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Life Cycle Cost Analysis of Flexible and Rigid Pavements: A Comprehensive Review

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Abstract

This paper presents a comprehensive review of the comparative performance of flexible and rigid pavements through Life Cycle Cost Analysis (LCCA), a decision-making framework that integrates economic principles into pavement engineering. LCCA provides a systematic evaluation of the total costs associated with pavement construction, maintenance, rehabilitation, and operation over the service life, enabling highway agencies to adopt cost-effective and sustainable investment strategies. While initial construction costs of flexible pavements are generally lower, rigid pavements often demonstrate reduced maintenance needs and longer service lives under heavy traffic loading, making the economic trade-offs context-dependent. This review synthesizes findings from national and international studies, with particular emphasis on Indian traffic and climatic conditions, to examine the relative suitability of each pavement type. It identifies key determinants influencing LCCA outcomes, including design life, traffic loading (expressed in million standard axles), discount rate, salvage value, and agency/user costs. The analysis underscores that while flexible pavements may be advantageous in regions with moderate traffic volumes and limited budgets, rigid pavements can provide superior long-term economic performance under high-volume, heavy axle load conditions. Critical research gaps remain, particularly in standardizing methodologies for incorporating user delay costs, environmental impacts, and risk/uncertainty factors into LCCA models. Addressing these gaps is essential for developing robust, evidence-based guidelines to support sustainable and cost-efficient pavement selection in India and other developing economies.

Keywords: *Pavement performance; Economic evaluation; Maintenance and rehabilitation; Pavement management; Sustainable infrastructure; Highway design; Traffic loading (msa)*

INTRODUCTION:

The cost reduction for building transport infrastructure has become a future challenge for researchers. Due to the rapidly increasing population, industrialization and urbanization progress in developing countries like India, there is vast need for transport infrastructure systems. The substantial cost of addressing infrastructure needs places a substantial liability on the government's limited resources, necessitating efficient oversight of the transport infrastructure system.

There is requirement of large capital investment for the road transport development, operational and maintenance and repair costs. The road network plays key role in the growth of a country. Long lasting roads that require minimal repair and operational costs play a key role in supporting development. Therefore, road agencies globally are struggling to identify pavement types that reduce periodic expenses. These pavements must also adapt to rising traffic volumes and changing vehicle types to meet user demands efficiently.

Highways are a crucial component of the transportation network and involve high construction expenses.

The overall cost of highway development is typically categorized into agency costs, user costs, and social costs. These categories, along with the subcomponents, are outlined in Table 1. Agency costs consist of two parts: initial construction costs and maintenance & rehabilitation (M&R) expenses. Initial construction costs include design work, land acquisition, and building elements like pavements, bridges, and tunnels. M&R costs involve all activities needed to ensure the highway remains in good condition and meets required standards. This includes preservation, rehabilitation, restoration, and reconstruction of both roads and associated infrastructure. All agency-related expenses are funded by transportation departments or highway authorities [5].

Table 1: Total Highway construction cost categories and sub-categories [5].

Category	**Agency costs**		**User costs**	**Social costs**
Subcategory	**Initial construction costs**	**M&R costs**		**Environmental costs**
Key components contributing to the overall cost of highway construction	Design	Preservation	Vehicle operation costs	Emissions and energy consumption at the time of construction and maintenance
	Right-of-way acquisition	Rehabilitation	Value of time costs	Energy consumption and emissions of vehicles
	Pavement and other highway elements.	Re-establishment	Work zone costs	
		Reconstruction	Accident costs	

User costs include vehicle operating expenses, time delays, costs associated with work zones, and accident-related expenditures. Social costs encompass environmental impacts arising from construction and maintenance activities, particularly affecting the areas adjacent to the highway.

The cost of primary materials is a significant factor influencing agency costs in road construction. With aggregate quantities assumed to be roughly equivalent in both pavement types, the comparison is drawn between cement for rigid pavements and bitumen for flexible pavements. Between 2002 and 2011, rigid pavements were generally more expensive to construct than flexible pavements. This was primarily due to the higher cost of cement concrete materials and the more labor-intensive construction methods required.

