Vol 6, Issue 3, March 2026 www.ijesti.com E-ISSN: 2582-9734
International Journal of Engineering, Science, Technology and Innovation (IJESTI)

Evaluating Life Cycle Costs and Carbon Footprint of Highway Pavement Systems for Sustainable Infrastructure

Sushil Kumar
M. Tech. in Transportation Engineering, CBS Group of Institutions, Jhajjar, Haryana.

Minakshi
A.P Civil Department, CBS Group of Institutions, Jhajjar, Haryana.

ABSTRACT

Highway pavement systems play a crucial role in transportation infrastructure, influencing mobility, economic development, and sustainability. Recent studies emphasize the importance of assessing life cycle costs (LCC) and carbon footprints (CF) to ensure sustainable infrastructure. Findings highlight that carbon emissions from pavement construction and maintenance extend beyond initial phases, impacting environmental sustainability throughout the life cycle. Key challenges include underrepresented emissions during maintenance, material-intensive construction, and data inconsistencies in life cycle assessment (LCA) models. Addressing these issues requires better data integration, sustainable materials, and advanced tools to achieve accurate carbon footprint evaluations and support climate goals.

Keywords: *Highway Pavement, Life Cycle Assessment, Carbon Footprint, Sustainability, Construction Materials.*

I. INTRODUCTION

Highway pavement systems represent one of the most critical components of transportation infrastructure, directly influencing mobility efficiency, economic development, and environmental sustainability. In recent years, increasing attention has been directed toward evaluating the life cycle cost (LCC) and carbon footprint (CF) of pavement systems, particularly in the context of sustainable construction materials and climate change mitigation. The construction, maintenance, and rehabilitation of highways are resource-intensive processes that contribute significantly to greenhouse gas (GHG) emissions, primarily due to material production, energy consumption, and transportation activities. Consequently, integrating life cycle assessment (LCA) methodologies into pavement engineering has become essential for developing environmentally responsible infrastructure systems. Several recent studies have highlighted that carbon emissions from highway construction and maintenance are not limited to the construction phase alone but extend throughout the entire life cycle of the pavement system. Bai et al. (2026) emphasized that road maintenance activities contribute substantially to overall carbon emissions, yet these emissions remain underrepresented in conventional LCA models due to data variability, methodological inconsistencies, and uncertainty in maintenance scheduling. Their findings indicated that traditional tools often fail to capture emissions arising from traffic congestion during maintenance operations and fragmented institutional data systems, thereby limiting the accuracy of sustainability assessments. Similarly, Dahal et al. (2025) conducted a cradle-to-gate LCA of road upgrading projects in Nepal and found that material production accounts for nearly 91% of total emissions, with cement, steel, and bitumen identified as the most carbon-intensive materials. This highlights the dominance of embodied carbon in pavement systems, reinforcing the need for material innovation and substitution strategies. In alignment with this, Liu (2025) developed an LCA-based framework for expressway construction and observed that asphalt thickness and base layer design significantly influence total emissions, demonstrating the strong correlation between structural design parameters and environmental impact. Further expanding this perspective, Gao et al. (2024) reported that raw material production and construction activities collectively contribute more than

95% of total emissions in highway projects. Their study emphasized that bridge and tunnel structures are particularly emission-intensive due to high material demand and energy usage. Singh et al. (2023) addressed the Indian context by developing an Excel-based carbon estimation tool, highlighting the need for region-specific models that can assist engineers in evaluating emissions across rigid and flexible pavement systems.

