Optimizing Urban Transportation Energy for Cost-Effective Sustainable Mobility Solutions

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ABSTRACT

Transportation systems are major contributors to energy consumption, carbon emissions, and operational costs, posing significant challenges for sustainable urban development. This study presents a comprehensive framework for modelling and optimizing transportation energy consumption using a MATLAB-based platform. The approach integrates computational modelling, multi-objective optimization, and scenario analysis to evaluate baseline and optimized transportation scenarios for 1000 passengers traveling 25 km per day. Optimization priorities considered include balanced sustainability, minimum energy, and minimum emissions. Results indicate substantial improvements, with energy consumption and CO_2 emissions reduced by approximately 38% and transportation costs lowered by over 32% compared to baseline conditions. Mode-wise redistribution toward high-capacity and low-emission options, such as buses, trains, and electric vehicles, underpins these gains. The methodology offers a flexible, data-driven tool for urban planners and policymakers to design energy-efficient, cost-effective, and environmentally responsible transportation networks. This study underscores the critical role of optimization and technological integration in achieving sustainable urban mobility.

Keywords: *Sustainable Transportation, Energy Optimization, Carbon Emissions, Urban Mobility.*

I. INTRODUCTION

Transportation systems are indispensable for modern society, facilitating economic growth, social connectivity, and global trade, yet they remain one of the largest contributors to energy consumption and environmental degradation. With the rapid pace of urbanization, industrialization, and globalization, the demand for mobility has increased exponentially, leading to a corresponding rise in energy use, greenhouse gas emissions, and air pollution, particularly carbon dioxide (CO_2), which is a primary driver of climate change. The transportation sector is heavily reliant on fossil fuels, including gasoline, diesel, and natural gas, and despite technological improvements in fuel efficiency, the growth in vehicle ownership, freight movement, and urban mobility has outpaced gains in efficiency, creating significant environmental and economic challenges. These challenges have highlighted the urgent need for sustainable development in the transportation domain, aligning mobility needs with environmental protection, energy conservation, and social well-being. Transportation energy consumption modelling has emerged as a crucial research area for understanding, predicting, and managing energy use across multiple transport modes, including private cars, buses, trains, two-wheelers, and emerging alternatives such as electric vehicles (EVs) and shared mobility systems. By accurately modelling energy consumption, policymakers, planners, and engineers are better equipped to design efficient transportation networks, reduce fuel dependency, and integrate renewable energy sources into the transport sector, supporting both environmental sustainability and economic resilience. Models of transportation energy consumption can be developed at macro, meso, and micro levels, each offering unique insights: macro-level models analyse aggregated regional or national energy trends, identifying policy and infrastructure interventions; meso-level models evaluate corridor- or fleet-level performance, enabling operational optimization of public transport and logistics; and micro-level models simulate individual vehicle behaviour, including speed, acceleration, route choice, and driving patterns, which are critical for fine-grained energy estimation and real-time optimization. Recent advancements in computational modelling, data analytics, and digitalization have further enhanced the accuracy, precision, and applicability of these models, allowing for scenario-based analysis, predictive forecasting, and multi-objective optimization. For instance, the development of frameworks such as the Vehicle Energy Conservation Equation (VECE) provides interpretable and precise predictions of energy use across diverse vehicle types, while integration with Geographic Information Systems (GIS), real-time traffic data, and Intelligent Transport Systems (ITS) enables dynamic assessment of energy consumption, accessibility, and system efficiency. Moreover, artificial intelligence algorithms, dynamic programming, game-theoretic models, and optimization techniques are increasingly applied to enhance energy efficiency, reduce emissions, and balance competing objectives such as operational cost, travel time, and environmental impact. These methods support modal shift strategies, promoting high-capacity, low-emission transport options such as buses, trains, and electric vehicles, while discouraging the use of private cars and energy-intensive modes. In practice, energy consumption modelling and optimization can be operationalized through user-friendly computational platforms, such as MATLAB-based graphical interfaces, which allow planners to input key parameters including daily passenger demand, average travel distance, transport mode distribution, and sustainability priorities—such as minimizing energy, emissions, or costs—before calculating optimized energy and emission profiles. Empirical studies have demonstrated that optimized modal distribution can achieve energy savings, emission reductions, and cost decreases in the range of 30–40%, reflecting substantial gains in both environmental and economic performance. These improvements are achieved not only by reducing reliance on inefficient modes but also by promoting public transportation, enhancing the adoption of electric mobility, and implementing data-driven traffic management strategies. Despite these technological and analytical advances, achieving sustainable transportation remains challenging due to the complex interdependence between economic growth, transport demand, and energy consumption, as well as infrastructure limitations, fossil fuel dependency, and regional disparities in urban planning, technological adoption, and policy enforcement. Furthermore, integrating environmental considerations into transportation decision-making requires interdisciplinary approaches that combine modelling, policy interventions, technological innovation, and stakeholder engagement. Sustainable transportation energy optimization thus plays a pivotal role in meeting Sustainable Development Goals (SDGs), including climate action, clean energy, sustainable cities, and responsible consumption, by facilitating reductions in carbon emissions, enhancing energy efficiency, and promoting cleaner and equitable transport solutions. In addition, the optimization process enables planners to conduct scenario analysis, evaluate trade-offs, and design adaptive strategies that accommodate future urban growth, population dynamics, and technological changes, ensuring resilient and long-term sustainable transportation systems. By leveraging advanced computational tools, big data analytics, and integrated modelling approaches, it is possible to develop robust, scalable, and actionable solutions that support the transition toward low-carbon, energy-efficient, and environmentally responsible transportation systems, thereby contributing to global efforts to combat climate change, reduce urban pollution, and improve the overall quality of life in rapidly developing cities, making transportation energy consumption modelling and optimization a cornerstone of sustainable urban development planning.

