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Economic Evaluation of Pavements under Changing Traffic Load Conditions

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ABSTRACT

This study presents a Life Cycle Cost Analysis of flexible and rigid pavement systems under varying traffic conditions. The analysis compares both pavement types by considering initial construction cost, maintenance cost, rehabilitation cost, user cost, service life, and long-term performance. The result shows that flexible pavement is more economical for low and medium traffic roads due to its lower initial cost and easy maintenance. However, rigid pavement becomes more cost-effective under high traffic and heavy commercial vehicle conditions because of its durability, longer service life, and reduced maintenance frequency.

Keywords: *Life Cycle Cost Analysis, Flexible Pavement, Rigid Pavement.*

I. INTRODUCTION

Life Cycle Cost Analysis of Flexible and Rigid Pavement Systems under Varying Traffic Conditions is an important area of study in highway engineering because pavement construction requires large financial investment and long-term planning. Roads are essential infrastructure for economic growth, transportation efficiency, trade, social connectivity, and regional development. However, the selection of a pavement type should not be based only on the initial construction cost, because pavements continue to generate expenses throughout their service life in the form of maintenance, repair, rehabilitation, resurfacing, user delay, vehicle operating cost, and eventual reconstruction. Flexible pavements and rigid pavements are the two major pavement systems used in road construction. Flexible pavement is generally constructed using bituminous materials and granular layers, and it transfers wheel loads to the subgrade through grain-to-grain contact and layer-wise distribution. It usually has lower initial construction cost and is easier to repair, but it may require frequent maintenance under heavy traffic and adverse environmental conditions. Rigid pavement, on the other hand, is mainly constructed with cement concrete and possesses higher flexural strength, allowing it to distribute traffic loads over a wider area. Although rigid pavement generally involves higher initial construction cost, it often provides longer service life, better load-carrying capacity, and lower maintenance requirements, especially under high-volume and heavy-load traffic conditions. Traffic condition is one of the most important factors affecting pavement performance and cost. Roads carrying low traffic volumes may not experience rapid deterioration, while roads exposed to heavy commercial vehicles, overloaded trucks, and repeated axle loads may suffer faster structural damage. Under low and medium traffic conditions, flexible pavement may appear more economical because of its lower initial investment and simple maintenance techniques. However, when traffic intensity increases, flexible pavement may develop defects such as rutting, fatigue cracking, potholes, bleeding, and surface deformation, which increase maintenance frequency and long-term expenditure. Rigid pavement performs better under heavy traffic because of its high stiffness and durability, but it may also require joint maintenance, crack sealing, slab replacement, and surface restoration over time. Therefore, a proper economic comparison between flexible and rigid pavement systems must include all costs occurring during the entire analysis period rather than considering only construction cost. Life Cycle

Cost Analysis provides a systematic method for evaluating pavement alternatives by converting future costs into present value using discount rate and economic evaluation techniques. Important components of LCCA include initial construction cost, periodic maintenance cost, rehabilitation cost, user cost, vehicle operating cost, salvage value, inflation effect, and analysis period. Methods such as Net Present Value, Equivalent Annual Cost, Benefit-Cost Ratio, and sensitivity analysis are commonly used to compare pavement alternatives under different traffic scenarios. Sensitivity analysis is especially useful because pavement cost may vary due to changes in material prices, fuel cost, labour charges, traffic growth rate, discount rate, and maintenance strategy. The study of LCCA under varying traffic conditions helps engineers, planners, and policymakers identify the most economical and sustainable pavement option for different categories of roads such as rural roads, urban roads, highways, industrial corridors, and expressways. It also supports better budget allocation and reduces unnecessary expenditure by selecting pavement systems based on long-term performance. In the present context, where infrastructure development must balance cost efficiency, durability, sustainability, and service quality, Life Cycle Cost Analysis becomes a valuable decision-making tool. It helps ensure that pavement selection is not influenced only by short-term construction savings but by total economic performance throughout the design life. Hence, the comparative analysis of flexible and rigid pavement systems under varying traffic conditions is essential for achieving durable, economical, and efficient road infrastructure.