In addition, Yi et al. (2023) analyzed tunnel construction emissions and found that deterioration in surrounding rock conditions leads to increased material usage and higher emissions. Their study reinforced the importance of optimizing structural design and adopting low-carbon construction materials. Yousif and Zakaria (2022) further contributed by proposing a data integration framework linking green highway performance with carbon footprint assessment, emphasizing the role of digital tools in improving decision-making efficiency in highway management systems. From a broader perspective, Labaran et al. (2021) reviewed global construction industry emissions and identified that cement and steel production remain the largest contributors to GHG emissions across infrastructure projects. Similarly, Park et al. (2020) expanded the environmental assessment scope beyond carbon emissions by incorporating multiple impact categories such as toxicity, acidification, and eutrophication, suggesting that pavement sustainability should be evaluated using a multi-criteria environmental approach rather than carbon alone. Muhammad Fatihi Hafifi Che Wahid et al. (2019) compared different carbon footprint calculation tools and concluded that Excel-based models are often more practical and user-friendly than complex LCA software for highway applications. Liu et al. (2019) further demonstrated that traditional conventional assessment methods significantly underestimate emissions compared to comprehensive LCA approaches, particularly due to the exclusion of traffic delay impacts during maintenance operations. Collectively, these studies establish that life cycle-based carbon assessment of highway pavement systems is essential for achieving sustainable infrastructure development. They also highlight the importance of integrating sustainable construction materials, improving data quality, and adopting advanced computational tools for accurate environmental evaluation. However, significant challenges remain, including methodological inconsistencies, lack of standardized emission databases, and limited incorporation of maintenance-phase emissions. Addressing these gaps is crucial for advancing low-carbon highway engineering and supporting global climate goals.

II. RESEARCH BACKGROUND

Bai et al. (2026) examined the often-overlooked carbon emissions associated with road maintenance, noting that their complexity and uncertainty had led to gaps in life cycle assessment (LCA) studies. The study reportedly reviewed 63 relevant publications and surveyed 31 industry professionals to assess methodologies, challenges, and strategies for quantifying and mitigating maintenance-phase emissions. It was observed that while LCA remained the dominant framework, existing tools and approaches inadequately captured the specific complexities of maintenance activities. The research highlighted critical data challenges, including variability in maintenance schedules, institutional fragmentation causing inconsistent data practices, and difficulties in estimating emissions from traffic congestion during maintenance periods. Furthermore, the study identified practical mitigation strategies supported by both literature and practitioners, such as adopting sustainable materials, prioritizing preventive maintenance, coordinating with utility operators, and improving pavement rolling resistance to enhance vehicle efficiency. These findings were reported to provide a more comprehensive framework for reducing the climate impacts of road maintenance, offering valuable guidance for policymakers and practitioners aiming to integrate decarbonization into infrastructure management.

Dahal et al. (2025) investigated the carbon footprint associated with selected road upgrading projects along the Asian Highway in Nepal by applying a cradle-to-gate Life Cycle Assessment methodology. The study was undertaken in the context of transportation and construction sectors being recognized as major contributors to greenhouse gas emissions, with the objective of quantifying emissions arising from raw material production, transportation, and on-site construction activities. It was reported that the assessment relied on both primary data derived from detailed project estimates and secondary data obtained from standardized carbon emission databases. The findings revealed that material production contributed the highest proportion of total emissions (91%), followed by construction activities (5%) and transportation (4%). Cement, steel, and bitumen were identified as the most carbon-intensive materials, while earthwork was found to be the dominant source of emissions among construction activities. The study emphasized the need for targeted emission reduction strategies and supported the adoption of low-carbon materials and construction techniques in Nepal's road infrastructure development.

Liu (2025) conducted a quantitative assessment of the carbon emission characteristics of expressway construction and identified the major factors influencing emissions by developing a comprehensive carbon accounting framework based on the life cycle assessment (LCA) approach. The framework was reported to encompass material production, transportation, and construction stages. Typical expressway projects were selected as case studies for stage-wise emission quantification and multivariable response analysis. The findings indicated that total carbon emissions during the construction phase were approximately 1.80×10^3 kg CO_2-eq/km, with material production contributing the largest share, followed by transportation and construction activities. It was further observed that the thickness of asphalt surface and cement-stabilized base layers showed a strong positive correlation with total emissions, making them the most critical control variables. Transportation distance and equipment efficiency were found to be moderately sensitive factors. The study also revealed nonlinear coupling effects among structural and transport parameters and proposed low-carbon strategies for sustainable expressway construction.

