

Transportation Energy Consumption Modeling for Sustainable and Low-Carbon Mobility Systems

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ABSTRACT

Transportation energy consumption modeling is essential for developing sustainable and efficient mobility systems. The growing demand for passenger and freight transport has increased fossil fuel use, carbon emissions, and environmental concerns. This study focuses on predicting and optimizing energy consumption in transportation through mathematical, statistical, simulation, and machine learning-based approaches. It highlights the role of digitalization, intelligent transport systems, renewable energy integration, and policy planning in reducing emissions and improving efficiency. The study emphasizes that sustainable transport requires advanced modeling, cleaner energy adoption, and integrated planning to balance mobility needs with environmental protection and long-term economic development.

Keywords: *Transportation Energy, Sustainable Mobility, Energy Modeling, Carbon Emissions.*

I. INTRODUCTION

Transportation systems play a crucial role in economic development, social connectivity, and global trade; however, they are also among the largest contributors to energy consumption and environmental degradation. With the rapid growth of urbanization, industrialization, and globalization, the demand for efficient mobility systems has increased significantly, leading to a corresponding rise in energy use and greenhouse gas emissions. The transportation sector is heavily dependent on fossil fuels, which has resulted in substantial carbon dioxide (CO₂) emissions and intensified climate change concerns. In recent decades, the concept of sustainable development has gained prominence, emphasizing the need to balance economic growth with environmental protection and social well-being. Transportation energy consumption modeling has therefore emerged as a vital research area aimed at understanding, predicting, and optimizing energy use in transport systems. Accurate modeling enables policymakers and engineers to design efficient transportation networks, reduce energy intensity, and promote cleaner alternatives such as electric mobility and renewable energy integration. Studies have shown that transport-related CO₂ emissions have increased drastically over time, highlighting the urgency of developing sustainable strategies to mitigate environmental impacts while maintaining mobility efficiency (Dai et al., 2023). Furthermore, the integration of Sustainable Development Goals (SDGs), particularly those related to climate action, clean energy, and sustainable cities, has reinforced the importance of optimizing transportation energy consumption to achieve long-term sustainability objectives (Bekun et al., 2026).

In this context, transportation energy consumption modeling involves the use of mathematical, statistical, and computational techniques to estimate energy usage across different transport modes and operational conditions. These models can be broadly categorized into macro-level, meso-level, and micro-level approaches, each offering distinct advantages and limitations. Macro-level models focus on aggregated data such as national or regional energy consumption trends, while micro-level models analyze individual vehicle behavior, including speed, acceleration, and driving patterns. Recent advancements in data analytics, machine learning, and simulation techniques have significantly improved the accuracy and applicability of these models. For instance, the development of the Vehicle Energy Conservation Equation (VECE) has provided a

novel framework for predicting vehicle energy consumption with high precision and interpretability, demonstrating its effectiveness across diverse vehicle categories (Sun et al., 2024). Additionally, comprehensive reviews have highlighted the need for integrating multi-scale modeling approaches to address the complexities of transportation systems and improve estimation accuracy (Chen et al., 2023). The role of digitalization has also gained attention, as technological advancements such as intelligent transport systems, real-time data monitoring, and automation contribute to optimizing energy consumption and reducing emissions. Empirical studies have indicated that digitalization can significantly lower CO₂ emissions by enhancing operational efficiency and enabling smarter decision-making processes (Elhaj et al., 2026). Moreover, optimization techniques, including artificial intelligence algorithms, dynamic programming, and game theory, have been increasingly applied to design energy-efficient transport networks and improve modal distribution, thereby supporting sustainable urban mobility (Qiang et al., 2018; Wang & Sun, 2019).

