

# Enhancing Road Freight Transportation Sustainability: A Review of Optimisation Methods and Industry

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## Abstract

Considering the relation of global importance of reducing the increases in greenhouse gases being detailed in the environmental study, RFT's contribution to the deficiency of energy and environmental decay in modern world single handedly becomes the focus of study. Sustainability in Road Freight Transport is analysed using the country level and intercontinental level framework, distinguishing more than 400 peer reviewed works in the base. Legally binding obligations between 2014 English Civil Aviation and 2023 are classified in the peer reviewed works vis-a-vis the environmental and social factors upon multi-level interconnect. The findings indicate a deep-rooted focus on strategic research efforts directed towards enhancement of public health vis-a-vis enhancement of emission control in conjunction with the cost-effective logistical frameworks. The goals of alternative fuelling, modern logit strategic and modern intermodal transport of connected goals, community level of impacts and counter impacts, sustaining a balance between space assets and global interconnect transcend to being inter principal base decadence of transcend level. With further research and revision, the outcomes of modern intermodal transport supported with IoT, AI, and telematic level blockchain and Fleet Engineering 4.0 planning on inter-modal transport road networks will increase the effectiveness and increase the road transport systems of the country vis a vis border country net. The research work over strategic planning will help practitioners, inter, country border, and area planners in easy planning, soft logic building and enlighten the inter country border.

**Keywords:** *Road freight transportation, Optimization models, Industry 4.0 technologies, Transportation sustainability, Environmental factors, Logistics efficiency, green supply chain, Alternative fuels*

## Introduction

The urgency of reducing greenhouse gas emissions has made sustainability in road freight transport (RFT) a global priority. As one of the largest contributors to energy consumption and environmental degradation, RFT directly influences both national and international sustainability agendas. Research at country and intercontinental levels has highlighted not only the economic role of freight transport but also its environmental and social implications, particularly in relation to public health and emission control. Recent advancements in alternative fuels, intermodal transport strategies, and digital technologies such as IoT, AI, telematics, and blockchain are reshaping freight systems into more efficient, cost-effective, and environmentally responsible networks. This evolving framework positions RFT as a critical domain for policymakers, planners, and practitioners working towards sustainable infrastructure and resilient logistics for the future. Whiteing, A., and Piecyk, M. (2021) [1] – Green Logistics: Improving the Environmental Sustainability of Logistics. This book explores the concept of green logistics, focusing on methods to reduce the environmental footprint of transportation and supply

chain operations. It discusses key strategies such as improving fuel efficiency, reducing carbon emissions, optimizing delivery routes, and integrating renewable energy into logistics systems. The authors also address challenges in balancing economic performance with sustainability goals, highlighting case studies from major logistics firms that have successfully implemented green initiatives.

Sun, D., et al. (2021) [2] – Usage of I4.0 Technologies in Logistics Sustainability This study investigates how Industry 4.0 (I4.0) technologies—such as the Internet of Things (IoT), Artificial Intelligence (AI), Big Data analytics, and autonomous systems—can enhance the sustainability of logistics operations. It demonstrates how digitalization enables real-time tracking, predictive maintenance, and demand forecasting, which collectively improve resource efficiency and reduce environmental impacts. The paper emphasizes the transformative potential of smart technologies in achieving sustainable logistics networks.

Lu, J., et al. (2023) [3] – Emission Reductions from Heavy-Duty Freight Electrification Aided by Smart Fleet Management, Lu and colleagues analyze the environmental and operational benefits of electrifying heavy-duty freight vehicles. The study combines data-driven modeling with smart fleet management strategies, such as optimized routing and charging schedules, to assess potential emission reductions. Their findings show that electrification, when supported by intelligent logistics planning, can significantly lower greenhouse gas emissions and improve overall fleet efficiency. The paper provides a practical framework for transitioning to sustainable freight systems.

Iasef Md Rian and Mario Sassone (2014) [4] – Fractal-Based Generative Design of Structural Trusses Using Iterated Function System. *International Journal of Space Structures*, Vol. 29, This paper presents a novel approach to structural design that uses fractal geometry and iterated function systems (IFS) to generate truss structures. The method mimics patterns found in nature, creating complex yet efficient geometries that optimize material use while maintaining structural stability. The authors demonstrate how fractal-based algorithms can generate lightweight yet strong structural frameworks, making this approach valuable for architecture and engineering design optimization.

