



A Systematic Review of Life-Cycle Cost Analysis in Transportation Infrastructure: Applications to Pavement Preservation, Bridge Rehabilitation, and Long-Term Investment Planning

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Abstract

Life-cycle cost analysis (LCCA) has become a foundational economic evaluation tool for transportation agencies seeking to allocate constrained public resources across competing pavement, bridge, and network-level investment needs. This paper presents a systematic review of the LCCA literature as applied to three interrelated domains of transportation infrastructure management: pavement preservation, bridge rehabilitation, and long-term investment planning within transportation asset management (TAM) frameworks. Drawing on peer-reviewed studies, agency guidance documents, and national research syntheses, the review traces the conceptual foundations of LCCA net present value, equivalent uniform annual cost, agency and user cost accounting, and discounting and examines how these principles have been adapted to the distinct deterioration mechanisms, treatment strategies, and decision contexts of pavements and bridges. The review finds that deterministic, single-point LCCA remains the dominant practice among transportation agencies, even though probabilistic and stochastic approaches (Monte Carlo simulation, Bayesian updating, fuzzy logic) demonstrably improve the treatment of uncertainty in discount rates, traffic growth, material prices, and deterioration timing. At the network and program level, LCCA increasingly underpins transportation asset management plans mandated by federal regulation, shaping multi-year capital programming and preservation-versus-reconstruction trade-offs. Persistent gaps include inconsistent inclusion of user and social costs, limited integration of environmental life-cycle assessment (LCA) with LCCA, weak empirical validation of deterioration and treatment-effectiveness models, and uneven data infrastructure across agencies. The paper concludes by synthesizing common methodological threads across pavement and bridge applications and proposing a research and practice agenda centered on probabilistic modeling, LCA-LCCA integration, climate resilience, and standardized data governance.

Keywords

Life-Cycle Cost Analysis; Pavement Preservation; Bridge Rehabilitation; Transportation Asset Management; Infrastructure Investment Planning; Net Present Value;

INTRODUCTION

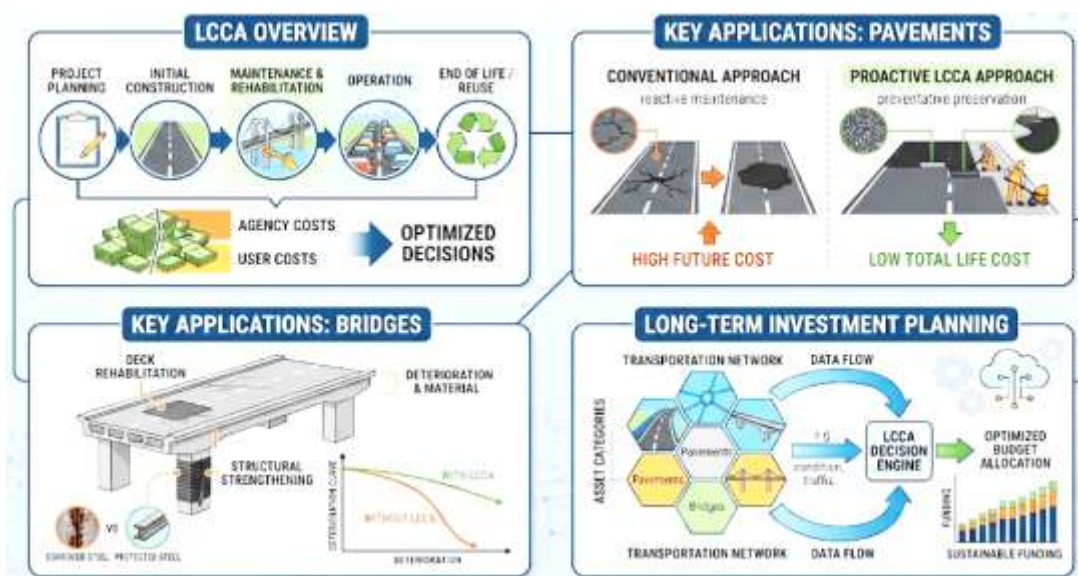
Transportation agencies across the world manage vast portfolios of aging pavements, bridges, and ancillary assets under conditions of persistent fiscal constraint. In the United States alone, decades of deferred maintenance, increasing traffic demand, climate-related stresses, inflation, and rising construction costs have widened the gap between the funding available for highway and bridge preservation and the funding required to keep the transportation system in a state of good repair. Similar challenges are evident internationally, where transportation authorities must balance limited public resources with growing demands for safe, reliable, resilient, and sustainable infrastructure. Against this backdrop, life-cycle cost analysis (LCCA) has emerged as a principal economic evaluation technique used by transportation agencies to compare design, preservation, and rehabilitation alternatives on the basis of their total discounted cost over an extended analysis period, rather than on the basis of initial construction cost alone. The fundamental premise of LCCA is that infrastructure investments should be evaluated according to the costs incurred throughout the entire service life of an asset, including initial construction or rehabilitation expenditures, routine and preventive maintenance, periodic rehabilitation, agency costs, user-related costs, and, where applicable, salvage or residual value at the end of the analysis period. By incorporating these cost components and discounting future expenditures to their present value, LCCA provides decision-makers with a systematic basis for identifying alternatives that offer the greatest economic efficiency over time. This approach is particularly important for transportation infrastructure because an alternative with a relatively low initial cost may require more frequent maintenance or earlier reconstruction, ultimately becoming more expensive than a higher-quality alternative with greater durability.

In pavement management, LCCA is commonly applied to compare competing preservation and rehabilitation strategies, including asphalt overlays, concrete rehabilitation, reconstruction, preventive maintenance treatments, and combinations of these interventions. The analysis enables agencies to examine how differences in material durability, expected service life, maintenance frequency, rehabilitation timing, and construction requirements influence long-term costs. For bridge infrastructure, LCCA can similarly support decisions concerning rehabilitation, replacement, strengthening, protective treatments, and maintenance strategies, thereby extending the decision-making process beyond the question of how much an intervention costs today to consider how that investment will perform economically throughout the asset's expected life. The growing importance of LCCA is also associated with the increasing emphasis on transportation asset management and performance-based planning. Modern transportation agencies are expected not only to preserve infrastructure but also to demonstrate that limited public funds are being allocated efficiently, transparently, and strategically. LCCA contributes to this objective by providing a quantitative framework for linking investment decisions with expected life-cycle performance and by helping agencies prioritize interventions that minimize long-term expenditure while maintaining acceptable levels of safety, serviceability, mobility, and network performance.

Furthermore, contemporary applications of LCCA increasingly recognize uncertainties associated with infrastructure deterioration, construction costs, traffic growth, discount rates, material performance, maintenance requirements, and future economic conditions. Traditional deterministic LCCA approaches often rely on fixed assumptions about these variables, which may not adequately reflect real-world conditions. Consequently, researchers and transportation agencies have increasingly explored probabilistic approaches, sensitivity analysis, scenario analysis, and risk-based LCCA to evaluate the potential range of future costs and improve the robustness of investment decisions. These developments are particularly relevant in the context of climate change, extreme weather events, supply-chain disruptions, technological innovation, and changing traffic patterns, all of which can influence infrastructure performance and expenditure requirements over long analysis periods. Despite its advantages, LCCA is not without limitations. The quality of an LCCA outcome depends heavily on the accuracy of input data, assumptions regarding service life and deterioration, appropriate

selection of discount rates, and the ability to forecast future maintenance and rehabilitation requirements. Differences in agency practices and analytical assumptions can also make comparisons across projects and jurisdictions difficult. Moreover, conventional LCCA tends to emphasize monetary costs and may not fully capture non-monetary considerations such as environmental impacts, social disruption, equity, resilience, user delay, safety benefits, and broader economic consequences. For this reason, LCCA is increasingly being integrated with multi-criteria decision analysis, environmental life-cycle assessment, risk analysis, and transportation asset-management frameworks rather than being used as a stand-alone decision-making tool. Overall, the expanding application of LCCA reflects a broader shift in transportation infrastructure management from short-term, project-based decision-making toward long-term, performance-oriented investment planning. By accounting for the timing and magnitude of costs throughout an asset's service life, LCCA can help transportation agencies identify preservation and rehabilitation strategies that provide greater economic value, improve infrastructure reliability, and reduce the risk of premature deterioration or inefficient investment. A systematic examination of LCCA applications across pavement preservation, bridge rehabilitation, and long-term investment planning is therefore important for understanding how the methodology has evolved, identifying the analytical approaches most frequently employed, assessing their strengths and limitations, and determining future research directions that can improve the reliability, adaptability, and practical usefulness of life-cycle economic evaluations in transportation infrastructure.

