-cycle and achieve acceptable degrees of service. The methods could consider the connection existing between assets, traffic, and the effects of work-zone, which will enable staged interventions that minimize recurring disturbances and wasteful material utilization. The network optimization artificial intelligence supports aims to align the asset management practices with the stewardship goals by explicitly introducing environmental goals to the traditional performance metrics [66].

5.3. Traffic Operations and User-Related Environmental Impacts

The state of infrastructure and its management are heavily reflective on traffic processes and, therefore, emissions of vehicles, noise, and air quality. Traffic management applications of AI have been applied since the beginning of time to enhance efficiency and safety, and when environmental metrics are explicitly taken into account, these applications can play a key role in environmental stewardship. Traffic prediction and control systems based on AI will be able to minimize congestion and stop-and-go situations, which are the primary sources of fuel consumption and emissions [67].

The AI-based work-zone management can be utilized during the maintenance and rehabilitation activities to optimize lane closures, signal timing, and traveler information to reduce the emissions caused by congestion. Through synchronization of infrastructure interventions and traffic management, agencies are able to mitigate the indirect environmental effects that the users and the local communities will realize. This integration demonstrates the significance of thinking about the user behavior and system dynamics as an environmentally responsible way of operating infrastructure [68].

5.4. Climate Adaptation and Resilience-Oriented Stewardship

Climate change brings new factors of sustainable functioning of road and bridge infrastructure, such as the increased number of extreme temperatures, floods, and other dangers, which speed up the process of deterioration and disturb the service. Climate impact models and hazard prediction models based on AI have become useful in anticipating such challenges and proactive adaptation strategies. Through the analysis of both the historical climate data and the future predictions, the machine learning models can be used to define assets and network segments that are especially susceptible to climate-related stressors [69].

The integration of such inferences in maintenance and rehabilitation planning facilitates offering stewardship because the risk of emergency repair and catastrophic breakdown is minimized, which is normally linked with high environmental costs. Resilience planning provided through AI, therefore, complements conventional environmental goals to advance sustainable and flexible structures of infrastructures that can sustain varied environments without the need to spend a lot of resources.

5.5. End-of-Life Management and Circular Infrastructure Practices

There are significant environmental impacts on the end-of-life decision on road and bridge assets, including the decommissioning, replacement, and major rehabilitation. AI may assist in making end-of-life management more sustainable by comparing the trade-offs between alternative strategies as strengthening versus replacement or phased rehabilitation versus full reconstruction. With machine learning that builds on past project information, there are possible emissions, material, and service disruptions that can be predicted between various alternatives, which can inform stewardship-based decision-making [70,71].

AI is also having a new role in facilitating circular infrastructure at the end of life. Individual components can be selectively deconstructed and reused with the help of automated material identification and condition assessment technologies, and recycling and reuse routes can be optimized with the help of data-driven logistics models. AI helps in minimizing waste and embodied emissions due to the need to renew infrastructure by enabling the recovery of materials of higher value.

5.6. Performance Evaluation and Continuous Improvement

Operational and maintenance environmental stewardship is a continuous process that needs to be evaluated and learnt. The AI-powered analytics can help the agencies track the performance indicators of the environment over time, evaluate the performance of the implemented strategies, and improve models and policies based on the outcomes. The adaptive management provided by feedback loops with the help of AI enables the infrastructure systems to react to the changing conditions and newly developed knowledge.

Nevertheless, the implementation of such advantages hinges on access to high-quality data, unified measures of performance, and institutional capability to capitalize on AI-generated information and take action. With the continued adoption of AI in infrastructure management systems, transparency, robustness, and accountability will be even more important in ensuring that trust is not lost and that the ultimate goal of becoming a long-term environmental steward is attained [5].

In short, the use of AI-enabled solutions regarding operation, maintenance, rehabilitation, and end-of-life management can provide considerable possibilities to decrease the overall environmental costs of road and bridge infrastructure. AI assists in making long-term infrastructure management decisions consistent with the notion of environmental stewardship by aiding predictive, network-level, and resilience-focused decision-making. The final part, the synthesis part, brings together the observations made throughout the infrastructure life cycle and the future research and practice directions of the fast-changing discipline. **Figure 3** illustrates adaptive asset management of long-term environmental stewardship under traffic and climate uncertainty, closed-loop, AI-assisted, and based on monitoring, deterioration forecasting, network optimization, intervention choice, and performance assessment. The issue of scaling AI-enabled stewardship[72–74]. Translating AI-enabled stewardship. Viewing it as a solution to these repeated technical and governance pitfalls is crucial to enable knowledge, both within the research prototype and practice, ready to scale[75–78]. **Table 4** consolidates main categories of challenges, their implication on implementation, and high-priority research directions.

Figure 3. Closed-loop, AI-supported adaptive asset management for long-term environmental stewardship, integrating monitoring, deterioration prediction, network optimization, intervention selection, and performance evaluation under traffic and climate uncertainty.

Table 4. Cross-cutting challenges, practical implications, and research directions for AI-enabled environmental stewardship in road and bridge infrastructure.