G. Díaz, et al. (2021) [5] – Applications of Generative Design in Structural Engineering. Díaz and colleagues provide a comprehensive review of generative design techniques within structural engineering. The paper highlights how algorithmic and computational design tools are transforming the way engineers approach optimization problems. Applications discussed include topology optimization, material reduction, and automated form finding. The study underscores generative design's ability to produce innovative, performance-driven solutions that are both sustainable and cost-effective.

O. Peckham, et al. (2025) [6] – Artificial Intelligence in Generative Design: A Structured Review. This structured review focuses on how Artificial Intelligence (AI) is revolutionizing the generative design process. It examines the integration of machine learning, reinforcement learning, and deep learning algorithms into design workflows. The authors discuss AI's role in automating complex design iterations, improving design quality, and enabling adaptive solutions based on performance feedback. The paper also outlines future challenges, including data quality, model transparency, and computational cost.

Amin Heyrani Nobari and Faez Ahmed (2021) [7] – Deep Generative Models in Engineering Design: A Review. This review paper explores deep generative models—including Generative Adversarial Networks (GANs) and Variational Autoencoders (VAEs)—and their application in engineering design. The authors discuss how these models can learn design patterns from existing datasets and generate new, optimized design alternatives. Applications span across product design, aerodynamics, structural optimization, and materials science. The study highlights how deep generative methods enable innovation through data-driven creativity and rapid design iteration.

Sida Dai and Mostafa Alani (2025) [8] – Bio-Generative Design Morphology with Radiolaria: An Application of a

Nature-Based Generative Shape Grammar for Geometrical Design of Space Frames. Vol. 27. Dai and Alani's research presents a bio-inspired generative design framework based on the geometry of Radiolaria—microscopic marine organisms known for their intricate lattice-like structures. The study introduces a nature-based shape grammar that translates biological forms into architectural and structural design systems, particularly for space frames. This approach bridges biology, computation, and design, showing how natural morphologies can inform efficient, aesthetically appealing engineering solutions.

Iasef Md Rian and Mario Sassone (2014) [9] – Fractal-Based Generative Design of Structural Trusses Using Iterated Function System. *International Journal of Space Structures*, Vol. 29. It reiterates the importance of using fractal algorithms in creating structural designs that mirror natural growth patterns. The method enhances design creativity, reduces material waste, and produces lightweight yet strong structural systems suitable for both architectural and civil engineering applications'. Díaz et al. (2021) [10], This paper reviews how generative design methods are used in structural engineering to create optimized, efficient, and innovative structures. It explains how algorithms and computational tools can automatically generate multiple design alternatives based on performance criteria such as strength, weight, and material use. The authors highlight applications like topology optimization, parametric modeling, and form-finding, showing how these techniques improve sustainability and reduce construction costs'. Peckham et al. (2025) [11], This study provides a structured overview of how artificial intelligence (AI) enhances generative design processes. It explores how AI algorithms—especially machine learning, deep learning, and reinforcement learning—can automate design exploration, evaluate performance outcomes, and optimize complex geometries. The review discusses AI's role in making generative design faster, more adaptive, and capable of producing designs that are both efficient and innovative.

## Implementation

### i. Implementation of AI and Automation in Construction

The implementation of Artificial Intelligence (AI) within construction projects, as outlined as follows a cyclical framework that begins with knowledge acquisition and proceeds through application, assessment, and refinement. At the core of this cycle is the integration of AI-driven tools into sustainable construction engineering management (SCEM). For instance, Building Information Modelling (BIM) and digital twins enable real-time monitoring of energy efficiency, carbon emissions, and structural integrity. Implementation involves creating virtual models that simulate construction processes, allowing project managers to optimize material use, reduce waste, and enhance worker safety.

Another key aspect of implementation is project management automation (PMA), where algorithms are used to predict costs, durations, and quality outcomes. By embedding AI into project management workflows, contractors can forecast delays, detect errors through computer vision, and adjust resource allocations dynamically. These practices require substantial digital infrastructure, including IoT sensors on worksites, cloud-based data platforms, and predictive analytics tools. Despite challenges such as high costs and data security concerns, the integration of AI into construction offers measurable benefits, including reduced environmental footprint and improved operational efficiency.