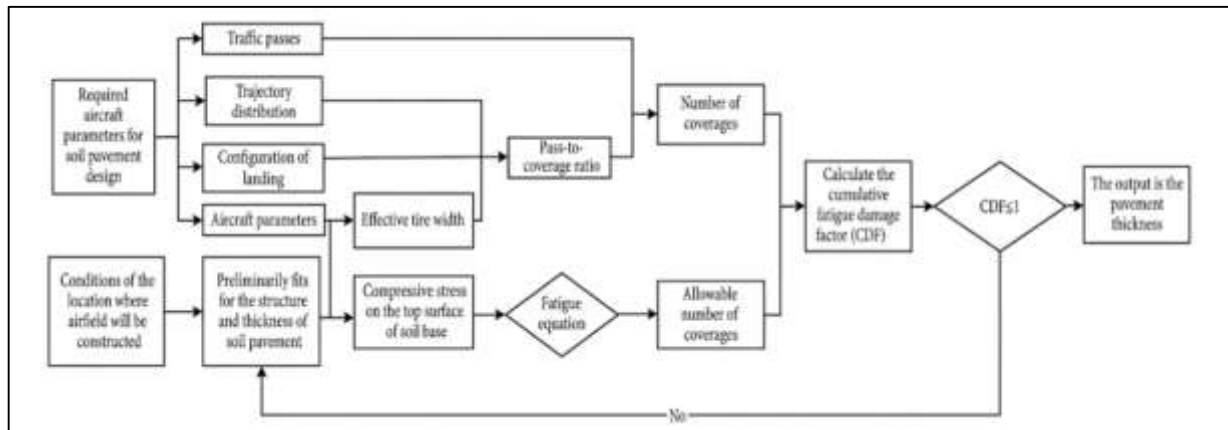
Figure 1: System Overview of LCCA Integration in Pavement Preservation, Bridge Rehabilitation, and Network-Level Investment Planning.



LCCA is grounded in engineering economics: it converts the stream of costs that an agency and the traveling public are expected to incur over an asset's service life—including initial construction, periodic maintenance, preventive treatments, rehabilitation, reconstruction, and user delay—into a single comparable economic metric, typically net present value (NPV) or equivalent uniform annual cost (EUAC). This economic framework enables transportation agencies to compare alternatives that differ not only in their initial investment requirements but also in their expected service lives, maintenance schedules, deterioration patterns, and future rehabilitation needs. By discounting future costs to their present value, LCCA recognizes the time value of money and allows expenditures occurring at different points in the life cycle to be evaluated on a common basis. The technique has been formally endorsed by the U.S. Federal Highway Administration (FHWA) since the 1990s and has subsequently become an important component of transportation investment decision-making,

particularly for pavement design, preservation, rehabilitation, and asset-management planning. Its institutional importance has increased as transportation agencies have moved toward performance-based and risk-informed approaches to infrastructure management. LCCA is now closely associated with the broader framework of transportation asset management plans (TAMPs), in which agencies are required to demonstrate how investment decisions can support the long-term condition and performance of transportation assets while operating within available financial resources. Within this framework, LCCA provides an analytical mechanism for evaluating whether alternative investment strategies can achieve desired performance outcomes at the lowest feasible long-term cost.

Figure 2 : Diagram Pavement Bridge Infrastructure



Although the underlying economic logic of LCCA is common across asset types, its practical implementation differs substantially between pavements and bridges because of differences in deterioration behavior, treatment options, data availability, structural characteristics, inspection practices, and the relative magnitude and timing of user costs. Pavement LCCA has matured around relatively well-documented deterioration relationships, extensive empirical performance data, standardized treatment strategies, and national research initiatives such as the Long-Term Pavement Performance (LTPP) program. Transportation agencies can draw on historical pavement condition data, traffic information, material characteristics, climate variables, and maintenance records to estimate the expected performance of alternative pavement strategies over an extended analysis period. Standardized analytical tools, including the Federal Highway Administration's RealCost framework, have further supported the consistent application of LCCA by providing agencies with structured procedures for estimating agency and user costs, discounting future expenditures, and comparing competing pavement alternatives. Pavement analysis can therefore incorporate recurring preventive maintenance, rehabilitation, resurfacing, and reconstruction activities into a relatively predictable sequence of interventions, although uncertainty in deterioration rates and treatment effectiveness remains an important methodological consideration. resilience, sustainability, and network-level interactions into comprehensive life-cycle investment decisions.

Background of the study

Transportation infrastructure is a critical component of economic and social development because roads, pavements, bridges, and related facilities support mobility, trade, employment, regional connectivity, and access to essential services. However, transportation agencies increasingly face the challenge of maintaining aging infrastructure while operating under constrained financial resources and responding to growing demands for safety, reliability, mobility, sustainability, and resilience. The long-term management of transportation assets is particularly challenging because infrastructure deterioration occurs progressively and is influenced by traffic loading, environmental conditions, construction quality, maintenance practices, material characteristics, and extreme weather events.

These conditions have encouraged transportation agencies to move beyond short-term project decisions based primarily on initial construction expenditure and toward life-cycle approaches that consider the economic consequences of investment decisions over an asset's entire service life (Federal Highway Administration [FHWA], 2002, 2022). Life-cycle cost analysis (LCCA) has become an important engineering-economic method for supporting these long-term transportation investment decisions. FHWA defines LCCA as a present-value analysis of agency and user costs occurring throughout the life of a highway asset, with the objective of identifying the strategy that achieves a specified performance objective at the lowest life-cycle cost (FHWA, 2017). Unlike conventional project evaluation that may emphasize initial construction or rehabilitation expenditure, LCCA considers the timing and magnitude of future costs associated with maintenance, preservation, rehabilitation, reconstruction, and user impacts. Future expenditures are discounted to present-value terms so that alternatives with different cost profiles and intervention schedules can be compared on a common economic basis. This approach is particularly important when a higher initial investment can provide a longer service life or reduce future maintenance and rehabilitation requirements, potentially producing lower total costs over the analysis period. The institutional development of LCCA has been closely associated with the broader evolution of transportation asset management. FHWA promotes LCCA as an engineering-economic tool that can be applied to both new construction and preservation strategies for existing transportation assets (FHWA, 2022). Within transportation asset-management planning, life-cycle planning is used to connect asset condition, performance, risk, investment strategies, and financial requirements.

Problem statement

Transportation agencies worldwide face a persistent challenge of maintaining aging pavements, bridges, and other transportation infrastructure while operating under limited and increasingly uncertain financial resources. Growing traffic demand, rising construction and material costs, deferred maintenance, climate-related deterioration, and increasing requirements for safety, reliability, sustainability, and resilience have intensified the difficulty of determining how limited transportation funds should be allocated. Traditional investment decisions that emphasize initial construction or rehabilitation costs may fail to capture the substantial maintenance, rehabilitation, reconstruction, user-delay, and disruption costs that occur throughout an infrastructure asset's service life. Consequently, transportation agencies require economic evaluation approaches that can compare alternative investment strategies from a long-term perspective rather than focusing exclusively on short-term expenditures (Federal Highway Administration [FHWA], 2017, 2022). Life-cycle cost analysis (LCCA) provides an established framework for addressing this problem by comparing the present value of agency and user costs associated with alternative infrastructure strategies over a defined analysis period. However, despite the extensive adoption of LCCA in transportation engineering, its application is not methodologically consistent across pavement preservation, bridge rehabilitation, and long-term investment planning. Pavement LCCA has benefited from extensive longitudinal performance data, established deterioration models, standardized treatment strategies, and analytical tools such as FHWA's RealCost (FHWA, 2015; FHWA, 2023). Bridge LCCA, in contrast, is complicated by structural heterogeneity, component-level deterioration, limited prediction of remaining service life, diverse rehabilitation strategies, and potentially substantial denial-of-use and detour costs. These differences create challenges in applying a common LCCA framework across transportation asset classes and raise questions regarding the comparability, reliability, and practical interpretation of existing LCCA results. A further problem concerns the treatment of uncertainty in long-term infrastructure economic evaluation. LCCA requires assumptions regarding discount rates, analysis periods, construction costs, deterioration rates, treatment effectiveness, traffic growth, maintenance schedules, service life, and future rehabilitation requirements. Because these variables are inherently uncertain, deterministic LCCA results may provide an incomplete representation of the range of possible future costs. Although probabilistic analysis, sensitivity analysis, scenario analysis, and risk-based approaches have

increasingly been incorporated into transportation LCCA, their adoption and methodological consistency remain uneven.