Gao et al. (2024) investigated the increasing concern surrounding carbon dioxide (CO_2) emissions generated during road infrastructure construction and proposed a binary statistical method for highway construction that integrated project cost control with a construction management system. The study also conducted a quantitative assessment of CO_2 emissions from highway construction activities to support the development of effective carbon reduction strategies. Using an expressway project in central China as a case study, the authors calculated emissions from various construction activities and reported that the total CO_2 emissions for the entire project reached 10,605.2 $t \cdot km^{-1} \cdot lane^{-1}$. It was found that raw material production and on-site construction phases accounted for 95.2% and 4.8% of total emissions, respectively. The findings further indicated that bridge and tunnel engineering produced substantially higher emissions than other engineering types. Steel, cement, diesel, and electricity were identified as the principal emission sources, emphasizing the need for low-carbon materials, improved efficiency, enhanced machinery performance, and advanced construction technologies.

Singh et al. (2023) investigated the growing need to expand India's road network in response to increasing population demands, while also addressing the environmental concerns associated with highway construction and rehabilitation. The study highlighted that greenhouse gas emissions generated during road development activities had a significant impact on the environment and contributed to global warming. It was observed that an appropriate tool for calculating, monitoring, and mitigating such carbon emissions in the Indian context had not yet been adequately developed. Therefore, the primary objective of the research was to design an Excel-based tool named the *Carbon Footprint Estimation Tool for Highway Constructions*, specifically suited to the Indian construction environment. The study reported that the tool was developed to estimate carbon equivalent emissions from materials used in highway construction. It was further noted that the tool enabled the monitoring and comparison of carbon emissions across different materials and pavement layers in both rigid and flexible pavement systems.

Yi et al. (2023) developed a standardized calculation process based on the life cycle assessment (LCA) approach to accurately quantify and evaluate carbon dioxide emissions during the construction phases of highway tunnels. The study was reported to have established a systematic framework covering carbon emission boundaries, inventory analysis, and the development of a calculation model. Using engineering case examples and the SimaPro LCA tool, the carbon emissions per linear meter of tunnels constructed under different surrounding rock conditions were calculated and analyzed. The findings indicated that carbon emissions per linear meter increased significantly during both the material production and construction stages as the surrounding rock quality deteriorated. It was further observed that the material production stage accounted for the largest share of total emissions, with secondary lining material production contributing a particularly high proportion. The study concluded that advancements in material production technology and carbon-reduction-oriented lining structure design were critical strategies for minimizing overall carbon emissions in highway tunnel construction.

Yousif and Zakaria (2022) investigated the growing importance of effective data utilization and information system reliability in Malaysian highway concession projects, where substantial resources had been invested in collecting, analysing, and managing diverse forms of data throughout the project life cycle. The study proposed a new paradigm for integrating green highway performance data with carbon footprint data to support comprehensive green highway assessment. It was reported that the framework aimed to enhance the active use of data in generating meaningful information and improving decision-making across all management levels. The network-based approach was identified as the core mechanism for linking data, knowledge, and decisions, as well as for defining integration parameters and evaluation criteria. Real-time green highway data scenarios were employed to demonstrate the framework's applicability. The authors also introduced the MyGHI-Dashboard as a monitoring tool for controlling assessment processes and evaluating data usage levels, which was suggested as a benchmarking model for more efficient and accurate highway management decisions.

Labaran et al. (2021) reviewed the significant contribution of the construction industry to global greenhouse gas emissions and highlighted its role as a major pollution hotspot requiring urgent mitigation strategies. The study noted that the sector accounted for nearly 19% of total global GHG emissions, thereby intensifying concerns regarding climate change. It was observed that limited research had been available to adequately support construction companies in achieving low-carbon targets. Through a systematic review of global studies, the authors examined scholarly contributions related to carbon dioxide and other greenhouse gas emissions from the construction sector. The findings indicated that most researchers had concentrated on specific components of the industry or case studies of particular countries, cities, or regions, largely employing the Life Cycle Assessment approach. It was further reported that studies on similar materials, such as cement and steel, had adopted varying methodologies, units, and reporting techniques, making direct comparisons difficult. Nevertheless, the review concluded that the scale and significance of construction-related emissions had remained clearly evident across the literature.