II. RESEARCH BACKGROUND

Al-Taher et al. (2026) had reviewed the growing environmental and public health concerns in road construction and emphasized the increasing importance of sustainable, eco-friendly technologies and asphalt mixture durability in pavement engineering. The study had explained that durability was associated with the long-term response of asphalt mixtures to moisture and temperature variations, while balanced mix design practices were considered essential for achieving desirable properties such as stability, flexibility, tensile and fracture strength, fatigue resistance, skid resistance, and moisture damage resistance. The authors had presented a comprehensive review of the factors influencing asphalt pavement durability, including relevant indicators, laboratory evaluation methods, and advanced techniques used for durability assessment. They had further examined moisture susceptibility as a major cause of reduced pavement life, noting that water weakened the asphalt–aggregate bond, promoted stripping, and caused cohesive failure within the binder. In addition, the study had assessed the selection and effectiveness of material additives for enhancing durability and discussed key durability performance indicators. Overall, the review had contributed valuable guidance for improving field-based durability assessment and narrowing the gap between laboratory investigations and actual pavement performance over the design life.

Tiwari et al. (2025) investigated pavement management systems, emphasizing the role of maintenance and rehabilitation (M&R) in delaying reconstruction by mitigating early-stage pavement deterioration. The study employed life-cycle cost analysis (LCCA) as a financial evaluation tool to compare flexible and rigid pavement alternatives over a 50-year period, considering initial construction costs, M&R expenses for both users and agencies, and salvage value. Four roadways with varying traffic levels were analyzed using a deterministic approach, accounting for differences in treatment frequency based on average daily truck traffic. Findings indicated that initial construction costs dominated net present value (NPV), comprising 72% to 91%, while user costs were minimal, contributing less than 6% of NPV. The highest NPV recorded was $0.90 M for flexible pavements and $1.34 M for rigid pavements, with percentage differences in NPV ranging from 39% to 56%. The study concluded that flexible pavements appeared more cost-effective across diverse traffic and thickness scenarios, although actual field performance would ultimately determine their long-term effectiveness.

Abid et al. (2025) investigated the role of transportation infrastructure in fostering regional economic growth, particularly in rapidly industrializing and residential areas, by conducting a comparative analysis of rigid (concrete) and flexible (asphalt) pavements on the Kedamean Sidoraharjo Randegan road section in Gresik Regency, East Java. The study was motivated by the strategic significance of the region, reinforced by the Krian Legundi Bunder Manyar (KLBM) toll road, which had substantially increased traffic flows and underscored the need for durable and sustainable road infrastructure. The researchers employed a quantitative descriptive approach, integrating traffic projections (Average Daily Traffic for 20th and 40th year horizons), CESAL calculations, and pavement design using MDPJ 2017 for flexible pavement and Pd T-14-2003 for rigid pavement, while cost estimations were based on regional unit prices from the Gresik Regency Public Works Department. They reported that flexible pavement offered shorter construction time and lower initial costs, but rigid pavement was more cost-effective over the long term due to greater durability and lower maintenance requirements. The study also noted that leveraging existing pavement layers could reduce construction costs by up to 10%, supporting sustainable infrastructure practices, and suggested that these findings could guide civil engineers and local authorities in selecting pavement types based on traffic intensity, budget constraints, and long-term planning.

Manjunatha et al. (2024) highlighted that rapid urbanization over the last century had influenced both rural and urban regions, prompting the accelerated construction of roads and transportation infrastructure to meet rising demands for connectivity and services. They reported that researchers, designers, and builders had been exploring innovative and cost-effective construction materials to streamline building processes and enhance structural robustness. The study indicated that concrete pavements had gained popularity in India due to the increasing costs of bituminous pavements, with stiff pavements being valued for their resilience under extreme weather and heavy traffic. It was noted that despite higher initial costs, concrete pavements often proved more economical over time due to reduced maintenance needs and extended design life. The research aimed to provide a comparative assessment of pavement suitability considering longevity, durability, and cost-effectiveness. Simulations were employed to quantify dynamic strains and deflections in rigid and flexible pavements, revealing that surface roughness significantly affected the dynamic response and service life of slab structures. Furthermore, the model was adaptable for determining the k-value necessary to evaluate subgrade support as pavements aged.