Objectives of The Study

The primary objective of this study is to systematically review and synthesize the existing literature on Life-Cycle Cost Analysis (LCCA) in transportation infrastructure, with particular emphasis on pavement preservation, bridge rehabilitation, and long-term investment planning. Specifically, the study aims to examine the methodological foundations of LCCA, including cost components, discounting methods, analysis periods, service-life assumptions, deterioration models, and economic evaluation measures used in transportation infrastructure decision-making. The study further aims to compare the application of LCCA across pavement and bridge assets by examining differences in maintenance and rehabilitation strategies, deterioration characteristics, agency costs, user costs, data availability, and performance evaluation approaches. Another objective is to evaluate how existing studies address uncertainty associated with construction costs, deterioration rates, treatment effectiveness, traffic growth, discount rates, service life, and future maintenance requirements, including the use of sensitivity analysis, scenario analysis, probabilistic approaches, and risk-based methods. The study also seeks to investigate the extent to which environmental sustainability, climate change, resilience, greenhouse-gas emissions, social impacts, and other non-traditional considerations have been incorporated into conventional LCCA frameworks. In addition, the study aims to assess how project-level LCCA is connected with transportation asset-management systems, network-level prioritization, budget allocation, and long-term investment planning under financial and institutional constraints. Finally, the study intends to identify recurring methodological gaps and limitations in the existing literature and propose future research directions for developing more comprehensive, transparent, reliable, and decision-relevant LCCA frameworks that can support economically efficient, sustainable, and resilient transportation infrastructure management.

Research hypotheses

The research hypotheses of this systematic review are developed to examine the methodological relationships and differences identified across the existing literature on Life-Cycle Cost Analysis (LCCA) in transportation infrastructure. The first hypothesis (H1) proposes that the application of LCCA significantly improves the identification of economically efficient alternatives for transportation infrastructure investment compared with decision-making based primarily on initial construction or rehabilitation costs. The second hypothesis (H2) proposes that LCCA approaches incorporating both agency costs and user costs provide more comprehensive estimates of the long-term economic consequences of pavement preservation and bridge rehabilitation alternatives than approaches that consider agency costs alone. The third hypothesis (H3) proposes that incorporating uncertainty through probabilistic analysis, sensitivity analysis, scenario analysis, or risk-based methods improves the robustness and reliability of LCCA-based transportation investment decisions. The fourth hypothesis (H4) proposes that LCCA outcomes differ significantly between pavement preservation and bridge rehabilitation because of differences in deterioration characteristics, intervention strategies, data availability, service-life assumptions, and user-cost impacts. The fifth hypothesis (H5) proposes that integrating LCCA with transportation asset-management and network-level investment-planning frameworks improves the effectiveness of long-term resource allocation compared with project-level LCCA applied independently. The sixth hypothesis (H6) proposes that incorporating environmental sustainability and climate-resilience considerations into LCCA can change the relative economic attractiveness of transportation infrastructure alternatives compared with conventional LCCA based primarily on agency and user costs. The seventh hypothesis (H7) proposes that the reliability and comparative outcomes of LCCA are significantly influenced by methodological assumptions, including discount rates, analysis periods, deterioration models, treatment effectiveness, construction costs, and service-life estimates. Finally, the eighth hypothesis (H8) proposes that the integration of advanced analytical approaches, including probabilistic modeling, data-driven deterioration prediction, and

machine-learning techniques, can improve the accuracy, robustness, and decision relevance of transportation LCCA compared with conventional deterministic approaches. Collectively, these hypotheses provide a structured basis for examining whether methodological developments in LCCA contribute to more reliable, comprehensive, sustainable, and economically efficient transportation infrastructure investment decisions across pavement preservation, bridge rehabilitation, and long-term investment planning.

Significance of the research

The significance of this research lies in its systematic examination of Life-Cycle Cost Analysis (LCCA) as a decision-support approach for transportation infrastructure management, with particular emphasis on pavement preservation, bridge rehabilitation, and long-term investment planning. Transportation agencies face increasing pressure to maintain aging infrastructure while managing limited financial resources, rising construction costs, changing traffic demand, and growing risks associated with climate change and extreme weather. In this context, the research is significant because it provides an integrated understanding of how LCCA can support decisions that consider not only initial construction or rehabilitation costs but also maintenance, preservation, reconstruction, user delay, and other costs incurred throughout an asset's service life. By synthesizing findings across different transportation asset classes, the study helps clarify the methodological similarities and differences in LCCA applications and identifies factors that influence the reliability and usefulness of life-cycle economic evaluations. The research is also significant from a methodological perspective because it identifies recurring limitations in existing LCCA practices, particularly regarding uncertainty, deterioration forecasting, discount rates, analysis periods, treatment effectiveness, user-cost estimation, and service-life assumptions. By examining how previous studies have addressed these issues, the research can identify opportunities for improving the robustness and transparency of LCCA. Greater attention to probabilistic analysis, sensitivity analysis, scenario analysis, and risk-based approaches can help transportation agencies better understand the range of potential future costs rather than relying exclusively on deterministic estimates. This is particularly valuable for infrastructure decisions involving long analysis periods, where uncertainty can substantially influence the economic ranking of competing alternatives. From an infrastructure-management perspective, the study contributes to the integration of project-level economic evaluation with broader transportation asset-management and long-term investment-planning practices. LCCA can help agencies identify strategies that minimize long-term expenditure while maintaining acceptable infrastructure condition, safety, serviceability, and performance. The systematic synthesis provided by this research can therefore support more informed prioritization of preservation and rehabilitation activities and improve the allocation of scarce public funds across competing transportation assets. The findings may also assist policymakers and transportation managers in understanding why an alternative with a higher initial cost can sometimes provide greater long-term economic value because of its longer service life, lower maintenance requirements, or reduced user impacts. The research is further significant because it addresses the growing need to incorporate environmental sustainability and climate resilience into transportation investment decisions. Conventional LCCA primarily emphasizes monetary agency and user costs, while emerging transportation challenges require greater consideration of greenhouse-gas emissions, embodied carbon, resource consumption, environmental impacts, climate vulnerability, resilience, and disruption risks. By reviewing the extent to which these considerations have been incorporated into existing LCCA frameworks, the study identifies opportunities to move toward more comprehensive life-cycle decision-making approaches. Such integration can help agencies evaluate infrastructure alternatives not only according to their financial efficiency but also according to their ability to withstand future environmental and operational uncertainties. The study also has practical significance for researchers and transportation practitioners. For researchers, it identifies gaps in the existing literature and provides directions for future investigations involving probabilistic LCCA, advanced deterioration modeling, machine learning, digital asset-management systems, resilience