However, this trend reversed between 2012 and 2025, as bitumen prices rose sharply, driven by volatility in global crude oil markets. This significant increase in bitumen costs elevated the construction cost of flexible pavements, making them less economically favorable compared to rigid pavements in several cases.

A comparative cost analysis of cement and bitumen prices for a two-lane National Highway (1 km stretch) over the period 2002 to 2025 is presented in Figure 1, illustrating this shift in cost dynamics.

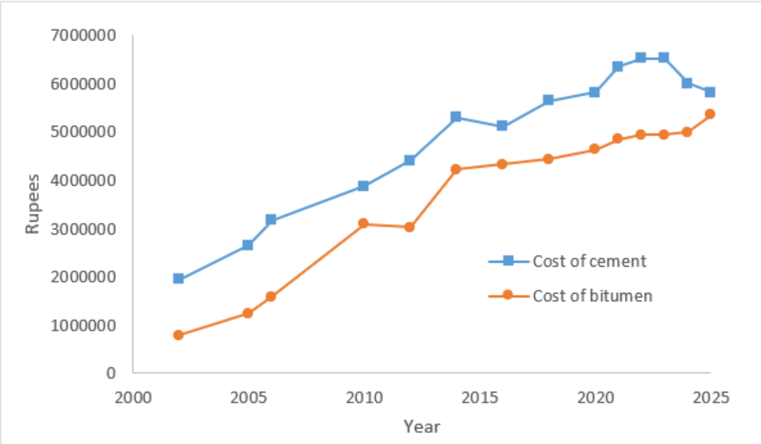

Figure 1: Cost comparison of cement and bitumen for a 2-lane National highway (1 Km stretch)

Further considering the M&R costs for the pavements, rigid pavements do not require any scheduled maintenance throughout its design life, minimum 30 years, whereas flexible pavements are more maintenance-intensive, typically requiring overlay or resurfacing every 5 years, depending on traffic and climate in a design life of 15 years [18-19]. Due to the regular increase in expenses related to the construction, repair, and rehabilitation of highway pavements, highway authorities across the globe have initiated implementing various methodologies to support effective decision-making [10]. LCCA is one of the verified approaches for road design and management to assess the long-term financial competence of several investment alternatives.

LIFE–CYCLE COST ANALYSIS (LCCA)

Life Cycle Cost (LCC) broadly refers about the expenditures (as outlined in Table 1) incurred throughout the complete lifespan of a highway. Given the significant financial investment involved over a highway's life cycle, even a small percentage of cost savings can result in considerable overall benefits [14–17].

In India, a developing country with varying climatic conditions and repeated overloading, highway maintenance management has become an important issue for road authorities. Moreover, funding challenges in developing economies often hinder road authorities from allocating sufficient resources for development projects. Costs related to road pavement construction, repair and re-establishment have a rising drift, making it critical for road agencies to implement a tool that can streamline decision-making by the use of economics and operations research methodology such as LCCA for the effective feasible investments for long-term [10].

LCCA plays a crucial role in infrastructure management and has been widely applied to evaluate various pavement alternatives based on their life cycle costs. This forms the basis to help in the selection of appropriate pavement structures for a national highway. Numerous research studies have effectively demonstrated life cycle cost practices, highlighting specific assumptions and data sources. These studies too reveal that such findings may not

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be directly applicable for different geographical locations or technical settings. Therefore, it becomes essential to undertake research focused on evaluating the relevance and effectiveness of LCCA in regards to developing nations, for example India's road management system.

LCCA can assist in identifying the most economically viable pavement type that ensures long-term serviceability under India's current traffic conditions. To fulfill this objective, real-world data from a highway section incorporating both rigid and flexible pavements must be utilized for a comparative LCCA. Moreover, evaluating and contrasting the life cycle costs for these two pavement types can offer valuable insights into selecting the most appropriate option for India's existing traffic scenario.

The idea of using benefit-cost analysis (BCA) for choosing among different pavement design options first emerged in the 1950s. Later, during the 1970s, the uses of LCCA principles became more common in major projects at local, state, and national levels to help decide on pavement designs and types. Today, many agencies rely on LCCA to assess the long-term economic performance of pavement choices. To make LCCA truly effective, it is vital for agencies to carry out realistic economic evaluations of pavements. As shown in Figure 2, the objective of LCCA helps outline the next steps and the level of detail required. For the best results, it is important that managers and stakeholders work closely together.