Sharma et al. (2023, March) investigated the impact of geogrid on the performance of flexible pavements and assessed its cost-effectiveness. The study encompassed laboratory testing, pavement design, and Life Cycle Cost Analysis. It was reported that soil samples reinforced with geogrid exhibited an approximate 40% improvement in strength, as measured by CBR tests. Based on these CBR values, two pavement sections were designed following IRC 37:2018 guidelines for a design traffic of 50 MSA. The findings indicated that the section with geogrid reinforcement required reduced layer thicknesses compared to the conventional pavement, with a maximum reduction of about 20% observed in the Wet Mix Macadam layer. Furthermore, initial construction and maintenance costs were estimated, and life cycle cost analyses were performed considering inflation and discount rates. Results suggested that pavements incorporating geogrid reinforcement were approximately 5% less expensive than conventional sections. The study was envisioned to provide valuable insights for road agencies, practitioners, and stakeholders regarding geogrid use in pavement construction.

Zhang et al. (2023) investigated the optimal application of pavement rehabilitation, emphasizing the importance for highway agencies to efficiently allocate limited budgets. They applied life-cycle cost (LCC) analysis in combination with probabilistic pavement performance models based on survival analysis to assess the cost-effectiveness of various overlay strategies. Survival models were developed using the international roughness index (IRI) as a performance indicator, while accounting for terminal IRI values, discount rates, precipitation, and traffic volumes. The study reported significant differences in survival probabilities between thin (2 in.) and thick (5 in.) overlays, whereas pavement service life was found to be largely independent of overlay material type (virgin or recycled) and milling. It was concluded that sequences of thin overlays were generally more cost-effective than thick overlays under moderate traffic conditions, but in wet regions with annual traffic exceeding 500,000 equivalent single axle loads, thick overlays were considered more cost-effective.

Zhang et al. (2022) investigated the sustainable design of pavements in the context of achieving carbon neutrality, highlighting its significance for green pavement development. They examined the impacts of key design parameters on the environmental and economic performances of asphalt pavements by applying process life cycle assessment (LCA) and life cycle cost (LCC) methods. Their study primarily focused on the effects of pavement type, resilient modulus of subgrade, adjustable layer thickness, traffic level, and bidirectional annual average daily traffic of two-axis six-wheel and above vehicles (AADTT) on energy consumption, greenhouse gas (GHG) emissions, construction budgets, and environmental economy costs during the construction period. The findings suggested that for both heavy and medium traffic pavements, the largest contributions to energy use, GHG emissions, and costs occurred during the materials preparation stage, followed by transportation and construction stages. The indicators were reported to be strongly influenced by AADTT, layer thickness, and pavement type, whereas the resilient modulus of subgrade had minimal effect. Overall, flexible base asphalt pavements were found to have lower energy consumption and GHG emissions than semi-rigid base pavements, despite higher construction budgets and environmental economy costs.

He et al. (2021) investigated the enhancement of transportation asset management practices over the past decade through the integration of sustainability considerations. They highlighted that although organizational- and network-level guidelines had been developed to support sustainability-driven highway network prioritization, quantifying life cycle economic, social, and environmental impacts of highway treatment activities at the project level remained challenging due to inconsistent and unreliable data. The study proposed a decision support framework that integrated life cycle assessment (LCA) and life cycle cost analysis to identify major project-level impacts, enabling practitioners to select the most appropriate alternatives. Databases such as RSMeans and simulation models including Athena Pavement LCA and MOtor Vehicle Emission Simulator were employed to assess impacts from both agency and user perspectives. Various sustainable techniques—warm mix asphalt overlay, cold in-place recycling, full depth reclamation, intelligent compaction, and precast concrete pavements—were analyzed, and the results were shown to assist practitioners in understanding trade-offs, performing what-if analyses, and achieving sustainability-related objectives.

Llopis-Castelló et al. (2020) investigated the prediction of urban flexible pavement conditions over time, noting that previous studies had mostly been region-specific with constant climate conditions or had focused on single distress parameters. Their research aimed to assess the influence of pavement structure, traffic demand, and climate factors on pavement performance. They used the Structural Number as an indicator of pavement capacity, defined multiple traffic and climate variables, and employed the Pavement Condition Index as a surrogate measure of pavement condition. Regression models were calibrated using the K-Fold Cross Validation technique. Their findings suggested that, for a given pavement age, higher Equivalent Single Axle Load and greater Annual Average Height of Snow accelerated pavement deterioration. Similarly, cold Annual Average Temperatures (5–15 °C) and large Annual Average Temperature Ranges (20–30 °C) promoted faster deterioration, whereas warm climates with low temperature variations and minimal precipitation contributed to longer pavement service life. The study also proposed a new classification of climate zones based on their influence on pavement deterioration.