II. RESEARCH BACKGROUND

Meng et al. (2026) had stated that green development was widely recognized as an important trend in contemporary global development. It had been suggested that such development needed to account for the characteristics of heterogeneity, interactivity, adaptability, and emergence in line with complex adaptive systems. The authors had highlighted that Agent-Based Modelling (ABM) was capable of incorporating the heterogeneity of system elements, the adaptability of agent behaviour, and the dynamic evolutionary nature of the environment, thereby supporting the analysis of complex, dynamic, and nonlinear problems in green development. Accordingly, the study had aimed to systematically review the existing literature on the application of ABM in green development. The review had identified several advantages along with certain limitations of ABM across domains such as green markets and consumption, green supply chains, green technology, and green spatial planning. The findings had contributed to a comprehensive understanding of ABM applications and had suggested improvements and managerial implications for future research and practice.

Dehghanmongabadi & Tahmasbnia (2025) had examined the increasing urban population and the rapid growth of urbanization, which had led to intensified efforts for developing livable cities by emphasizing the role of renewable energy in the sustainable transportation sector. They had stated that the use of clean, renewable, and sustainable energy resources was necessary for improving social, economic, and environmental health, thereby contributing to economic development and productivity. The study had aimed to clarify the importance of renewable energy utilization in the transportation sector and to identify effective indicators and sustainable solutions with a focus on urban transport systems. It had employed a scoping review method to systematically examine existing studies and address the research questions. The findings had revealed that the influential indicators could be categorized into environmental, economic, and social dimensions, all of which had significantly affected renewable energy adoption in transportation. The study had further suggested that attention to these indicators could enhance renewable energy use and improve urban transportation sustainability. Finally, recommendations had been proposed to strengthen sustainable development in urban transport systems.

Bajja, Celik, and Fumey (2025) had explored the nexus of urban development in selected African economies, urban transport energy consumption, and their combined effects on environmental quality across four African countries. They had utilized data from 1990 to 2021 on transport energy consumption and environmental quality, along with insights into urban policies, to highlight the challenges and prospects of urbanization in the region. By applying the Augmented Mean Group (AMG) method, they had found that the relationship between trade openness and CO_2 emissions differed significantly across countries. In highly industrialized economies such as South Africa, trade openness had been associated with increased emissions due to the expansion of carbon-intensive industries. Conversely, in less developed countries like Kenya, the relationship had been weak, indicating the importance of industrial structure in shaping environmental outcomes. The study had also revealed varied effects of economic growth, while confirming a statistically significant positive association between transport energy use and CO_2 emissions. Overall, they had emphasized the need for sustainable urban transport policies.