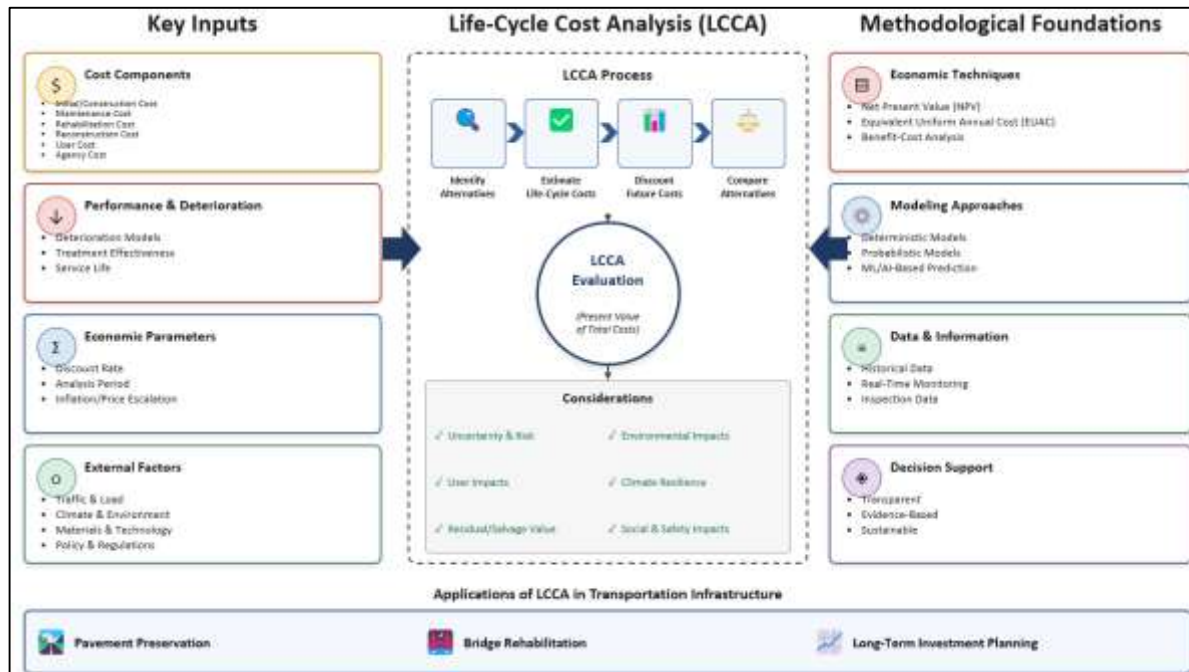
assessment, and integrated economic-environmental evaluation. For transportation agencies, the findings can provide guidance on selecting appropriate LCCA methodologies, improving data requirements, evaluating uncertainty, incorporating user costs, and connecting project-level analyses with network-level investment strategies. For policymakers, the research can contribute to more transparent and evidence-based infrastructure investment decisions by demonstrating the importance of evaluating long-term consequences rather than focusing solely on immediate project expenditure. Overall, this research is significant because it contributes to the development of a more comprehensive understanding of LCCA across pavement preservation, bridge rehabilitation, and long-term transportation investment planning. By identifying methodological strengths, limitations, inconsistencies, and emerging developments, the study can support the advancement of LCCA from a conventional cost-comparison technique toward a broader decision-support framework that incorporates economic efficiency, uncertainty, sustainability, resilience, and network-level performance. The resulting knowledge can ultimately help transportation agencies make more reliable, transparent, economically efficient, and sustainable decisions for preserving and managing transportation infrastructure over the long term.

LITERATURE REVIEW

Concept and Evolution of LCCA

Life-Cycle Cost Analysis (LCCA) has evolved into one of the most important economic evaluation approaches for supporting long-term decisions in transportation infrastructure. The fundamental concept of LCCA is based on the recognition that the economic performance of an infrastructure asset cannot be adequately assessed by considering its initial construction or rehabilitation cost alone. Transportation assets such as pavements and bridges require continuous expenditure throughout their service lives, including routine maintenance, preventive preservation, periodic rehabilitation, reconstruction, inspection, operation, and, in many cases, costs imposed on road users through delays, detours, and service disruptions. LCCA provides a structured framework for identifying, estimating, and comparing these costs over a specified analysis period and converting future expenditures into present-value terms using an appropriate discount rate. In this way, alternatives with different initial costs, maintenance requirements, intervention schedules, and expected service lives can be evaluated on a consistent economic basis. The conceptual foundation of LCCA is rooted in engineering economics and the time value of money, which recognizes that a monetary expenditure occurring in the future has a different economic value from the same expenditure occurring today. This principle is particularly important in transportation infrastructure because many investment decisions have consequences extending over several decades. A pavement rehabilitation strategy, for example, may require a relatively low initial investment but repeated maintenance and resurfacing activities, whereas a more expensive reconstruction or high-durability treatment may require greater initial expenditure but fewer interventions over its service life. LCCA enables agencies to examine these alternative expenditure patterns and determine which strategy provides the most favorable long-term economic outcome. The development of LCCA in transportation has been strongly influenced by the Federal Highway Administration (FHWA), which established formal guidance for conducting life-cycle cost evaluations and promoted its application to pavement design, preservation, rehabilitation, and investment decisions (Federal Highway Administration [FHWA], 1998, 2017). The institutionalization of LCCA represented an important shift in transportation decision-making because it encouraged agencies to consider future maintenance and user consequences when selecting infrastructure alternatives rather than relying predominantly on initial project cost. Over time, the methodology has expanded from relatively simple deterministic comparisons toward more sophisticated approaches incorporating uncertainty, probabilistic analysis, risk assessment, sensitivity analysis, and scenario modeling. These developments reflect the increasing recognition that long-term transportation investments are exposed to uncertainty in construction prices, traffic demand, deterioration rates, treatment effectiveness, climate conditions, and future maintenance requirements. The evolution of

LCCA has also been closely associated with the development of transportation asset-management systems. Rather than evaluating projects independently, agencies increasingly seek to understand how investment decisions affect the condition, performance, risk, and financial requirements of entire transportation networks. LCCA therefore provides an important connection between engineering decisions at the asset level and strategic investment decisions at the program and network levels. Within pavement management, the availability of long-term performance information through programs such as the Long-Term Pavement Performance (LTPP) program has strengthened the empirical basis for predicting deterioration and evaluating alternative maintenance and rehabilitation strategies (FHWA, 2015). Similarly, developments in bridge-management systems have encouraged the use of deterioration models, intervention strategies, life-cycle agency costs, user costs, and risk considerations in bridge investment decisions. The evolution of LCCA has also involved greater attention to user costs. Earlier applications often emphasized agency expenditures, but contemporary approaches recognize that transportation interventions can impose substantial costs on road users through travel delays, increased vehicle operating costs, detours, freight disruptions, and reduced accessibility. These costs can be particularly significant for high-volume roadways and strategically important bridges where maintenance or closure can affect large numbers of users. Consequently, the inclusion of user costs has expanded the analytical scope of LCCA from a narrow agency-budget perspective toward a broader economic perspective. More recently, environmental sustainability and climate resilience have emerged as important dimensions of life-cycle economic evaluation. Conventional LCCA generally focuses on monetizable financial and user costs, but transportation agencies increasingly need to consider greenhouse-gas emissions, embodied carbon, energy consumption, resource use, environmental impacts, climate vulnerability, and resilience to extreme events. This has encouraged researchers to explore integration between LCCA, Life-Cycle Assessment (LCA), climate-risk analysis, resilience assessment, and multi-criteria decision-making. At the same time, advances in artificial intelligence, machine learning, digital twins, remote sensing, structural health monitoring, and large-scale infrastructure databases are creating new opportunities for improving deterioration prediction and life-cycle cost estimation. These technological developments may enable LCCA to become more dynamic and data-driven, allowing agencies to update cost and performance estimates as new condition and operational information becomes available. Despite these advances, important challenges remain concerning data quality, model transparency, methodological consistency, uncertainty representation, and the integration of non-monetary impacts. Different assumptions regarding discount rates, analysis periods, service-life estimates, deterioration functions, treatment effectiveness, and user-cost calculations can produce substantially different LCCA results, limiting comparability among studies and agencies. Therefore, the evolution of LCCA should be understood not simply as a progression toward increasingly complex economic models but as a broader transition toward integrated, risk-informed, performance-based, and sustainability-oriented infrastructure decision-making. The contemporary literature increasingly positions LCCA as a decision-support framework that can help transportation agencies balance short-term financial constraints with long-term asset performance, economic efficiency, environmental responsibility, and resilience. This evolution provides an important foundation for systematically reviewing how LCCA is currently applied to pavement preservation, bridge rehabilitation, and long-term transportation investment planning and for identifying the methodological gaps that must be addressed to improve its future effectiveness.