Given the reality of limited funding, road authorities often struggle to secure enough resources for planned projects. At the same time, the demand for new road construction continues to rise, alongside the need to manage existing infrastructure more efficiently. Added to this, there are growing expectations for road protection, approachability and the adoption of innovative traffic management systems to decrease the wider financial impact of roadworks and linked disruptions. However, backlogs in maintenance work still tend to increase. As a result, road authorities are under pressure to find ways to be more efficient and reduce costs. Since maintenance often accounts for about half of the yearly road budget, it becomes especially important to focus on its cost-effectiveness. This makes life-cycle costs (LCCs) more significant than just the initial construction costs. Therefore, it is essential for road agencies to understand the benefits of LCCA and to establish reliable methods for its calculation and use.

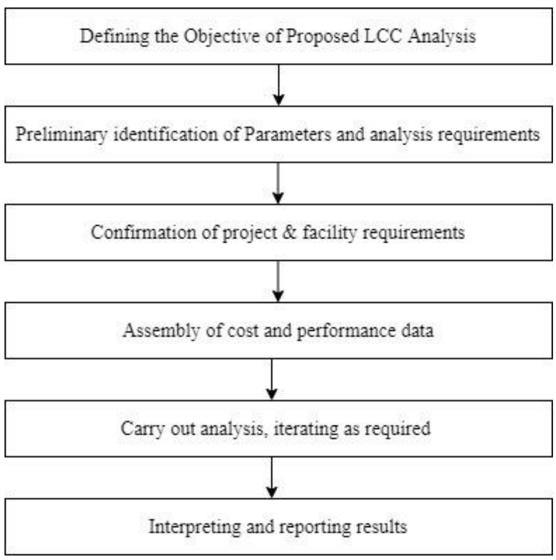

Figure 2: Core process of LCCA [10]

There are numerous approaches for the economic assessment of road projects, like Net Present Value (NPV), Net Annual Value (NAV), Rate of Return (ROR) and Cost Benefit Analysis (CBA). The Net Present Value (NPV) method is employed in LCCA of pavement systems due to its straightforward nature and suitability for project comparison. This technique consolidates all pavement-related costs into a single, equivalent present cost.

Standard equation (1) for calculating Net Present Value (NPV) is as below: -

$$NPV = \text{Initial Cost} + \Sigma \text{ Upkeep Cost}_k \text{ X } [1/(1+ i)n_k] \quad \ldots\ldots(1)$$

where

- i = discount rate;
- k = individual M&R activity;
- n = years of expenditure.

In conducting LCCA, 3 primary cost components are typically evaluated: construction costs, maintenance and rehabilitation (M&R) costs, and user costs. Figure 3 illustrates the flowchart for LCC comparison, along with the data inputs required for each type. Tools such as KENPAVE and Highway Development and Management 4 (HDM-4) can be employed to estimate the life-cycle costs of both flexible and rigid pavements over a 30-year analysis period for National Highways.