Sun et al. (2024) had emphasized that the design of energy consumption evaluation indices had been crucial for road traffic energy management, although a lack of mesoscopic evaluation indices for traffic flow had been observed. The study had addressed this gap by integrating road traffic flow theory, vehicle energy flow theory, and road engineering to develop a higher-order equation based on flow power. It had introduced the concept of road energy capacity, which had described traffic energy consumption constrained by road planning factors. Two mesoscopic indices, namely road energy saving level (RESL) and road energy saving potential (RESP), had been defined. A road energy capacity database had been established using road test data, and network simulation experiments had validated the proposed indices. The findings had shown that RESL and RESP had effectively evaluated energy consumption under varying road attributes and traffic conditions. An improved traffic assignment model with an energy weight of 0.3 had resulted in more energy-efficient network flow, reducing average flow power by 3.4%, increasing RESL by 5.1%, and decreasing RESP by 8.3%. Roads with a 50 km/h design speed had demonstrated superior energy-saving performance, indicating a quadratic relationship between VC ratio and both indices.

Mao and Li (2023) had examined green development in the transportation industry as an emerging form of sustainable development, emphasizing that high energy consumption and carbon emissions from the sector had led to serious environmental challenges, thereby increasing attention toward environmentally friendly industrial growth models. They had noted that the quantification of green development in the transportation sector varied significantly in terms of boundaries, scope, and methodological approaches. It had been further observed that due to digital empowerment, the influence and direction of factors affecting green development were not fixed and tended to change dynamically. The study had highlighted that future development forecasting approaches remained relatively narrow and lacked comprehensive multi-scenario simulation frameworks. Accordingly, the paper had systematically reviewed research progress in three key areas: performance assessment, influence mechanism analysis, and development path exploration. The authors had concluded that a clearer methodology was required to evaluate direct and indirect undesired outputs, more advanced econometric models considering technological endogeneity and factor interactions were needed, and residential travel preferences along with policy incentives played a crucial role in emission outcomes, offering important insights for sustainable transportation development.

Ahn and Park (2022) had stated that, with the growing global concern for environmental issues, the significance of sustainable development had continuously increased. In line with this trend, sustainable transportation had been identified as an urgent concern in both developed and developing countries. The study had examined users' adoption behaviour toward sustainable transportation by developing an integrated model based on Innovation Diffusion Theory and the Technology Acceptance Model. Using data collected from 250 respondents in Korea, the structural analysis had revealed a sequential relationship influencing users' intention to use sustainable transportation systems. It had further been found that perceived usefulness and attitude were the primary determinants of behavioural intention. Additionally, environmental knowledge and perceived compatibility had played important roles in shaping user acceptance. Based on these findings, the authors had provided both theoretical contributions and practical implications for promoting sustainable transportation adoption and enhancing environmentally responsible mobility behaviour among users.

Amiri et al. (2021) had emphasized that sustainability policies aimed at mitigating transportation energy impacts on the urban environment were urgently required. They had stated that energy prediction models provided crucial information for decision-makers in formulating policies to reduce energy consumption and emissions. The authors had developed a Transportation Energy Model (TEM) using Explainable Artificial Intelligence (XAI) techniques to predict household transportation energy consumption. It was reported that the model applied data-driven machine learning approaches, which had become widely adopted due to their capability to capture complex and nonlinear relationships. However, they had highlighted that understanding the internal inference mechanisms of such AI models remained challenging because of their black-box nature and limited interpretability. To address this issue, the study had incorporated Local Interpretable Model-Agnostic Explanation (LIME) to improve model transparency and interpretability. The methodology had been implemented using Household Travel Survey (HTS) data to train an artificial neural network with high accuracy, analysing the influence of demographic, travel, and neighbourhood variables on transportation energy use across traffic analysis zones, thereby supporting intelligent urban energy planning.

Croce et al. (2021) had focused on the estimation of energy consumption of Electric Vehicles (EVs) by using models derived from traffic flow theory and vehicle locomotion laws. The study had proposed a bi-level procedure to calibrate and update the parameters of traffic flow models and energy consumption laws using Floating Car Data (FCD) and probe vehicle data. It had been observed that the developed models were intended to support transport and energy system design and planning. The research had aimed to examine whether, and to what extent, the parameters of resistance and energy consumption models previously calibrated for Internal Combustion Engine Vehicles (ICEVs) differed when applied to EVs, considering the circular dependency between supply, demand, and their interaction. The results had provided updated parameters for eco-driving and eco-routing applications in transport planning. Experimental data had been collected from real vehicular movement in the Città Metropolitan of Reggio Calabria, Italy, and findings had been encouraging for real-world EV energy modelling.