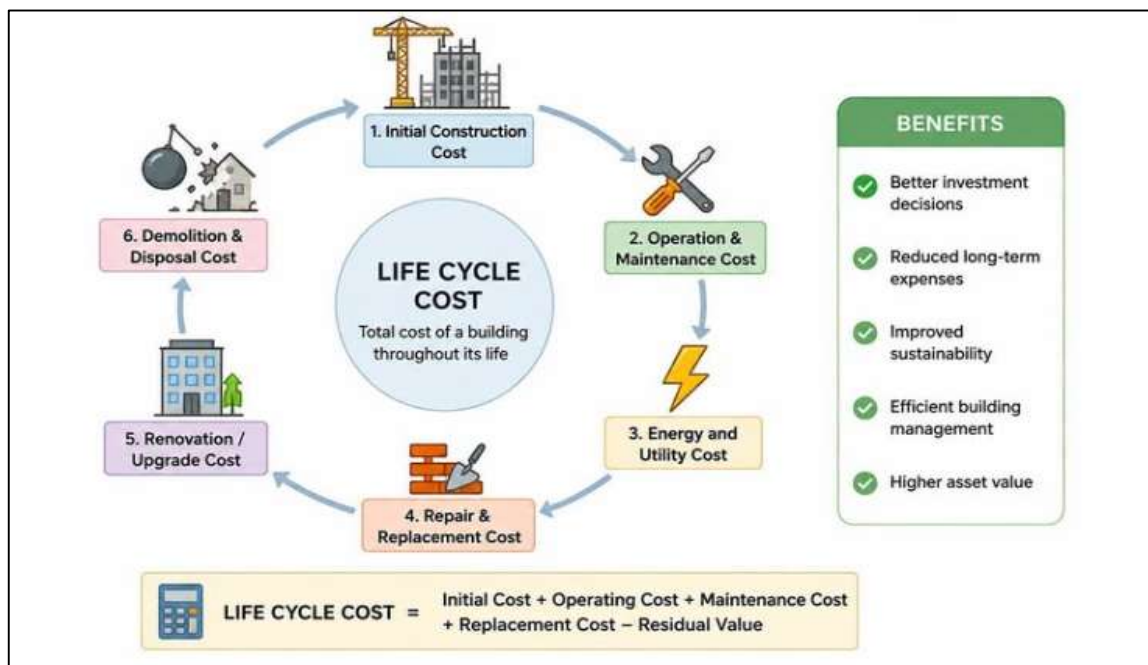
Figure 3 : Evolution Of LCCA

Theoretical and Economic Foundation

The theoretical and economic foundation of Life-Cycle Cost Analysis (LCCA) is rooted primarily in engineering economics, investment theory, and the principle of the time value of money, which recognizes that the economic value of a monetary amount depends on when that amount is received or spent. In transportation infrastructure, this principle is particularly important because projects involve substantial expenditures that occur at different points over long service lives. Initial construction or rehabilitation costs are generally incurred at the beginning of a project, whereas routine maintenance, preventive preservation, major rehabilitation, reconstruction, and user-related costs occur periodically throughout the analysis period. LCCA provides a systematic economic framework for converting these future costs into equivalent present values so that alternative infrastructure strategies with different expenditure patterns and service lives can be compared consistently. The fundamental objective is not simply to identify the alternative with the lowest initial cost, but to determine the strategy that provides the required level of performance at the lowest total discounted cost over the selected analysis period (Federal Highway Administration [FHWA], 1998, 2017). The theoretical foundation of LCCA is therefore closely connected to the concept of economic efficiency, in which scarce financial resources are allocated to alternatives that generate the greatest long-term value relative to their costs. A central component of this framework is the discount rate, which is used to convert future costs into present-value terms. The choice of discount rate can have a substantial influence on LCCA results because transportation infrastructure decisions frequently involve costs extending several decades into the future. A higher discount rate places relatively less weight on future expenditures, while a lower discount rate gives greater importance to costs occurring later in the asset's life. Consequently, the selection of an appropriate discount rate is not merely a mathematical decision but an important methodological and policy consideration that can influence whether agencies favor alternatives with lower initial costs or alternatives requiring greater upfront investment but lower future maintenance and rehabilitation expenditures. FHWA guidance emphasizes the importance of applying appropriate real discount rates and maintaining consistency between the treatment of inflation, costs, and discounting assumptions in LCCA (FHWA, 2017). Another important theoretical component is the definition of the analysis period. The analysis period must be sufficiently long to

capture the major rehabilitation and maintenance activities associated with competing alternatives and should allow meaningful comparison of strategies with different expected service lives. More recent developments have extended the economic foundation of LCCA to include sustainability and resilience. Conventional LCCA primarily evaluates costs that can be expressed in monetary terms, but transportation infrastructure also generates environmental and social consequences that may not be fully reflected in conventional economic calculations. The integration of LCCA with Life-Cycle Assessment (LCA), climate-risk analysis, resilience assessment, and multi-criteria approaches seeks to address this limitation by considering environmental impacts, greenhouse-gas emissions, embodied carbon, resource consumption, vulnerability to extreme events, and service disruptions alongside conventional financial costs. This broader perspective is increasingly important because an infrastructure alternative with a favorable financial NPV under historical conditions may not remain economically optimal when future climate risks, environmental regulations, or resilience requirements are considered. Overall, the theoretical and economic foundation of LCCA rests on several interconnected principles: economic efficiency, time value of money, discounting, life-cycle perspective, cost internalization, service-life evaluation, uncertainty management, and optimization under resource constraints. These principles provide the basis for comparing transportation infrastructure alternatives in a systematic and transparent manner. The continuing development of LCCA reflects an increasing recognition that transportation investments should be evaluated not only according to what they cost to build today but also according to how they perform, what they cost to maintain, what risks they create, and what economic, environmental, and social consequences they generate throughout their service lives. This theoretical foundation provides the basis for applying LCCA to pavement preservation, bridge rehabilitation, and long-term transportation investment planning and establishes an essential framework for evaluating the methodological differences, limitations, and emerging developments identified in the broader literature.

Figure 4 : Theoretical And Economic Foundation

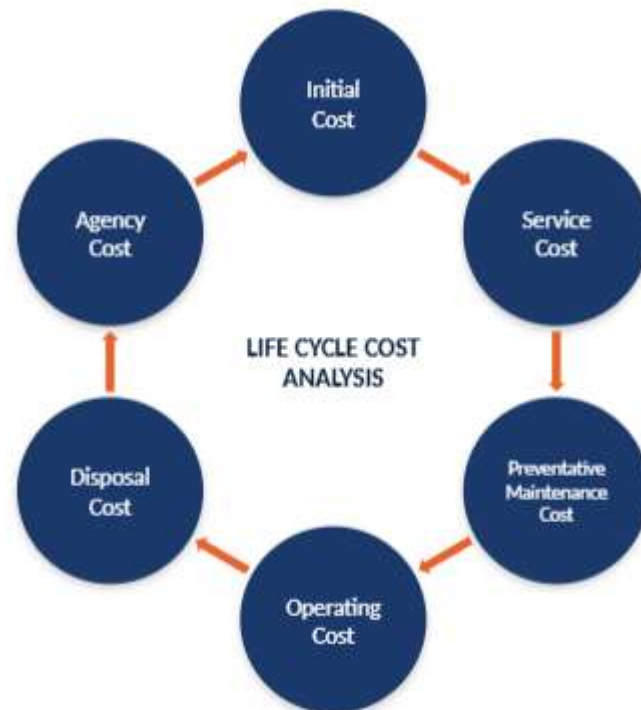


Cost Components Of LCCA

The cost components of Life-Cycle Cost Analysis (LCCA) represent the financial and economic consequences associated with an infrastructure asset throughout its entire service life, and their accurate identification is essential for producing reliable and comparable economic evaluations. Unlike conventional project appraisal, which often emphasizes initial construction or rehabilitation expenditure, LCCA considers the complete stream of costs incurred by transportation agencies and, where appropriate, by infrastructure users over the selected analysis period. The major cost components generally include initial construction or rehabilitation costs, routine maintenance costs, preventive preservation costs, periodic rehabilitation costs, reconstruction or replacement costs, agency administrative and operational costs, user costs, residual or salvage value, and, increasingly, costs associated with risk, environmental impacts, and resilience. The Federal Highway Administration (FHWA) emphasizes that LCCA should consider relevant agency and user costs occurring throughout the life of a transportation facility and should discount future costs to present-value terms to facilitate comparison among alternatives (FHWA, 1998, 2017). The initial construction cost is normally the first and most visible component of LCCA and includes expenditures for materials, labor, equipment, site preparation, design, engineering, construction management, traffic control, and other activities required to place an asset into service. For pavement projects, initial costs may include earthwork, base and sub-base preparation, asphalt or concrete placement, drainage, shoulders, markings, and associated roadway components, while bridge projects may include structural materials, foundations, superstructure components, substructure work, expansion joints, bearings, protective systems, and traffic-management arrangements. Although initial cost is important, it should not be treated as the sole criterion because an alternative with a lower initial expenditure may require more frequent maintenance or earlier rehabilitation. The second major component consists of routine maintenance and operational costs, which are expenditures required to preserve an asset in an acceptable condition during normal operation. Pavement maintenance can include crack sealing, patching, surface treatments, drainage maintenance, joint maintenance, and minor repairs, while bridge maintenance may include cleaning, painting, corrosion protection, bearing maintenance, joint repair, deck maintenance, and inspection-related activities. These costs may occur repeatedly throughout the asset's service life, and therefore their timing and frequency can substantially influence the present value of competing alternatives. Preventive maintenance and preservation costs constitute another important component of contemporary LCCA because transportation agencies increasingly seek to intervene before significant deterioration occurs. Preservation treatments can delay major structural deterioration and extend service life, potentially reducing future rehabilitation and reconstruction requirements. However, preservation requires agencies to make expenditures earlier in the asset life, creating an economic trade-off between immediate investment and potential future savings. LCCA provides a mechanism for evaluating whether these early interventions generate sufficient long-term economic benefits to justify their cost. This is particularly important in pavement management, where the timing of preservation treatments can have a substantial effect on the rate of deterioration and subsequent rehabilitation requirements. Rehabilitation costs are generally larger periodic expenditures associated with restoring or improving an asset after deterioration has progressed beyond the level appropriate for routine maintenance. For pavements, rehabilitation may involve overlays, milling and resurfacing, structural strengthening, full-depth reclamation, or other major treatments. For bridges, rehabilitation can include deck replacement, structural strengthening, member replacement, corrosion repair, bearing replacement, expansion-joint replacement, and other component-level interventions. The timing of rehabilitation is a critical LCCA variable because delaying intervention may reduce short-term expenditure but increase future rehabilitation or reconstruction costs. Conversely, early rehabilitation may require greater current expenditure but prevent more expensive deterioration later in the asset's life. Reconstruction and replacement costs are also incorporated when an asset reaches the end of its functional or structural service life. Reconstruction generally represents one of the largest future