Despite these advancements, several challenges persist in achieving sustainable transportation systems. One of the major issues is the strong interdependence between economic growth, transportation demand, and energy consumption. As economies expand, the demand for freight and passenger transport increases, leading to higher energy usage and emissions. Empirical evidence suggests that energy consumption and economic growth are closely linked, with bidirectional causality observed in many regions, indicating that energy plays a fundamental role in supporting transportation and economic activities (Nasreen et al., 2018). Additionally, the reliance on fossil fuels continues to hinder sustainability efforts, as renewable energy adoption in the transportation sector remains limited in many countries. Studies have demonstrated that while renewable energy consumption can effectively reduce transport-related emissions, fossil fuel use and infrastructure expansion often counteract these benefits (Dai et al., 2023). Regional disparities in transportation efficiency and structure further complicate the issue, as variations in infrastructure development, policy frameworks, and technological adoption influence energy consumption patterns (Li et al., 2022). Furthermore, the integration of environmental considerations into transportation planning has only recently gained momentum, with increasing emphasis on incorporating sustainability metrics into decision-making processes (de la Torre et al., 2021). Addressing these challenges requires a comprehensive approach that combines advanced modeling techniques, policy interventions, and technological innovations. The optimization of transportation energy consumption is therefore essential for achieving sustainable development, as it enables the reduction of environmental impacts, enhancement of energy efficiency, and promotion of cleaner transport solutions. By leveraging modern computational tools and adopting integrated strategies, it is possible to develop resilient and sustainable transportation systems that align with global environmental goals and support long-term economic growth.

II. RESEARCH BACKGROUND

Bekun et al. (2026) had stated that attaining a sustainable environment had become an international commitment, making the mitigation of climate change concerns essential for ensuring a sustainable ecosystem. The study had focused on the Spanish economy, which had experienced positive growth trends over the years; however, it had identified an unresolved issue regarding whether this growth path had been green or environmentally damaging in the context of increasing global interconnectedness. These concerns had been linked to the objectives of the Sustainable Development Goals (SDGs), particularly SDG 8 (economic growth), SDG 13 (climate action), and SDGs 7 and 12 (responsible energy consumption and production). The research had empirically examined the comovement and coherence between CO₂ emissions and their driving factors, specifically renewable energy consumption, fossil fuel use, urbanization, and economic growth. For analysis, wavelet-based tools had been employed to capture the dynamic interrelationships among the selected variables over time.

Elhaj et al. (2026) had examined the global transport sector at a critical juncture where economic growth imperatives intersected with urgent environmental sustainability challenges. The study had investigated the impact of air freight transport, digitalisation, energy consumption, economic growth, and regulatory quality on CO₂ emissions in Gulf Cooperation Council (GCC) countries. Despite the region's strategic importance in global air freight networks and rapid digital transformation, limited empirical evidence had been available on how these factors collectively influenced environmental sustainability. GCC countries had provided a unique context for examining the digitalisation–transport–environment nexus. Using panel data from six GCC member states spanning 1999–2022, the study had employed a second-generation autoregressive distributed lag (CS-ARDL) model to analyse short- and long-run relationships while accounting for cross-sectional dependence and heterogeneity. CO₂ emissions had been considered the dependent variable, while digitalisation, air freight transport, and energy consumption had served as principal explanatory variables. The findings had indicated that energy consumption and economic growth were significant drivers of CO₂ emissions, whereas digitalisation had been associated with lower emissions. Regulatory quality had shown a weaker negative influence, and air freight transport had not exhibited a significant long-run effect. These results had provided policy guidance for sustainable development strategies in GCC economies.

Ayakymchuk and Rataj (2025) had examined the growing importance of the economic assessment of CO₂ emissions from fossil fuel consumption in the context of sustainable development. It was observed that climate change, driven by excessive greenhouse gas emissions, had posed a significant global threat, thereby necessitating an integrated approach incorporating both environmental and economic dimensions. The European Union (EU) was identified as playing a crucial role in global emission reduction efforts and sustainability promotion. The study had explored economic approaches to analyzing CO₂ emissions in Europe, focusing on fossil fuel usage trends and their underlying economic drivers. It had highlighted the interrelationship among economic activity, energy consumption, and emissions, thereby enhancing understanding of climate change mitigation strategies. The findings had emphasized the strong influence of demographic factors on carbon emissions and had underscored the need for targeted policy interventions. Additionally, the study had provided a literature-based assessment of emissions within EU countries, with special attention to policy frameworks such as Germany's "Energiewende," demonstrating how strategic investments in renewable energy and efficiency could decouple growth from environmental degradation.