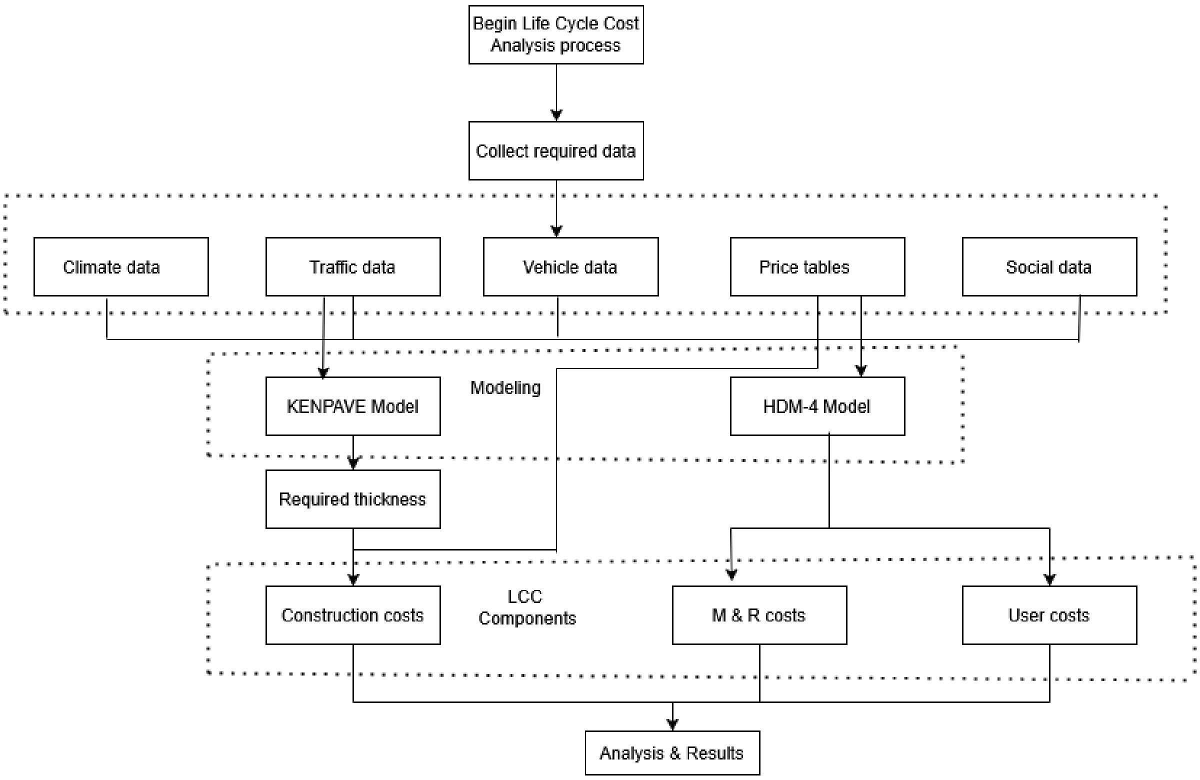

Figure 3: Flowchart of LCC comparison for Flexible and Rigid types of pavements [5].

WORK DONE ON LCCA OF FLEXIBLE AND RIGID PAVEMENTS: A REVIEW

There is a lot of literature available at various resources in the domain of LCCA. In this paper, we present a review of work done on Life cycle cost analysis of pavements in different regions with varied parameters to find out the applicability of LCCA for Flexible & Rigid Pavements.