expenditures in an LCCA and can strongly influence the economic ranking of alternatives, particularly when competing strategies have substantially different expected service lives. For example, an alternative with a longer service life may require a higher initial investment but postpone reconstruction and reduce the frequency of major future interventions.

Figure 5: Life Cycle Cost Analysis

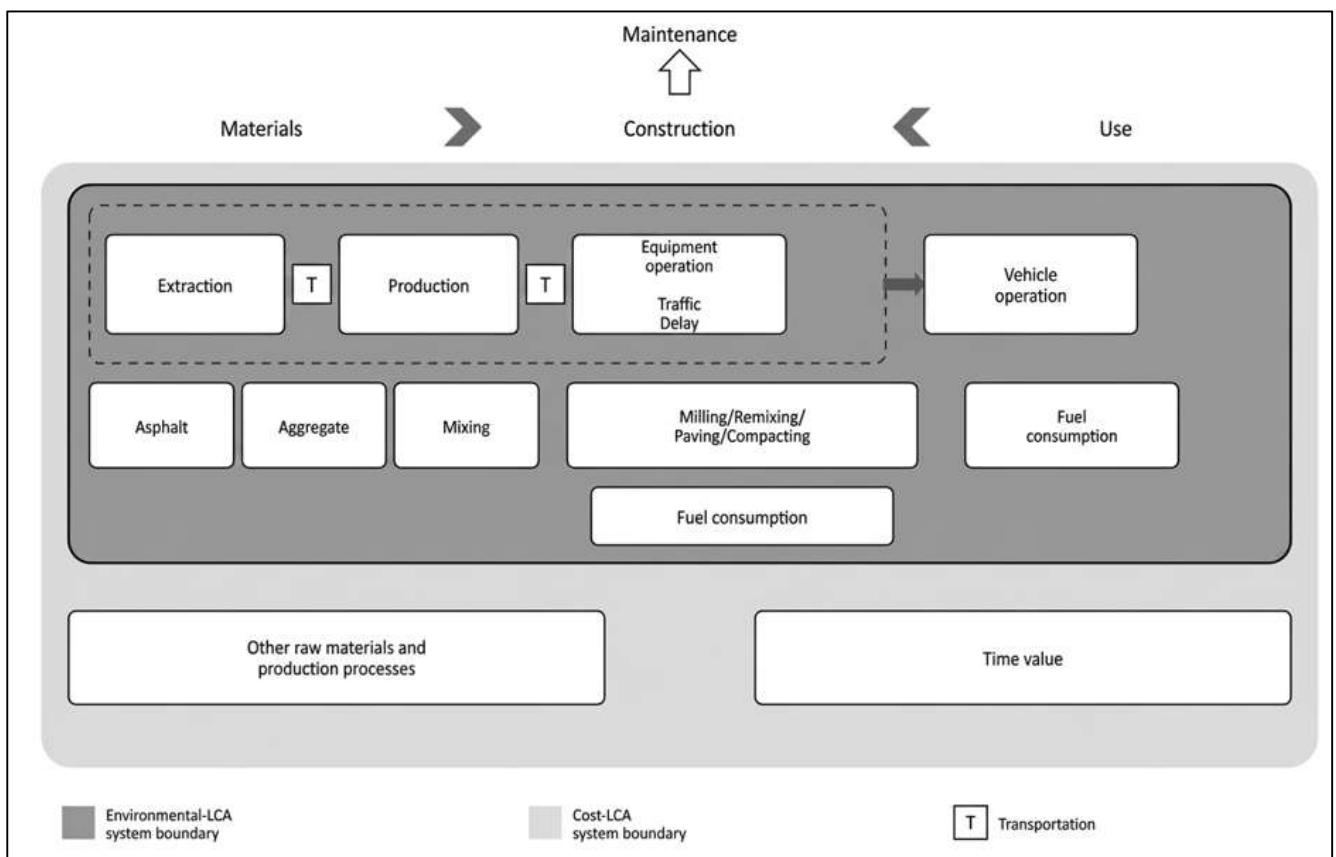


LCCA for Pavement Preservation

Life-Cycle Cost Analysis (LCCA) has become an important decision-support methodology for pavement preservation because transportation agencies must determine how limited maintenance and rehabilitation resources can be used to maintain pavement condition, safety, serviceability, and long-term performance at the lowest feasible total cost. Pavement preservation involves a range of interventions, including routine maintenance, preventive maintenance, surface treatments, overlays, rehabilitation, and reconstruction, each of which differs in initial cost, expected effectiveness, service life, maintenance requirements, and future intervention needs. LCCA provides a systematic framework for comparing these alternatives by evaluating the present value of costs expected to occur throughout the pavement's analysis period rather than selecting treatments solely on the basis of their initial expenditure. The Federal Highway Administration (FHWA) identifies LCCA as an important economic method for comparing alternative pavement strategies and emphasizes consideration of agency and user costs over the full analysis period (FHWA, 1998, 2017). This long-term perspective is particularly important because pavement deterioration is cumulative and nonlinear; relatively small defects that are inexpensive to address during the early stages of deterioration can develop into substantial structural or functional deficiencies when treatment is delayed. Consequently, LCCA is closely connected with pavement preservation strategies that seek to intervene at appropriate points in the deterioration process before extensive rehabilitation or reconstruction becomes necessary. Preventive maintenance represents one of the most widely examined applications of LCCA in pavement management. Treatments such as crack sealing, chip sealing, microsurfacing, thin overlays, surface recycling, and other preservation techniques generally require lower initial expenditures than major rehabilitation or reconstruction but must be applied at appropriate pavement condition levels to achieve their intended service-life benefits. The economic value of preventive preservation depends on whether the treatment successfully slows deterioration, extends pavement service life, and postpones

more expensive future interventions. LCCA allows agencies to compare a preservation strategy involving several relatively small expenditures with a strategy that permits deterioration to continue until major rehabilitation is required. The analysis therefore helps identify the economic trade-off between early intervention and deferred expenditure. This relationship is particularly important because the cost of pavement treatment generally increases as deterioration progresses, while the effectiveness of some low-cost preservation treatments decreases when pavement condition falls below an appropriate threshold. Pavement deterioration and service-life prediction are therefore central to the reliability of pavement LCCA. The timing of future maintenance, rehabilitation, and reconstruction activities depends on estimates of how rapidly pavement conditions will decline under traffic loading and environmental exposure. Factors such as axle loads, traffic volume, pavement structure, material properties, construction quality, drainage, temperature, precipitation, freeze-thaw cycles, and other environmental conditions influence deterioration rates. The Long-Term Pavement Performance (LTPP) program has provided extensive long-term pavement performance data that have supported the development and improvement of pavement deterioration models and treatment-performance relationships (FHWA, 2015).