Challenge Category	Description	Implications for Practice	Research Directions
Data availability and quality	Fragmented, incomplete, or biased datasets	Limited model reliability and transferability	Standardized data frameworks and benchmarks
Model transparency	Black-box AI models	Reduced trust and regulatory acceptance	Interpretable and physics-informed AI
Scalability	Project-level focus	Difficulty achieving network-level impact	Portfolio-scale and system-level models
Governance and equity	Uneven distribution of impacts	Risk of environmental injustice	Equity-aware and accountable AI frameworks
Integration	Disconnected tools and platforms	Inefficient decision workflows	AI-enabled digital twins and LCA integration

6. Conclusion

The capacity to treat infrastructure systems as long-lasting, resource-intensive socio-technical resources whose environmental effects spanning decades are gradually accumulated is becoming characteristic of environmental stewardship in the field of road and bridge engineering. The current review has integrated the fast-growing list of AI applications that facilitate the stewardship goals of infrastructure life cycle, including initial planning and design as well as delivery of construction, long-term operation and maintenance, and end-of-life choices. The main value proposition of AI remains the same throughout these phases: it allows the stakeholders of the infrastructure to shift their approach to the environment and environmental assessment to a proactive, data-driven, and adaptive approach to decision-making that can significantly decrease emissions, resource use, environmental disruption, and pollution and maintain safety, reliability, and service quality.

During the planning and design phases, AI increases the range of possible solutions and also speeds up the computation of alternative solutions because it considers geospatial constraints, performance-based determinism, and environmental metrics throughout the lifecycle. AI may be integrated into digital processes to facilitate the selection of materials with less carbon footprint, more material-efficient structures, and structures that are designed to be more durable and flexible. During the construction period, AI progresses stewardship, which streamlines the utilization of equipment and logistics, enhances the quality of alternative materials and recycling, and facilitates continuous monitoring of the environment to avoid accidents and mitigate local effects. When used in operation and maintenance, AI-based condition evaluation, condition-based prediction models, and network-optimization strategies can be applied to increase service-life, rank interventions to maximize the reduction of environmental burdens during the life-cycle, and minimize emissions of users in the form of congestion and work zones. Lastly, during end-of-life management, AI may reinforce rationale towards a more circular approach, enhance traceability in materials, selective deconstruction through AI, and improve the reuse and recycling route pathways.

The main lesson gained throughout this review is that the environmental advantages of AI can hardly be traced to an individual algorithm or application. The most significant funding returns to stewardship instead come about when AI becomes part of the end-to-end workflows, joining assessment frameworks, operational data streams, and decision processes. Often, this means that AI-led stewardship will be just as reliant as model accuracy on institutional preparedness, data governance, and interoperability. It is also a field that is moving into a new stage where system integration can play the most significant role: bridging AI with life-cycle assessment, digital twins, and asset-management offerings; harmonizing models with regulatory reporting and procurement, and making feedback mechanisms to continually quantify the environmental outcome and maximize decisions as time goes by.

Along with impressive improvements, there are a number of issues that limit the transfer of research prototypes into scalable, reliable stewardship tools. Limitations to data are still underpinning, with incomplete coverage of data, variation in standards among agencies, inadequate coverage of a range of climates and materials, and poor access to information about construction and maintenance processes. Another obstacle that still persists is model transferability because AI systems trained in a specific region or asset class might not reliably generalise to others unless they are customised.

To translate the identified challenges into actionable guidance, we propose a structured, three-tier research agenda that explicitly links each priority to gaps documented in earlier sections. High-priority (0–3 years): (i) Develop interoperable data platforms and standardized benchmarks for model validation, directly addressing the data fragmentation and transferability gaps noted in Sections 2.4 and 3.5; (ii) advance interpretable and physics-informed AI to meet regulatory requirements for transparency and accountability, responding to concerns raised in Sections 4.6 and 5.6; (iii) establish life-cycle performance benchmarks that integrate embodied carbon, operational emissions, and resilience metrics into unified functional units, filling gaps identified in Sections 2.2 and 3.3. Medium-priority (3–7 years): Create scalable network-level optimization frameworks and equity-aware governance models to prevent environmental injustice, building on discussions in Sections 3.5 and 5.2. Long-term priority (7–10 years): Achieve fully integrated AI-digital twin-LCA platforms for autonomous, closed-loop stewardship, as envisioned in Section 5.6. This agenda provides a clear, gap-linked roadmap for researchers and practitioners to advance AI-enabled environmental stewardship in road and bridge engineering.

The future studies and practice should then focus on five interrelated directions. To begin with, stewardship-oriented AI needs to be more coherently provided with life-cycle, system-level performance definitions that integrate the embodied impacts, operational effects, and resilience-related effects within harmonious functional units and decision levels. Second, it requires strong data ecosystems with standards of interoperability in BIM, GIS, monitoring systems, asset management databases, as well as protocols of data quality assurance, privacy, and cybersecurity. Third, there should be methodological innovations that focus on trustworthy AI, which consists of interpretable models, physics-informed learning, uncertainty quantification, and bias and model drift protection. Fourth, the field ought to come up with benchmarks and validation practices that are indicative of real-world deployment conditions, which can be compared among methods and provide an assurance of transferability. Fifth, more focus should be on implementation routes, such as workforce development, procurement processes, which promote performance and low-carbon choices, and legal systems that help understand who is responsible in case AI affects environmental and operational results.

To sum up, AI may not replace good engineering judgment or solid environmental policy. It serves to supplement human decision-making by converting fragmented information into actionable information and by facilitating exploration of trade-offs of complexities at previously impractical scales. Considerably applied together with life-cycle assessment, digital delivery, and asset management, AI has the potential to assist road and bridge systems to shift to a new paradigm of stewardship, a paradigm of continuous learning, quantifiable environmental responsibility, and adaptive resilience in the event of uncertainty. This paradigm will necessitate interdisciplinary effort comprising engineers, data scientists, environmental experts, and government departments, as well as long-term data infrastructure and data governance investment. All these in place, AI-enabled environmental stewardship will become a viable and effective way to mitigate the environmental footprint of the civil infrastructure, and protect the societal good that the roads and bridges deliver.

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