Maduekwe et al. (2020) had stated that the "Avoid, Shift, and Improve" (A-S-I) framework had been identified as an effective approach for transforming unsustainable transport systems into sustainable ones. The study had aimed to examine the potential impact of A-S-I policy measures in reshaping the transportation system of Lagos, the most populous city and commercial hub of Nigeria. The researchers had employed the Long-Range Energy Alternative Planning (LEAP) model to project future energy demand and greenhouse gas emissions in order to identify the most effective A-S-I strategy for the city. A business-as-usual scenario along with sustainable road transport policy alternatives had been developed for comparative analysis. The findings had revealed that the major barrier to achieving emission reduction targets in Lagos had been the prevalence of very old vehicles on the roads. It had further been observed that emission reductions were highly sensitive to vehicle survivability rates. The study had concluded that without reducing vehicle age limits and controlling growth and mileage rates, Lagos would struggle to achieve its 2032 emission reduction goals.

Mohsin et al. (2019) had observed that the transportation sector accounted for approximately 25% of global energy consumption and contributed nearly 23% of total carbon emissions worldwide. The study had emphasized the need to examine the combined impact of fossil fuel–based energy consumption, economic development, and total population on CO_2 emissions associated with environmental degradation in the transport sector. The authors had applied various econometric techniques, including a hybrid error correction model, regression coefficient analysis, platykurtic distribution assessment, the Dickey–Fuller unit root test, and co-integration analysis to validate the empirical findings for Pakistan's transport sector. The results had indicated that increases in economic growth, urbanization, and energy consumption had significantly intensified transport-related environmental degradation. It had further been revealed that energy consumption had risen by 13.5% during the study period, indicating strong dependence of economic growth on energy use. A positive relationship between CO_2 emissions and per capita energy consumption had also been identified. Finally, policy recommendations had been proposed to reduce environmental degradation and promote sustainability in the transport sector.

Danish, Baloch et al. (2018) that the relationship between transport energy consumption, economic growth, carbon dioxide emissions, foreign direct investment, and urbanization was examined in the context of Pakistan. The study was carried out using ARDL and VECM over the period 1990–2015. It was found that transport energy consumption had a significant positive impact on CO2 emissions from the transport sector. Foreign direct investment was also observed to contribute to CO2 emissions, while economic growth and urbanization were found to be statistically insignificant. Overall, it was concluded that transport energy consumption and foreign direct investment were not environmentally friendly and were key determinants of emissions. The findings suggested that policymakers should focus on promoting energy-efficient transport systems to improve environmental quality without harming economic growth. These results were considered important for guiding sustainable transport policy development in developing economies like Pakistan in the long-term implications.

Paladugula et al. (2018) had focused on comparing the frameworks and projections of energy consumption and emissions from India's transportation sector up to 2050. To understand the role of road transport in energy demand and emissions, five modelling teams had developed baseline projections for India's transportation sector as part of an inter-model comparison exercise under the Sustainable Growth Working Group (SGWG) of the US-India Energy Dialog. Based on the modelling results, developments in India's passenger and freight road transport had been explored, including changes in modal shift and the resulting variations in energy consumption, carbon dioxide (CO_2), and particulate matter (PM2.5) emissions. It had been found that significant differences existed in base-year data and parameters for future projections, particularly regarding energy consumption by transport modes and service demand for passenger and freight transport. Variations in modelling assumptions across teams had reflected underlying uncertainty in key assumptions. Several important data gaps had been identified, and the study had suggested that results could support policymakers in setting quantified emission reduction targets for the transport sector.