Figure 6 : LCCA for Pavement Preservation

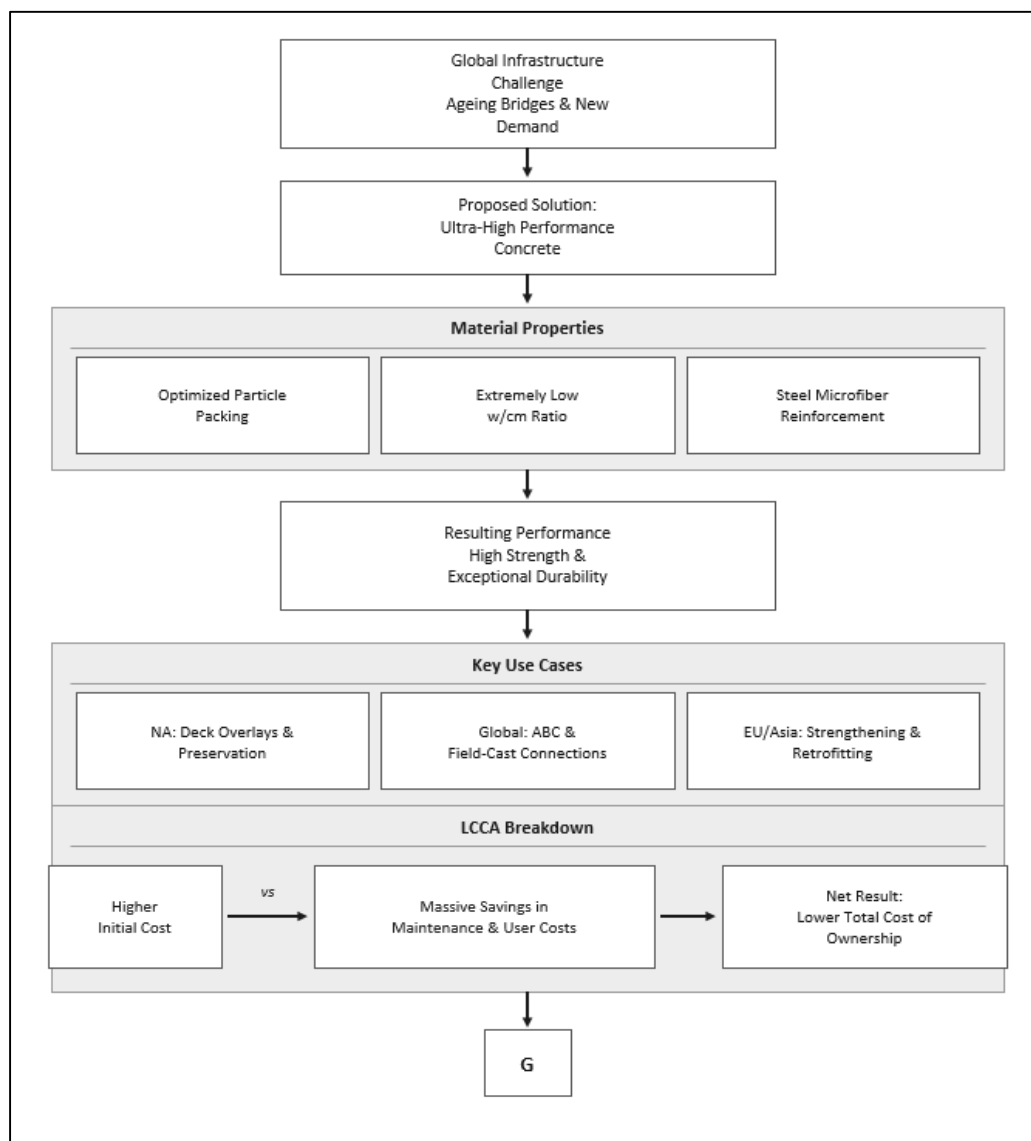


LCCA for Bridge Rehabilitation

Life-Cycle Cost Analysis (LCCA) has become an increasingly important tool for evaluating maintenance, rehabilitation, strengthening, and replacement strategies for bridges because bridge infrastructure requires substantial long-term investment and involves complex deterioration processes that can significantly affect safety, mobility, and network performance. Unlike pavements, which generally consist of relatively continuous structural layers and can often be evaluated using established pavement-condition measures and deterioration curves, bridges are composed of multiple structural and functional components, including decks, superstructures, substructures, bearings, expansion

joints, protective systems, and foundations, each of which may deteriorate at different rates and require different maintenance or rehabilitation treatments. Consequently, bridge LCCA requires a more detailed consideration of component-level deterioration, intervention timing, service life, structural condition, inspection requirements, and the consequences of delaying maintenance. The Federal Highway Administration (FHWA) recognizes life-cycle economic evaluation as an important element of bridge management and emphasizes the consideration of deterioration, maintenance and rehabilitation actions, agency costs, user costs, and risk when developing bridge investment strategies (FHWA, 2012, 2026). The fundamental purpose of bridge LCCA is to determine which combination of interventions can achieve an acceptable level of structural performance and safety over the analysis period at the lowest reasonable life-cycle cost. This requires transportation agencies to move beyond the immediate cost of a rehabilitation project and evaluate how current intervention decisions influence future maintenance requirements, deterioration, service life, and replacement needs. Bridge maintenance represents an essential component of life-cycle management because regular inspection, cleaning, painting, corrosion control, joint maintenance, drainage maintenance, bearing maintenance, and minor structural repairs can prevent localized deterioration from developing into more expensive structural deficiencies.

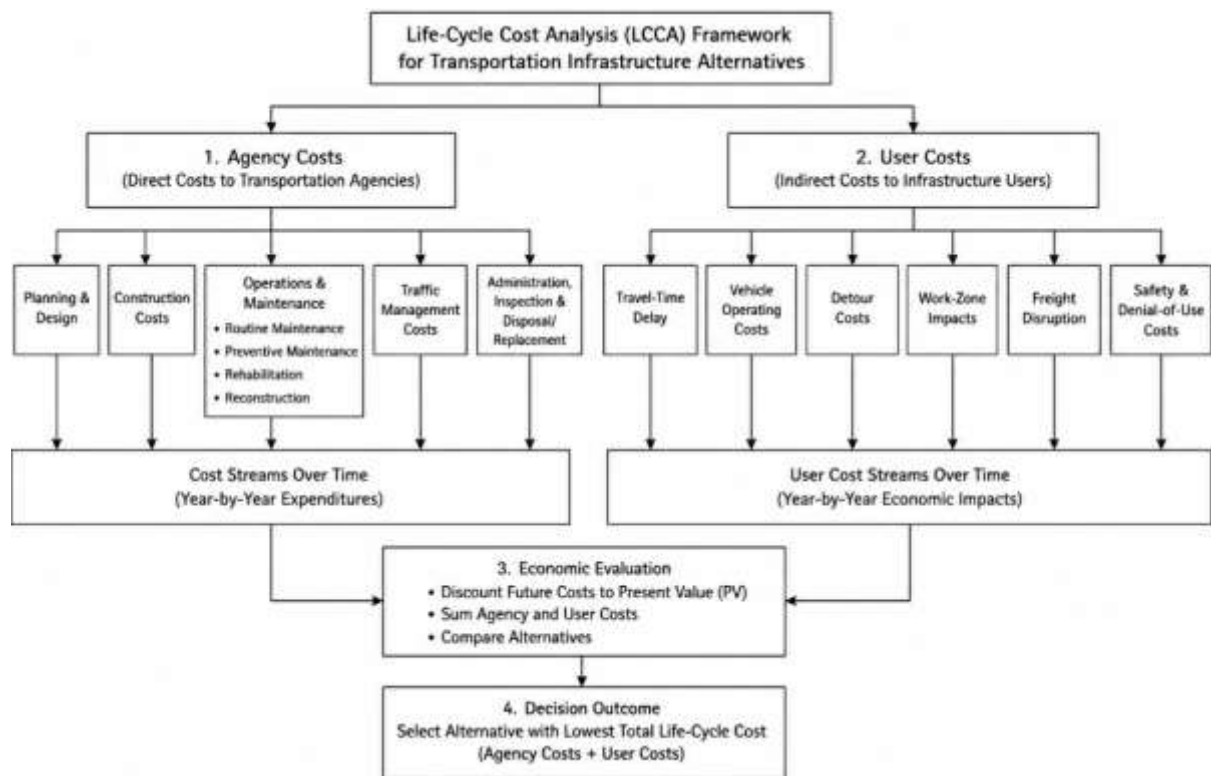
Figure 7: LCCA for Bridge Rehabilitation