A comprehensive review of the historical development of pavement design highlights major road experiments, key design considerations, and the differences between highway and airport pavement design methodologies. The discussion extends to methods for calculating stresses and strains in flexible pavements, including analyses based on homogeneous masses as well as layered systems comprising linear elastic, nonlinear elastic, and linear viscoelastic materials. In this context, a dedicated software tool based on Burmister's layered theory was developed to perform layered elastic analysis. Its theoretical basis, key functionalities, validation against benchmark solutions, and sensitivity studies examining the impact of input variables on pavement performance were comprehensively detailed. Additionally, another program based on the finite element method was described, outlining its theoretical underpinnings, analytical capabilities, validation efforts, and sensitivity assessments to support detailed pavement response analysis [1]. A review of life-cycle cost (LCC) practices, strategies, and methods in use or being developed across European Union member countries and other regions highlighted a representative set of national case studies, including examples from different countries. This examination covered the diversity and opportunity of existing methods, critically assessed the underlying practices, and evaluated both the reliability of the applied models and the practical significance of the outcomes for stakeholders. Drawing on insights from the review and complementary fieldwork, a consolidated LCC framework was proposed to identify common elements of good practice in construction within the European context. This framework also set out recommendations for addressing every phase of the project life cycle and key components of built assets or facilities, structured to guide decision-making at strategic, system, and detail levels. [2]. LCCA has been recognized as a valuable approach for comparing alternative pavement structures and enhancing cost-effectiveness in pavement design decisions. Noting a gap in research specific to evaluation methods for expressway asphalt pavement structures within the Chinese context, an exploratory study was undertaken to begin addressing this area and to develop an approach tailored to local conditions [3]. A study explored ways to better integrate road maintenance considerations into the planning and design stages. It identified key barriers that limit the systematic inclusion of future maintenance needs during these early project phases and examined how optimizing life-cycle costs could improve overall efficiency. The research specifically analyzed road planning and design practices within the context of Sweden [4]. A comparative analysis of life-cycle costs (LCC) between conventional pavements and perpetual pavements was carried out to evaluate which alternative offers greater economic viability under varying traffic volumes and climatic conditions on Iranian highways. The results suggested that adopting perpetual pavements could lower LCC by approximately 4–20%. It was noted that in oil-exporting countries such as Iran, the difference in initial construction costs between these two pavement types is often small, and in some scenarios, perpetual pavements may even have comparable or slightly lower upfront costs. The analysis also highlighted the significant sensitivity of LCC outcomes to the discount rate used; although adjustments in the discount rate affect the cost ratio between perpetual and conventional pavements, the ratio generally remains below one, supporting the economic preference for perpetual pavements. Moreover, incorporating additional user cost factors—such as environmental impacts, accident-related costs, and work zone delays—was identified as a way to enhance the accuracy of total LCC estimates [5]. Perpetual pavements have shown considerable potential but require thorough field studies to enable their effective use on Indian roads. While the suggested pavement thicknesses are not definitive, they offer a useful benchmark for comparing conventional asphalt pavements with perpetual pavement designs. Although the perpetual pavement concept primarily recommends increasing the thickness of hot mix asphalt layers to maintain critical strains within acceptable limits, it is equally important—both technically and economically—to ensure a stable foundation and incorporate high-stiffness base materials [6]. The combined use of LCCA and CBA supports development of fund allocation strategies and site-specific plans for maintenance, repair, and rehabilitation (MR&R) actions aimed at meeting performance objectives. Cost-benefit analysis compares the benefits gained from improved pavement performance against the costs of MR&R interventions. Common economic indicators applied in this context include Net Present Value (NPV), Internal Rate of Return (IRR) and Payback Period. This approach helps ensure that resources are directed to road sections with the highest need for repairs, leading to more effective use of financial resources. The resulting savings can then be reinvested into additional repair projects, further improving the network condition [7]. An integrated life-cycle cost (LCC) model was formulated to assess three alternates urban flexible pavement designs under different interest rate scenarios. The analysis treated pavement age as the independent variable and found it to be a significant predictor of the dependent variable, namely life-cycle cost measured in Million Naira per kilometer for an urban two-lane roadway. The model's mean square value (R^2) and significance value (F) for the HRA and ICBP alternatives were in line with results reported in similar studies conducted in Sweden. The outcomes indicated that the interlocking concrete pavement option delivered better long-term cost-effectiveness, whereas the do-nothing alternative incurred higher life-cycle costs and failed to achieve the required design level of service [8]. A review of literature related to cost components of highway construction, including design, material, equipment, repair-maintenance and restoration strategies and operational expenses over the complete life of a highway, was conducted. The discussion focused on LCCA, an economic assessment method that measures the economic efficiency of alternatives using the Net Present Value (NPV) approach. Existing LCCA methods were examined, and relevant LCCA software tools were introduced. By compiling and analyzing previous studies, the review identified the weaker aspects of current LCCA practices, offering insights into addressing these shortcomings to improve future analyses [9]. An economic evaluation technique known as LCCA was applied to assess the economic efficiency of different alternates using the NPV approach. It was noted