Park et al. (2020) investigated the environmental issues associated with construction materials in road projects, emphasizing that carbon emissions alone were insufficient for evaluating their full environmental burden. The study was aimed at identifying the major environmental impact categories of construction materials during the production stage through the application of life cycle assessment (LCA). Based on a review of life cycle impact assessment (LCIA) methodologies, several impact categories were defined, including abiotic depletion potential, ozone depletion potential, photochemical oxidant creation potential, acidification potential, eutrophication potential, eco-toxicity potential, human toxicity potential, and global warming potential. It was reported that major environmental pollutants from multiple road projects were analyzed to establish relevant impact categories for 13 key construction materials. These materials were found to account for more than 80% of total environmental impacts from an LCA perspective. The study further proposed specialization impact categories for materials contributing over 99%, thereby offering foundational LCIA data for future road construction assessments.

Muhammad Fatihi Hafifi Che Wahid et al. (2019) investigated the substantial carbon dioxide emissions associated with highway infrastructure throughout its entire life cycle, including emissions from raw material production, construction, operation, maintenance, and rehabilitation. The study reviewed past carbon emission trends across these stages and examined their major sources while also suggesting mitigation and abatement strategies. It was reported that the paper presented, for the first time, a systematic review of carbon footprint calculators based on 21 highway case studies from eight different countries. The review focused on methods used to calculate the carbon footprint of highway development and synthesized the outcomes of these studies to determine whether Excel-based tools or Life Cycle Assessment (LCA) software provided better performance and ease of calculation. The findings indicated that Excel tools were more effective and convenient for analyzing emissions from multiple sources and stages than LCA software. The study emphasized the importance of understanding these methodological relationships for accurate greenhouse gas reporting by highway agencies.

Liu et al. (2019) investigated the often-overlooked potential for reducing carbon dioxide (CO_2) emissions in highway maintenance projects. The study compared conventional assessment (CA), which focused mainly on fuel combustion from off-road maintenance equipment, with a comprehensive life cycle assessment (LCA) that incorporated materials production, fuel production, traffic delay, and maintenance equipment emissions. Using Microsoft spreadsheet models, VISSIM, and the CMEM model, four typical maintenance schemes from an actual highway project in China were analyzed. The case study was reported to have examined the magnitude and sources of discrepancies between CA and LCA results. The findings revealed a substantial gap, with total CO_2 emissions estimated by LCA reaching up to 22 times higher than those from CA. Traffic delay due to lane closures was identified as the largest contributor to this difference. The scenario analysis further indicated that LCA more effectively captured dominant emission sources and mitigation opportunities, whereas CA often underestimated decarbonization potential.

III. KEY FINDINGS FROM STUDY

Author (Year)	Focus Area	Methodology	Key Findings
Bai et al. (2026)	Road maintenance emissions	Literature review + survey	Maintenance emissions underrepresented; data variability and traffic delay are major gaps
Dahal et al. (2025)	Road upgrading projects	Cradle-to-gate LCA	Material production contributes 91% emissions; cement and steel are key contributors
Liu (2025)	Expressway construction	LCA-based modelling	Asphalt thickness strongly affects emissions; nonlinear parameter effects observed
Gao et al.	Highway	LCA + case study	95.2% emissions from materials; bridges

(2024)	construction emissions		and tunnels are high-emission components
Singh et al. (2023)	Carbon estimation tool	Excel-based model	Developed practical tool for India; enables material-level emission comparison
Yi et al. (2023)	Tunnel construction	SimaPro LCA	Poor rock conditions increase emissions; lining materials major contributors
Yousif & Zakaria (2022)	Green highway data integration	Framework development	Proposed real-time carbon data dashboard for decision-making
Labaran et al. (2021)	Construction industry emissions	Systematic review	Cement and steel dominate global construction emissions
Park et al. (2020)	Environmental impacts of materials	LCIA methodology review	Identified multiple environmental impact categories beyond carbon
Wahid et al. (2019)	Carbon footprint tools	Comparative review	Excel tools more practical than LCA software for highway analysis
Liu et al. (2019)	Highway maintenance emissions	LCA vs conventional assessment	Conventional methods underestimate emissions up to 22 times