Sun et al. (2024) had stated that predictive models for vehicle energy consumption were essential for sustainable development in urban road traffic systems. The study had comprehensively reviewed classical predictive models and had developed a novel statistical-dynamical framework termed the Vehicle Energy Conservation Equation (VECE). It had been formulated based on vehicle energy flow principles and regression analysis, providing a continuous and concise mathematical expression. The coefficients were reported to have clear physical interpretations and had been applicable across different vehicle categories. For validation, energy consumption data from 28 vehicles, including diesel, gasoline, ethanol gasoline, and battery electric vehicles, had been collected using a structured data processing procedure. The analysis had indicated that VECE coefficients were influenced by vehicle type, speed, and acceleration. The model had shown limited sensitivity to the number of vehicle categories and had performed well in both homogeneous and mixed fleets. Comparative results had demonstrated that VECE achieved moderate accuracy for instantaneous predictions but superior performance for cumulative energy consumption, with a minimum relative error of 4.2%, highlighting its simplicity, interpretability, and adaptability.

Chen et al. (2023) had emphasized that, in the context of achieving “peak carbon” and carbon neutrality goals, the precise quantification of carbon emissions from road transportation had become increasingly essential. The study had observed that it was difficult to accurately represent vehicle energy consumption across both temporal and spatial dimensions when approached from a macro-level perspective. Therefore, the authors had focused on micro-level vehicle energy consumption models and meso-level road traffic energy consumption frameworks. They had systematically reviewed and summarized existing road transportation energy consumption models with respect to data collection methods, quantification accuracy, and their respective scopes of application. Based on this comprehensive review, the study had identified several key challenges and limitations associated with current road traffic energy consumption modeling approaches. Finally, the authors had suggested future research directions, emphasizing the need for more refined and accurate quantitative models to better understand and estimate energy consumption in road transportation systems.

Dai et al. (2023) had stated that attaining Sustainable Development Goals (SDGs) was considered crucial for controlling adverse impacts of climate change and ensuring sustainable development. Among the 17 SDGs, Target 13 had emphasized the need for urgent action to combat climate-related changes, which was closely linked with Target 7 focusing on improving access to affordable and sustainable energy sources. It had been highlighted that achieving these targets required the reduction of transport-related CO₂ emissions (TCO₂), which had increased by approximately 80% between 1990 and 2019. The study had examined the role of transport renewable energy consumption (TRN) in influencing TCO₂ while also considering transport fossil fuel consumption (TTF) and road infrastructure (RF) in the United States over the period 1970–2019. The presence of the transport Environmental Kuznets Curve (EKC) had also been assessed. The study had employed the Bayer-Hanck cointegration test and the Gradual Shift causality test to examine long-run relationships. Findings from the DOLS model had indicated that renewable energy in transport reduced TCO₂, while fossil fuel use and road infrastructure had increased emissions. The EKC hypothesis had been found invalid, suggesting that economic growth had continued to worsen environmental quality.