that for LCCA to produce meaningful results, it must be implemented correctly, drawing on accurate historical data regarding initial construction costs, salvage values, rehabilitation schedules and costs, and discount rates. The LCCA process itself involves multiple assessments, forecasts, and assumptions, where variations in input data can significantly influence the degree of certainty in the ultimate results. Therefore, ensuring input accuracy is critical across all stages. The dependability of LCCA outcomes largely depends on how precisely analysts can predict pavement performance, future traffic over several decades, and anticipated costs [10]. Highway transportation has been recognized as a key contributor to economic development, leading to the construction of numerous high-grade highways over recent decades. Since 2000, China has introduced and advanced the investigation and use of perpetual asphalt pavement (PP) technology. Traditionally, semi-rigid pavements have been widely adopted as the standard design for high-class highways based on local experience. The performance of various Chinese perpetual pavement structures was evaluated using an active road management system to assess their adequacy for designing and building extra durable and cost-effective pavements. Findings suggest that incorporating thin bituminous overlays on semi-rigid pavements foundations in PP structures can produce pavements that are more sustainable, economical, and long-lasting when compared to conventional perpetual pavements with thicker asphalt layers [11]. HDM-4 is introduced as a software tool which serves as a primary tool for road administrations in the analysis, planning, management and appraisal of road maintenance, improvements, and investment decisions. As the updated Windows-based successor to HDM-III, HDM-4 includes numerous new features, making it adaptable to different regions worldwide regardless of local environmental or engineering conditions. The World Bank's Highway Development and Management model has been adapted for strategic-level decision-making enabling its use as a tailored economic evaluation tool. Specifically, HDM-4 can forecast budget needs, predict network conditions, and support urban road management based on robust engineering practices [12]. LCCA for road pavements is described as a process for calculating the total cost over the pavement's life span, which includes the initial construction cost along with ongoing operational and maintenance expenses. It is noted that various researchers in road construction have applied economic analysis and sensitivity analysis to interpret LCCA results derived from parameters like NPV and IRR, considering the influence of different input parameters. The procedure involves estimating the range of costs relevant to LCCA of roads and applying an appropriate methodology using representative road data [13]. LCCA was considered for both rigid and flexible pavements, using a case study of the Sylhet–Bholaganj Road Project in Bangladesh. Future costs were projected by applying a growth factor, and all related expenses were converted to NPV to determine the complete life cycle cost. This analysis used the Schedule of Rates (SOR) of Roads and Highways Department (RHD) from the years 2015 and 2002 to conduct a sensitivity analysis. The results indicated that while the initial construction costs of rigid pavements exceeded those of flexible pavements by 11.75% and 1.21%, respectively, the life-cycle cost analysis revealed that flexible pavements ultimately became more costly than rigid pavements by 38.3% and 52.4%, respectively. These results indicate that, economically, rigid pavement is the more suitable option for use in the Bangladeshi context [14]. A life-cycle cost analysis was conducted for both flexible and rigid pavement sections along the Sylhet–Bholagaj road. The study utilized pavement design data and various Schedule of Rates obtained from the Roads and Highways Department. To convert projected future costs into Net Present Value (NPV), a discount rate of 12% was applied. The analysis concluded that, from an economic standpoint, rigid pavement represents the more suitable choice for application in developing countries such as Bangladesh [15]. A comparative analysis was carried out on the LCCA and environmental impact (EIA) of concrete and bitumen roads over a 30-year period per kilometer length. Using the NPV method, findings indicated that concrete roads are roughly 20% more cost-effective than bitumen roads. The assessment covered raw material extraction, manufacturing, construction, and maintenance stages. Results showed that concrete pavements incur lower maintenance and user costs and require less energy over their life cycle. The environmental impact analysis further revealed that bitumen pavements generate higher greenhouse gas emissions, positioning concrete pavements as the more sustainable option. Overall, concrete roads demonstrate clear economic and environmental benefits compared to bitumen roads [16]. A methodological review was conducted on LCA and LCCA approaches for asphalt pavements. The review highlights the importance of integrating LCA and LCCA throughout the entire pavement life cycle, including performance-based maintenance forecasts and accounting for user and social costs. To address uncertainty, the use of probabilistic methods and sensitivity analyses is recommended. The review ultimately supports comprehensive, long-term evaluations as a foundation for making more sustainable and economically sound pavement design and management decisions [17].

Conclusion

The result of this Life Cycle Cost Analysis (LCCA) study reveals that although rigid pavement has higher initial construction cost than that of flexible pavement, the overall life cycle cost of flexible surpasses that of rigid pavement. With aggregate quantities assumed to be nearly equal for both pavement types, the comparison between cement (rigid pavement) and bitumen (flexible pavement) becomes a decisive economic factor. Notably, the cost difference between cement and bitumen has significantly narrowed—from 59% in 2002 to just 7% in 2025—largely driven by fluctuations in global crude oil prices. This shift has fundamentally redefined the economic viability of pavement choices. Through an extensive LCCA, it is evident that while rigid pavements incur higher initial construction costs, they prove to be more economical over the long term due to lower maintenance and rehabilitation expenses. Consequently, rigid pavements now present a more cost-effective and sustainable solution for National Highway development projects. From a long-term investment and planning perspective, rigid pavement emerges as the preferred option, aligning with both financial prudence and infrastructure sustainability goals.

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