Nezhadpour Esmaeeli and Heravi (2019) investigated the application of a fuzzy real options methodology to assist highway management organizations in selecting the optimal project implementation alternative. They reported that uncertainties in input factors, such as unit costs of construction items, user cost rates, annual traffic growth, and discount rates, were addressed through fuzzy set theory, while managerial flexibilities related to initial construction, preventive maintenance, and rehabilitation were modeled using real options (RO) theory. The authors developed a software package, Pavement Alternative Selection by RO-based Decision Support system (PASRODS), implemented in Microsoft Excel with Visual Basic for Applications, comprising database, model, and reporting components. PASRODS analyzed projects through a year-by-year backward dynamic programming approach. The application of PASRODS in a highway project case study in Iran demonstrated that accounting for managerial flexibilities enabled more rational and realistic project valuation, and that varying decision-maker attitudes could alter alternative rankings, thereby supporting the selection of the most suitable option across multiple criteria.

Hamim and Hoque (2019) investigated the prediction of service life for flexible pavements in Bangladesh under conditions of rampant overloading. They collected axle load data, international roughness index (IRI) measurements, and overlay histories for several road sections constructed by the Roads and Highways Department. Survival curves were developed, which indicated that the actual pavement life averaged around 4.88 years. Further analysis, using superimposed graphs of damaging factor versus axle load and pavement life versus axle load, revealed that premature pavement failure occurred at approximately 4.5 years. The study concluded that, under the prevailing overloaded traffic conditions, flexible pavements could sustain only about five years of service, which corresponded to roughly one-fourth of their intended design life. The authors highlighted that this significant reduction in pavement life generated major concerns for Bangladesh, as it increased maintenance costs and constrained funding for new infrastructure development.

III. METHODOLOGY

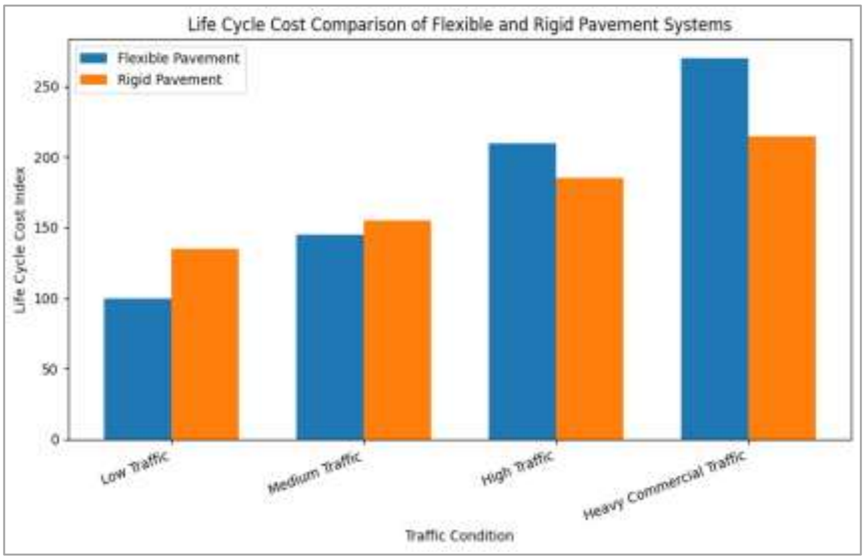
The methodology of this study was designed to compare the life cycle cost of flexible and rigid pavement systems under different traffic conditions. First, the pavement alternatives were identified as flexible pavement and rigid pavement. Then, traffic conditions were classified into low traffic, medium traffic, high traffic, and heavy commercial traffic to understand how traffic load affects pavement cost and performance. After this, important cost components were selected for analysis, including initial construction cost, routine maintenance cost, periodic rehabilitation cost, user delay cost, vehicle operating cost, and salvage value at the end of the analysis period.