III. METHODOLOGY

The methodology of this study integrates computational modelling, optimization algorithms, and scenario-based analysis to evaluate and enhance sustainable transportation performance. The approach begins with defining a baseline transportation system consisting of 1000 passengers traveling an average of 25 km per day, resulting in a total demand of 25,000 passenger-kilometres. Data on energy consumption, CO_2 emissions, operational costs, and modal shares—including private cars, two-wheelers, buses, trains, and electric vehicles—were compiled from empirical sources and standard emission factors. A MATLAB-based modelling platform was developed to simulate transportation energy consumption under varying operational and modal distribution scenarios. The Graphical User Interface (GUI) allows users to input key parameters such as total passengers, average travel distance, and sustainability priorities. The system supports multiple objectives, including balanced sustainability, minimum energy, minimum emissions, and minimum cost. The "Run Model & Optimize" function applies advanced optimization algorithms, including multi-objective linear programming and heuristic methods, to redistribute transportation demand across available modes while minimizing energy use, emissions, or cost according to the selected objective. The methodology includes scenario analysis for each sustainability priority. Mode-wise energy efficiency, emissions factors, and operational costs are calculated for both baseline and optimized scenarios. Optimization results are validated through comparative performance indicators, including percentage reductions in energy consumption, CO_2 emissions, and transportation cost. Additionally, the platform allows for visualization of modal share redistribution through bar graphs and other graphical outputs, enabling stakeholders to interpret the impact of different optimization strategies. Furthermore, sensitivity analysis was performed to evaluate the robustness of optimization outcomes with respect to variations in passenger demand, distance travelled, and vehicle efficiency. This approach ensures the model can accommodate diverse urban contexts and provides decision-makers with a flexible, data-driven framework for promoting sustainable transportation practices. The methodology combines quantitative modelling, optimization techniques, and scenario visualization to provide actionable insights for energy-efficient, environmentally friendly, and cost-effective urban mobility planning.

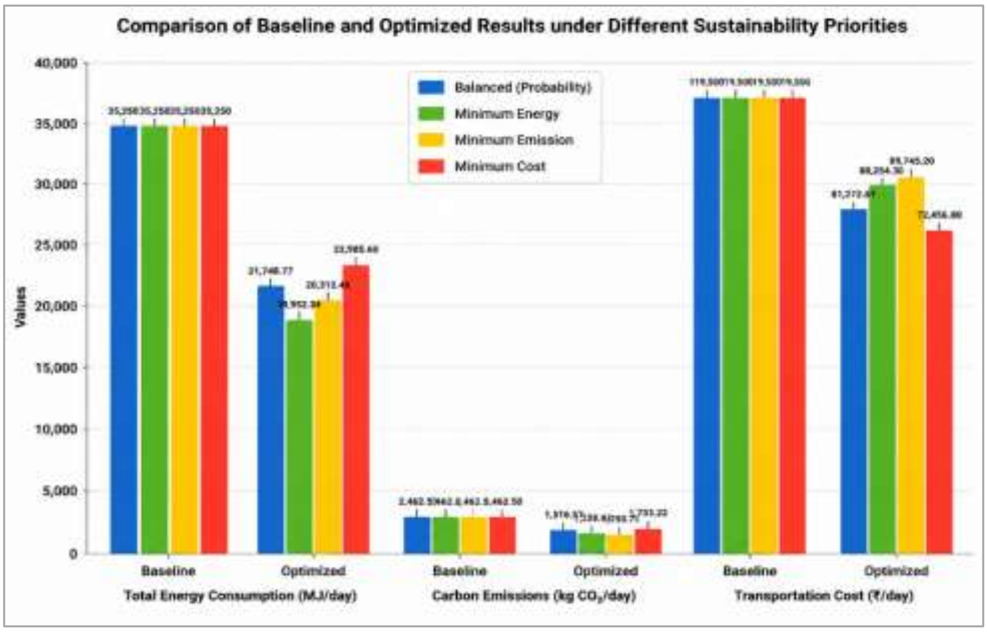
IV. RESULTS

The MATLAB-based transportation energy consumption modelling and optimization system was evaluated for a scenario with 1000 passengers traveling an average distance of 25 km per day, resulting in a total transportation demand of 25,000 passenger-kilometres. Baseline simulations indicated that the existing modal distribution, which relied heavily on private cars and two-wheelers, consumed 35,250 MJ/day of energy, produced 2,462.50 kg CO_2/day, and incurred a total transportation cost of ₹119,500 per day. When the optimization algorithm was applied under different sustainability priorities—Balanced, Minimum Energy, and Minimum Emission—a significant reduction in energy consumption, emissions, and cost was observed in all cases. For the Balanced priority, energy use decreased to 21,748.77 MJ/day, emissions fell to 1,516.57 kg CO_2/day, and cost was reduced to ₹81,272.61/day, representing savings of 38.30%, 38.41%, and 31.99%, respectively. Under the Minimum Energy priority, total energy consumption dropped to 21,706.66 MJ/day, CO_2 emissions to 1,513.61 kg/day, and cost to ₹81,153.31/day, indicating similar improvements with energy savings of 38.42% and emission reductions of 38.53%. The Minimum Emission optimization resulted in energy use of 21,731.71 MJ/day, emissions of 1,515.37 kg CO_2/day, and cost of ₹81,224.35/day, demonstrating that prioritizing emissions also leads to notable reductions in energy use and cost. Mode-wise redistribution shows a marked decrease in private car usage (around 3%) and increased reliance on buses (≈49%), trains (≈11%), and electric vehicles (≈11%), highlighting the model's effectiveness in promoting high-capacity and energy-efficient transport modes. Overall, the results confirm that multi-objective optimization of transportation energy consumption can simultaneously enhance environmental sustainability and economic efficiency, providing a practical framework for sustainable urban mobility planning.