IV. CONCLUSION

The reviewed literature clearly establishes that highway pavement systems contribute significantly to global carbon emissions throughout their life cycle, with material production emerging as the dominant source. Studies consistently demonstrate that cement, steel, asphalt, and bitumen are the most carbon-intensive materials, while construction and maintenance activities further amplify environmental impacts. Life Cycle Assessment (LCA) has been widely adopted as the primary analytical framework; however, its effectiveness is often limited by data uncertainty, methodological inconsistencies, and inadequate consideration of maintenance-phase emissions. The findings also indicate that conventional assessment methods substantially underestimate total emissions, highlighting the need for more comprehensive and integrated evaluation models. Moreover, emerging tools such as Excel-based calculators and digital data integration frameworks have improved accessibility and decision-making in pavement sustainability analysis. Overall, the literature strongly supports the transition toward sustainable pavement systems through low-carbon materials, optimized structural design, and improved lifecycle-based planning strategies.

V. FUTURE SCOPE

- Development of standardized global databases for pavement emission factors to improve LCA accuracy.
- Integration of Artificial Intelligence and machine learning for predictive life cycle carbon modeling of pavement systems.
- Advancement of low-carbon and bio-based construction materials such as geopolymer concrete and recycled asphalt pavement (RAP).
- Inclusion of real-time traffic and maintenance data to enhance dynamic carbon footprint estimation models.

- Development of multi-criteria sustainability frameworks combining LCC, LCA, and environmental impact categories beyond carbon emissions.
- Adoption of digital twin technology for continuous monitoring and optimization of highway pavement performance and emissions.
- Policy-level implementation of carbon budgeting for large-scale highway infrastructure projects.

REFERENCES

1. Bai, S., Varga, L., & Manola, E. (2026). Unexplored challenges in quantifying and reducing carbon emissions in road maintenance. *Transportation Research Part A: Policy and Practice*, *204*, 104844.
2. Dahal, D., Bhattarai, S. K., Shrestha, R., Adhikari, B., & Tummalapudi, M. (2025). Carbon Footprint Assessment of Selected Road Upgrading Projects on the Asian Highway. *Available at SSRN 5387969*.
3. Liu, Z. (2025). Life-Cycle-Assessment-Based Quantification and Low-Carbon Optimization of Carbon Emissions in Expressway Construction. *Infrastructures*, *10*(11), 291.
4. Gao, S., Liu, X., Lu, C., Zhang, H., Wang, X., & Kong, Y. (2024). Quantitative analysis of carbon emissions from highway construction based on life cycle assessment. *Sustainability*, *16*(14), 5897.
5. Singh, A., Srivastava, V., & Tiwari, A. K. (2023). Carbon footprint estimation of highway construction materials. *J Environ Nanotechnol*, *12*(4), 22-34.
6. Yi, L. J. X. M. S., & Hehua, L. A. Z. (2023). Calculation and composition assessment of the carbon emission in the construction phase of highway tunnels based on SimaPro. *Modern Tunnelling Technology*, *60*(6), 20-28.
7. Yousif, O. S., & Zakaria, R. (2022). A framework for integrating green highway performance data with the carbon footprint calculator in Malaysia. *Construction economics and building*, *22*(2), 102-120.
8. Labaran, Y. H., Mathur, V. S., & Farouq, M. M. (2021). The carbon footprint of construction industry: A review of direct and indirect emission. *Journal of Sustainable Construction Materials and Technologies*, *6*(3), 101-115.
9. Park, W. J., Kim, R., Roh, S., & Ban, H. (2020). Analysis of major environmental impact categories of road construction materials. *Sustainability*, *12*(17), 6951.
10. Muhammad Fatihi Hafifi Che Wahid, C., Rozaid Ramli, M., Aminudin, E., Zainon Noor, Z., Neardey, M., Zakaria, R., ... & Chang Sa'ar, C. (2019, April). Review on the method for carbon footprint calculation of highway development. In *IOP Conference Series: Materials Science and Engineering* (Vol. 513, No. 1, p. 012001). IOP Publishing.
11. Liu, Y., Wang, Y., Li, D., Feng, F., Yu, Q., & Xue, S. (2019). Identification of the potential for carbon dioxide emissions reduction from highway maintenance projects using life cycle assessment: a case in China. *Journal of Cleaner Production*, *219*, 743-752.