The study considered an assumed service life and analysis period for both pavement types. Future maintenance and rehabilitation costs were converted into present values using a suitable discount rate. This helped in comparing all costs on a common economic basis. Life cycle cost index values were then prepared for each traffic category to show the cost variation between flexible and rigid pavements. The results were arranged in tabular form and represented through a bar graph for better understanding. Finally, the pavement system with the lower total life cycle cost was identified for each traffic condition. The comparison helped determine whether flexible or rigid pavement was more economical under low, medium, high, and heavy traffic situations.

IV. RESULT

Traffic Condition	Flexible Pavement Result	Rigid Pavement Result	Economical Option
Low Traffic	Flexible pavement performed well because traffic load was limited. It had lower initial construction cost and required only minor maintenance.	Rigid pavement also performed satisfactorily, but its high initial cost was not justified for low traffic roads.	Flexible Pavement
Medium Traffic	Flexible pavement showed moderate performance. Maintenance such as patch repair, crack sealing, and resurfacing may be required after some years.	Rigid pavement showed better durability, but the construction cost was higher. Both systems may be suitable depending on local cost and design period.	Flexible or Rigid Pavement
High Traffic	Flexible pavement experienced faster deterioration due to repeated axle loads, rutting, fatigue cracking, and pothole formation. Maintenance and rehabilitation cost increased over time.	Rigid pavement performed better because of high strength, better load distribution, and longer service life. Maintenance frequency was comparatively lower.	Rigid Pavement
Heavy Commercial Traffic	Flexible pavement became less economical because heavy vehicles caused structural damage and frequent overlay requirements.	Rigid pavement was more suitable due to its capacity to resist heavy wheel loads and reduce long-term repair needs.	Rigid Pavement
Initial Construction Cost	Flexible pavement had lower initial cost and was easier to construct.	Rigid pavement had higher initial cost due to cement concrete construction and quality control requirements.	Flexible Pavement
Maintenance Cost	Flexible pavement required more frequent maintenance, especially under heavy traffic conditions.	Rigid pavement required less frequent maintenance, although joint repair and crack sealing may be needed.	Rigid Pavement
Service Life	Flexible pavement had comparatively shorter service life under heavy traffic conditions.	Rigid pavement had longer service life and better durability.	Rigid Pavement
Life Cycle Cost	Flexible pavement had lower life cycle cost under low and moderate traffic, but cost increased under high traffic.	Rigid pavement had higher initial cost but lower long-term cost under high traffic and heavy-load conditions.	Depends on Traffic Condition
Overall Result	Flexible pavement is more economical for low to medium traffic roads.	Rigid pavement is more economical for high traffic roads, highways, and industrial corridors.	Flexible for low/medium traffic; rigid for high traffic

Bar Graph



The graph compares the life cycle cost index of flexible and rigid pavement systems under different traffic conditions. It shows that flexible pavement has the lowest cost under low traffic because its initial construction cost is less. However, as traffic increases, the cost of flexible pavement rises sharply due to frequent maintenance, resurfacing, rutting, cracking, and rehabilitation needs. Rigid pavement has a higher cost at low and medium traffic levels, but it becomes more economical under high and heavy commercial traffic. This is because rigid pavement has greater strength, longer service life, and lower maintenance frequency under heavy axle loads.

V. CONCLUSION

The study concluded that Life Cycle Cost Analysis is an effective method for comparing flexible and rigid pavement systems under varying traffic conditions. The result showed that flexible pavement is more economical for low and medium traffic roads because it has lower initial construction cost and simple maintenance requirements. However, with an increase in traffic volume and heavy axle loads, flexible pavement requires frequent repair, resurfacing, and rehabilitation, which increases its total life cycle cost. Rigid pavement requires higher initial investment, but it performs better under high traffic and heavy commercial vehicle conditions. Its strong concrete structure, better load distribution capacity, longer service life, and lower maintenance frequency make it more economical in the long term for highways, industrial roads, and heavily loaded corridors. Overall, the selection of pavement type should not be based only on construction cost. It should include maintenance cost, rehabilitation cost, user cost, salvage value, traffic growth, and service life. Therefore, flexible pavement is suitable for low to moderate traffic conditions, while rigid pavement is more suitable and cost-effective for high traffic and heavy-load roads. Life Cycle Cost Analysis helps engineers and planners choose the most durable, economical, and sustainable pavement system.

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