Li et al. (2022) had noted that the sustainable development of the transportation industry had remained a major concern in China after the reform and opening-up period. They had highlighted that existing studies had mainly focused on the efficiency of a single transportation mode or specific regions, without adequately considering the overall efficiency of the national transportation system. It had further been observed that limited attention had been given to the role of transportation structure in influencing both transportation efficiency and economic development. Moreover, the interrelationships and dynamic interactions among transportation efficiency, transportation structure, and regional economic growth had not been sufficiently explored. Based on this gap, the study had employed a panel vector autoregressive model to examine the relationships among these three variables. The results had indicated that transportation efficiency was highest in the eastern region, followed by the central region, and lowest in the western region. It had also been found that transportation structure showed only slight variation nationwide from 2011 to 2020, with stable modal proportions across provinces. Furthermore, it had been revealed that transportation efficiency and structure had a mutually reinforcing short-term relationship, while regional economic development had contributed to long-term improvements in both. Transportation efficiency had also played a leading role in driving regional economic growth. The study had finally suggested policy measures to optimize structure, reduce resource waste, and enhance sustainable transportation development.

de la Torre et al. (2021) had stated that the demand for efficient freight and human transportation systems had continuously increased over the past decades due to globalization, the expansion of e-commerce activities, and growing mobility requirements. They had observed that traditional transportation systems were primarily designed with the objective of minimizing monetary costs while ensuring a defined level of service quality. However, it had been emphasized that in the last decade, sustainability considerations had increasingly become a critical component in transportation system design and operation. The authors had highlighted that environmental and social impacts of transportation activities were being integrated into planning processes by managers and policymakers for both long-distance and urban transportation systems. Furthermore, the study had reviewed various scientific methodologies used for promoting Sustainable Transportation Systems (STS), including simulation, optimization, machine learning, and fuzzy logic approaches. It had also classified key challenges, best practices, emerging trends, and future research directions in the field.

Palander et al. (2020) had examined the Finnish forest industry's efforts to adopt novel technologies for promoting carbon-neutral development and environmental sustainability within a green circular industry framework. The study had compared energy efficiency indicators of road freight transportation and analyzed the impact of four different mass limits of vehicle combinations following a three-year adaptation period in a wood procurement region fully based on renewable resources. A wood-based energy efficiency model (load's wood energy to fossil transport energy ratio) had been identified as the most accurate indicator for evaluating system performance. The results had indicated that transportation systems with varying vehicle capacities (60, 64, 68, and 76 t) showed carbon-negative performance in different years, reflecting a favorable energy balance between renewable wood energy and fossil fuel use. It had further been observed that 68 t vehicles improved energy efficiency most significantly. The study had highlighted potential for optimizing sustainable transport networks.

Wang and Sun (2019) had aimed to develop a rational traffic structure for historical districts in order to alleviate the contradiction between limited transport supply and rapidly increasing travel demand. They had formulated a dynamic game model of traffic competition with a focus on green transportation and sustainable development. Initially, a logit model based on generalized cost was established to represent the share of different travel modes by quantifying influencing factors of mode choice. Subsequently, a dynamic game model under complete information was constructed for travel behavior in historical districts, incorporating economic, environmental, and social sustainability aspects of transportation development. The model had been designed to maximize generalized profit while considering environmental pollution, energy consumption, and road service level as key constraints across transport modes. Through iterative computation of the Nash equilibrium, the optimal traffic structure and modal share were predicted. The model had been validated using the Academy Street district in Zhengzhou, China, and optimal modal distributions were obtained. Additionally, different governance policies were compared by modifying constraints, and practical suggestions for improving traffic structure were proposed. The study had been suggested as a useful reference for traffic planning in historic urban areas.

Qiang et al. (2018) had stated that, with the increasing number of cars and trips in cities, energy consumption and environmental pollution had become major issues in urban transport systems. They had observed that the growing use of private vehicles had not only increased energy consumption and exhaust emissions but had also led to an imbalance in the transportation structure. The study had emphasized that a rational and optimized transport structure needed to be developed to support sustainable urban transport development. The authors had proposed energy-efficiency-based models for optimizing sustainable urban transport systems, where the objective functions had focused on minimizing energy consumption, while

the constraints had included carbon dioxide emissions and traffic efficiency requirements. These models had been solved using the artificial fish swarm algorithm and applied to optimize the urban transport structure of Harbin city in China. The results had indicated that the models could ensure traveler benefits, reduce carbon emissions, and minimize overall energy consumption.