### ii. Implementation of Generative Design in Structural Engineering

Rusi and Allia (2025) demonstrate how generative design principles can be implemented to optimize the seismic performance of reinforced concrete (RC) structures. The implementation strategy relies on parametric design tools such as Grasshopper and Dynamo, which allow engineers to create iterative design models without requiring traditional coding expertise. These visual programming platforms enable engineers to manipulate structural parameters such as column dimensions, orientations, and stiffness while algorithms like Simulated Annealing search for optimal configurations that minimize torsional effects.

The implementation workflow begins with defining structural constraints (seismic loads, material properties, and architectural requirements) and encoding them into the generative design platform. The algorithm then generates multiple iterations, each evaluated for performance metrics such as torsional eccentricity, displacement, and stress distribution. By automating this process, engineers avoid the trial-and-error methods that traditionally consume significant time and resources. The application of APIs (Application Programming Interfaces) further extends the implementation, allowing engineers to connect structural analysis software like ETABS with parametric design platforms. This ensures that results from finite element analysis (FEA) can directly inform the optimization process. The implementation benefits are evident in both the design phase and construction execution. In practice, generative design allows engineers to produce structurally efficient plans that use fewer materials while maintaining resilience against seismic activity. Moreover, these tools foster collaboration between architects and engineers, bridging the gap between creative design and structural performance.

### iii. Implementation of Optimization and Industry 4.0 in Freight Transportation

The implementation of sustainable freight strategies requires both mathematical optimization and the adoption of Industry 4.0 (I4.0) technologies. As highlighted in the review on road freight transportation, the process begins with the classification of sustainability factors—environmental (emission reduction, fuel efficiency), social (public health, community impacts), and economic (cost efficiency, fleet modernization). Optimization models, such as linear programming, mixed-integer programming, and metaheuristic algorithms, are then applied to logistics problems such as route selection, vehicle scheduling, and load consolidation.

The implementation of I4.0 technologies enhances these models by providing real-time data. For example, IoT-enabled telematics systems track vehicle performance and fuel consumption, while blockchain platforms secure logistics data, ensuring transparency in supply chains. Artificial Intelligence can analyse this data to optimize fleet operations dynamically, recommending alternative routes to reduce congestion and emissions. Additionally, digital twins of logistics networks allow companies to simulate scenarios such as fuel price fluctuations or regulatory changes, helping decision-makers plan sustainable strategies.

For implementation at the industry level, companies need investment in smart infrastructure, regulatory incentives, and cross-border cooperation. Pilot projects that combine optimization algorithms with IoT-based fleet monitoring have already demonstrated reductions in fuel consumption and improved delivery reliability. Long-term implementation,

however, requires scaling these systems, integrating alternative fuels, and ensuring interoperability across transport modes.

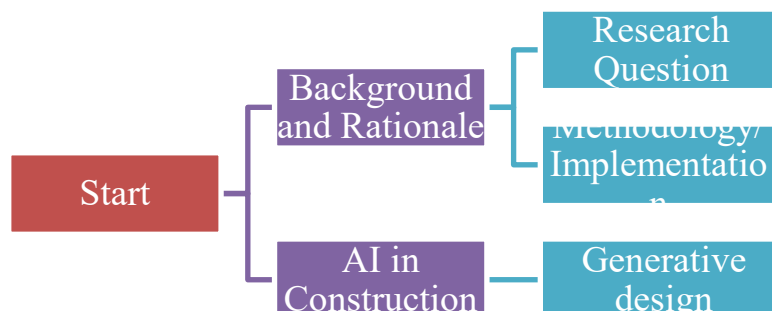
#### iv. Implementation of Fractal and Fractional Theories in Geotechnical Engineering

Geotechnical engineering has traditionally relied on deterministic models to predict soil-structure interaction, but recent advances show how fractal and fractional theories can be implemented to enhance predictive accuracy. Implementation involves replacing classical models of soil mechanics with fractional calculus-based formulations, which account for the heterogeneity and anisotropy of soils. These models allow for better representation of non-linear behaviour such as settlement, consolidation, and shear strength.

In practice, implementation requires collecting high-resolution geotechnical data through laboratory testing and in-situ monitoring. This data is then fitted into fractal models that describe pore distribution, permeability, and particle aggregation. By embedding fractional differential equations into numerical simulations, engineers can predict soil responses under various load conditions with greater accuracy than classical methods. The implementation also extends to tunnelling, slope stability analysis, and foundation design, where complex soil behaviour often challenges conventional approaches. The practical benefit of implementing fractal and fractional theories lies in their ability to reduce overdesign. By providing more realistic predictions, these models minimize the tendency to use excessive material safety margins, leading to cost savings and more sustainable use of resources.