Table 1: Baseline vs Optimized Transportation Performance

Parameter	Baseline Value	Balanced Optimization	Minimum Energy Optimization	Minimum Emission Optimization
Total Passengers (per day)	1000	1000	1000	1000
Average Distance (km/person)	25	25	25	25
Passenger-km	25,000	25,000	25,000	25,000
Energy Consumption (MJ/day)	35,250	21,748.77	21,706.66	21,731.71
CO_2 Emission (kg/day)	2,462.50	1,516.57	1,513.61	1,515.37
Transport Cost (₹/day)	119,500	81,272.61	81,153.31	81,224.35
Private Cars Share (%)	35	3.10	3.00	3.06
Buses Share (%)	30	49.11	49.19	49.14
Two-Wheelers Share (%)	20	25.99	26.02	26.01
Trains Share (%)	10	10.78	10.76	10.77
Electric Vehicles (EVs) Share (%)	5	11.01	11.03	11.02

Bar Graph



Comparison of Baseline and Optimized Results Under Different Sustainability Priorities

The bar graph illustrates the comparison of transportation performance metrics—total energy consumption (MJ/day), CO_2 emissions (kg/day), and transportation cost (₹/day)—under four scenarios: Baseline, Balanced Optimization, Minimum Energy, and Minimum Emission. Each metric is represented by a group of four color-coded bars corresponding to the scenarios. The graph shows that optimized strategies significantly reduce energy use, emissions, and costs compared to the baseline. Balanced optimization achieves overall sustainability, minimum energy prioritizes energy reduction, and minimum emission focuses on lowering CO_2 output. The clear visual distinction highlights the effectiveness of optimization in promoting sustainable transportation planning.

V. CONCLUSION

The study on transportation energy consumption modelling and optimization highlights the critical role of data-driven strategies in achieving sustainable urban mobility. The results demonstrate that computational modelling, coupled with advanced optimization algorithms, can significantly reduce energy consumption, carbon emissions, and operational costs, thereby contributing to environmental, economic, and social sustainability. MATLAB-based simulations show that optimized transportation scenarios—whether focusing on balanced sustainability, minimum energy, or minimum emissions—lead to energy reductions of approximately 38%, emission reductions of 38%, and cost savings of over 32% compared to baseline conventional systems. These improvements are achieved by redistributing passenger demand toward high-capacity, energy-efficient, and low-emission modes such as buses, trains, and electric vehicles. The findings underscore the importance of multi-objective optimization in urban transportation planning. Balanced optimization ensures that energy efficiency, environmental protection, and economic viability are simultaneously addressed, while specialized priorities like minimum energy or minimum emission demonstrate the potential for targeted interventions. The methodology, which integrates passenger demand modelling, modal analysis, and scenario-based optimization, provides a flexible framework for policymakers and urban planners to evaluate trade-offs between performance objectives and design sustainable transport networks tailored to specific urban contexts. Furthermore, the study emphasizes the complementary role of technologies such as Geographic Information Systems (GIS), Intelligent Transport Systems (ITS), and digital monitoring platforms. These tools enhance decision-making by providing real-time data, spatial analysis, and scenario visualization, which are essential for resilient and efficient transportation systems.

In conclusion, transportation energy consumption modelling and optimization offers a robust, practical approach for promoting sustainable development. By adopting optimized modal distributions, advanced computational models, and technological integration, cities can achieve cleaner, more efficient, and cost-effective transportation systems, support long-term sustainability goals and improve urban quality of life.

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