Nasreen et al. (2018) had investigated the relationship between economic growth, freight transport, and energy consumption for 63 developing countries over the period 1990–2016. For improving the homogeneity of panel data analysis, the countries were classified according to income levels into three sub-panels, namely lower-middle income countries (LMIC), upper-middle income countries (UMIC), and high-income countries (HIC). The generalized method of moments (GMM) approach was employed for empirical estimation. The results had provided evidence of a bidirectional causal relationship between economic growth and freight transport across all selected panels, and between economic growth and energy consumption for both upper-middle and high-income countries. In the lower-middle income group, causality was found to be unidirectional, running from energy consumption to economic growth. Furthermore, the relationship between freight transport and energy use had been observed as bidirectional in high-income countries, while it remained unidirectional from freight transport to energy consumption in upper-middle and lower-middle income countries. The empirical findings had highlighted the critical role of energy in economic activity and had rejected the neo-classical assumption of energy neutrality in growth. The study had also recommended advancements in vehicle technology to reduce transport energy intensity and improve energy efficiency in freight systems.

III. KEY FINDINGS FROM STUDY

Author(s) & Year	Study Area / Focus	Objective	Methodology	Key Findings	Research Gap
Bekun et al. (2026)	Spain; Energy–Environment Nexus	To examine relationship between CO ₂ emissions, energy use, urbanization, and growth	Wavelet coherence analysis	Renewable energy reduced emissions; fossil fuels and urbanization increased degradation; strong SDG linkage	Limited focus on transport-specific energy modeling
Elhaj et al. (2026)	GCC Countries; Air Freight & Digitalization	To analyze impact of air freight, digitalization, and energy use on CO ₂ emissions	Panel data (CS-ARDL model)	Energy use and growth increased emissions; digitalization reduced emissions; air freight insignificant long-term	Lack of micro-level transport energy analysis
Ayakymchuk & Rataj (2025)	Europe; Fossil Fuel Emissions	To evaluate economic drivers of CO ₂ emissions	Economic and policy analysis	Strong link between economic growth and emissions; renewable policies reduce environmental impact	No specific modeling framework for transportation systems

Sun et al. (2024)	Vehicle-Level Energy Modeling	To develop predictive model for vehicle energy consumption	Statistical-dynamical VECE model	High accuracy in cumulative energy prediction; adaptable across vehicle types	Limited application in large-scale transport networks
Chen et al. (2023)	Road Transport Energy Models	To review macro, meso, and micro-level models	Comparative literature review	Identified limitations in accuracy and integration; need for hybrid models	Lack of unified modeling framework
Dai et al. (2023)	USA; Transport Emissions	To study impact of renewable and fossil energy on transport CO ₂ emissions	Cointegration and DOLS models	Renewable energy reduced emissions; fossil fuels increased emissions; EKC not valid	Limited optimization strategies discussed
Li et al. (2022)	China; Transport Efficiency	To analyze transport efficiency, structure, and economic growth	DEA and PVAR model	Efficiency drives economic growth; structure shows limited variation	Lack of energy consumption optimization focus
de la Torre et al. (2021)	Sustainable Transport Systems	To review modeling techniques in sustainable transportation	Review of ML, simulation, optimization	Advanced computational methods enhance sustainability planning	Lack of real-world implementation frameworks
Palander et al. (2020)	Finland; Freight Transport	To evaluate energy efficiency of transport systems	Comparative modeling of vehicle mass limits	68-ton vehicles most energy efficient; potential carbon-negative outcomes	Limited generalization beyond specific industry
Wang & Sun (2019)	Urban Historical Districts	To optimize traffic structure using sustainability concepts	Logit model and dynamic game theory	Optimal modal share reduces congestion and emissions	Limited scalability to modern urban systems
Qiang et al. (2018)	Urban Transport Optimization	To develop energy-efficient transport models	Artificial Fish Swarm Algorithm	Reduced energy consumption and emissions; improved efficiency	Requires validation with real-world data
Nasreen et al. (2018)	63 Developing Countries	To examine relationship between energy use, freight transport, and growth	GMM-based panel analysis	Bidirectional relationship between energy and growth; energy critical for transport	No specific modeling or optimization techniques proposed