#### v. Implementation of Safety and Rehabilitation Methods in Bridge Engineering

The Galecopper Bridge case study illustrates how implementation of safety frameworks and monitoring systems can extend the lifespan of critical infrastructure. The project began with a detailed corrosion assessment of locked coil cables, followed by the development of a bridge-specific traffic model. Implementation required the integration of Weigh-in-Motion (WIM) data with finite element models, simulating the effects of heavy traffic loads on the corroded cables. This approach allowed engineers to determine safe load limits and prioritize cable replacements without closing the bridge entirely. Another key element of implementation was the use of measured permanent loads within pylons and cables to refine Ultimate Limit State (ULS) verifications. By continuously reassessing baseline assumptions as construction progressed, the project team was able to adapt safety measures dynamically. This iterative process illustrates a broader implementation principle: infrastructure rehabilitation requires both real-time monitoring and adaptive planning.



**Figure 1:** Research Framework for AI in Construction and Generative Design

**Step 1: Background and Rationale** This section is included to provide context and justification for the study. Why is the research necessary? What problems currently exist in the construction industry? How will the problems you identified be solved with the help of AI? Review of available literature and identified gaps.

**Step 2: Research Question** This section is derived from the background and serves to define the core question or problem statement. Example: “In what ways will AI-driven generative design enhance the efficiency of construction?” It narrows the focus of the research.

**Step 3: Methodology/Implementation** This section describes the research design. What data will be used? What tools or software will be used? How is AI going to be used in the construction context? This may also describe some case studies or pilot projects.

**Step 4: AI in Construction** This section describes the various uses of Artificial Intelligence in the construction industry. Such as: Project scheduling and forecasting Risk management Robotics and automation Quality control and safety monitoring.

**Step 5: Generative Design** A subsection under "AI in Construction" that focuses more on AI-powered generative design tools. These tools use algorithms to offer a wide variety of design alternatives. Architects and engineers receive optimized layouts of buildings for planning, and improved material use, and cost reduction are achieved. This is used primarily in the initial stages of construction planning.

### **Summary**

The study focuses on the sustainability of Road Freight Transport (RFT) in the context of global efforts to reduce greenhouse gas emissions. Using both national and international frameworks and analysing over 400 peer-reviewed studies, it examines how energy inefficiency and environmental degradation in modern freight systems can be addressed. The research highlights the growing importance of strategic emission control, public health improvement, and cost-effective logistics. It reviews legal and environmental developments between 2014 and 2023, particularly in relation to civil aviation and road transport. The findings emphasize the need for alternative fuels, modern logistics strategies, and intermodal transport systems that balance environmental sustainability with economic efficiency. The integration of Industry 4.0 technologies—including IoT, AI, blockchain, telematics, and smart fleet management—is seen as key to improving the effectiveness and connectivity of national and cross-border road networks. Ultimately, the study provides guidance for policymakers and planners in developing sustainable, data-driven, and technologically advanced freight transport systems.

### **Conclusion**

The study underscores the critical global significance of reducing greenhouse gas emissions through the advancement of sustainability in Road Freight Transport (RFT). Drawing from an extensive review of over 400 peer-reviewed works, it establishes that strategic, technologically integrated, and policy-aligned approaches are essential for mitigating environmental degradation while enhancing energy efficiency. Legally binding frameworks between 2014 and 2023 reveal a growing convergence between environmental, social, and logistical priorities at both national and intercontinental

levels. The integration of alternative fuels, smart logistics, intermodal transport, and emerging technologies such as IoT, AI, telematics, and blockchain presents a transformative potential for optimizing freight operations. These innovations not only enhance cost-effectiveness and operational efficiency but also contribute to broader public health and sustainability goals. Ultimately, the research highlights that future-oriented planning—rooted in technological innovation, regulatory coherence, and cross-border collaboration—will be pivotal in realizing resilient, low-emission, and intelligent road freight systems. This strategic shift will empower practitioners and policymakers to develop adaptive, interconnected, and sustainable transport networks that strengthen both national and international mobility infrastructures.

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