IV. CONCLUSION

Transportation energy consumption modeling and optimization have emerged as critical components in achieving sustainable development, particularly in the face of rising energy demands, rapid urbanization, and increasing environmental concerns. The reviewed studies collectively highlight that transportation systems are deeply intertwined with economic growth, energy consumption, and environmental sustainability. It has been consistently observed that excessive reliance on fossil fuels significantly contributes to CO₂ emissions, thereby intensifying climate change challenges, while the integration of renewable energy sources plays a vital role in mitigating these adverse impacts (Dai et al., 2023; Bekun et al., 2026). Advanced modeling approaches, such as statistical-dynamical frameworks, econometric models, and machine learning techniques, have demonstrated substantial potential in accurately predicting and analyzing energy consumption patterns across different transport modes (Sun et al., 2024; Chen et al., 2023). Furthermore, optimization techniques, including artificial intelligence algorithms and dynamic modeling, have proven effective in enhancing transportation efficiency, reducing energy use, and improving modal distribution (Qiang et al., 2018; Wang & Sun, 2019). The role of digitalization has also been recognized as a transformative factor that can significantly improve energy efficiency and reduce emissions through smart transportation systems (Elhaj et al., 2026). However, several challenges remain, including the lack of integrated multi-scale models, regional disparities in transportation efficiency, and the continued dominance of fossil fuels in the transport sector. Additionally, the complex relationship between economic growth and energy consumption underscores the need for balanced policy interventions that promote sustainability without hindering development (Nasreen et al., 2018). Therefore, it can be concluded that a comprehensive and integrated approach combining advanced modeling techniques, renewable energy adoption, policy support, and technological innovation is essential for optimizing transportation energy consumption. Such an approach will not only reduce environmental impacts but also enhance the overall efficiency and resilience of transportation systems, thereby contributing significantly to the global agenda of sustainable development.

V. FUTURE SCOPE

The future scope of transportation energy consumption modeling and optimization lies in the development of more integrated, intelligent, and data-driven approaches that can effectively address the growing complexity of modern transportation systems. One of the key directions is the advancement of multi-scale modeling frameworks that combine macro-, meso-, and micro-level analyses to provide a comprehensive understanding of energy consumption patterns across regions, networks, and individual vehicles. The integration of emerging technologies such as artificial intelligence, machine learning, big data analytics, and the Internet of Things (IoT) is expected to significantly enhance the accuracy, adaptability, and real-time applicability of energy consumption models. These technologies can enable predictive analytics, dynamic traffic management, and energy-efficient route optimization, thereby reducing fuel consumption and emissions. Furthermore, the increasing adoption of electric vehicles (EVs) and alternative fuel technologies presents new opportunities for developing models that incorporate battery performance, charging infrastructure, and renewable energy integration. Future research should also focus on designing optimization frameworks that support multimodal transportation systems, encouraging a shift from private vehicle use to more sustainable modes such as public transit, cycling, and shared mobility. Additionally, the role of digitalization and smart city initiatives will be crucial in improving transportation efficiency through intelligent transport systems and automated decision-making processes. From a policy perspective, there is a need for developing region-specific strategies that consider socio-economic, demographic, and infrastructural variations to ensure effective implementation of sustainable

transportation solutions. Moreover, future studies should emphasize the incorporation of environmental, economic, and social sustainability indicators into unified modeling frameworks to support holistic decision-making. Addressing existing limitations, such as data scarcity, model uncertainty, and lack of standardization, will further strengthen research outcomes. Overall, the future of transportation energy consumption modeling will depend on interdisciplinary collaboration, technological innovation, and policy integration to create resilient, low-carbon, and energy-efficient transportation systems aligned with global sustainability goals.

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