Agency Costs and User Costs

Agency costs and user costs constitute two fundamental categories in [Life-Cycle Cost Analysis \(LCCA\)](#) because they capture both the direct financial burden imposed on transportation agencies and the broader economic consequences experienced by infrastructure users throughout the asset's life cycle. The literature emphasizes that an evaluation based solely on agency expenditures may provide an incomplete representation of the economic performance of transportation alternatives because maintenance, rehabilitation, and reconstruction activities can generate substantial indirect impacts on travelers, freight operators, businesses, and surrounding communities. The [Federal Highway Administration \(FHWA\)](#) therefore recommends considering relevant agency and user costs when conducting highway [LCCA](#), particularly when alternative strategies differ substantially in construction timing, maintenance frequency, work-zone duration, or expected service life ([FHWA, 1998, 2017](#)). Agency costs generally represent expenditures directly incurred by transportation authorities and include planning, design, construction, routine maintenance, preventive preservation, rehabilitation, reconstruction, inspection, traffic management, administration, and disposal or replacement activities. Initial construction costs are usually the most visible agency expenditure, but they represent only one component of total life-cycle cost. Transportation agencies may incur repeated expenditures for pavement patching, crack sealing, resurfacing, bridge deck repair, structural strengthening, corrosion control, bearing replacement, joint rehabilitation, inspection, and emergency maintenance. The timing and frequency of these expenditures are critical [because LCCA](#) discounts future costs to present-value terms, meaning that two alternatives with similar total undiscounted expenditures can have substantially different economic outcomes depending on when those expenditures occur. Accurate estimation of agency costs therefore requires historical cost information, realistic treatment schedules, expected service lives, deterioration models, construction price assumptions, and appropriate discounting procedures. The literature also distinguishes between routine maintenance, preventive maintenance, and major rehabilitation costs, because each has different implications for asset performance and future expenditure requirements. Routine maintenance is generally performed regularly to preserve operational functionality, whereas preventive maintenance is intended to slow deterioration and postpone more expensive rehabilitation. Major rehabilitation and reconstruction occur less frequently but generally involve substantially greater expenditures. [LCCA](#) evaluates these cost streams collectively to determine whether a strategy involving relatively frequent low-cost interventions is economically preferable to one involving fewer but more expensive interventions. This approach is particularly important for pavement preservation, where the timing of preventive treatment can determine whether an asset remains in a manageable condition or progresses toward costly structural rehabilitation. For bridges, agency costs may be more complex because different structural components can require interventions at different times. A bridge may require periodic deck maintenance, bearing replacement, expansion-joint repair, painting, corrosion protection, and structural strengthening before complete replacement becomes necessary. Component-level [LCCA](#) can therefore provide a more realistic estimate of future agency expenditures by modeling the expected timing and cost of individual interventions. In addition to direct construction and maintenance expenditures, agency traffic-management costs can include temporary traffic control, lane-management systems, detour implementation, temporary structures, work-zone management, and other measures required to maintain traffic during construction. These expenditures are important because work-zone strategies can vary considerably between alternatives and may influence both agency and user costs. An alternative that is more expensive to construct may nevertheless be economically preferable if it significantly reduces construction duration and associated traffic impacts. User costs, in contrast, represent economic impacts borne by individuals, businesses, freight operators, and other users as a result of transportation infrastructure interventions. These costs are generally indirect from the agency's accounting perspective but may represent substantial economic losses at the societal level. The most commonly considered user-cost components include travel-time delay, vehicle

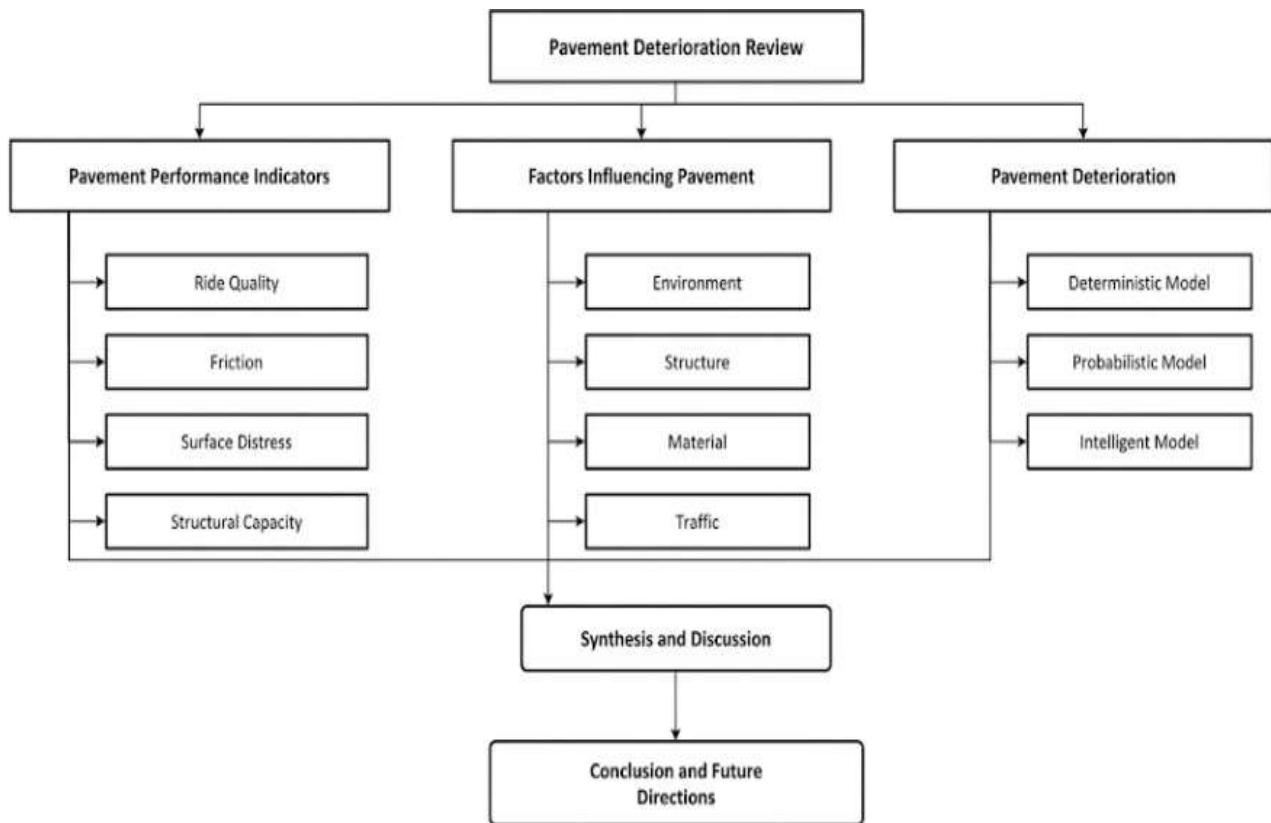
operating costs, detour costs, work-zone impacts, freight disruption, crash-related effects, and denial-of-use costs. Travel-time delay occurs when construction or maintenance reduces roadway capacity, lowers travel speeds, creates queues, or requires traffic to follow temporary routes. The economic value of delay is generally estimated by multiplying additional travel time by an appropriate value of time for different categories of users, such as passenger vehicles, commercial vehicles, and freight traffic. The estimation of travel delay can be complex because traffic demand, congestion, work-zone configuration, time of day, seasonal conditions, and driver behavior can influence the magnitude of delay. Consequently, assumptions about traffic volumes and operational conditions can have a substantial effect on estimated user costs.



Deterioration and Performance Modeling

Deterioration and performance modeling forms one of the most important methodological foundations of Life-Cycle Cost Analysis (LCCA) because the timing, magnitude, and frequency of future maintenance, rehabilitation, and reconstruction activities depend directly on predictions of how transportation infrastructure will change over time. In both pavement and bridge applications, LCCA requires analysts to estimate when an asset will reach specified condition or performance thresholds and how different intervention strategies will alter its subsequent deterioration path. The literature demonstrates that a wide range of modeling approaches has been developed for this purpose, ranging from relatively simple deterministic deterioration curves to more sophisticated probabilistic, Markov-chain, reliability-based, survival-analysis, and data-driven machine-learning models. Each approach reflects different assumptions regarding uncertainty, data availability, asset characteristics, and the intended level of analysis, and the choice of deterioration model can substantially influence the resulting life-cycle cost estimates and the economic ranking of competing investment alternatives. Deterministic deterioration models represent the earliest and most widely used approach in transportation infrastructure management.

Figure 8 : Deterioration and Performance Modeling

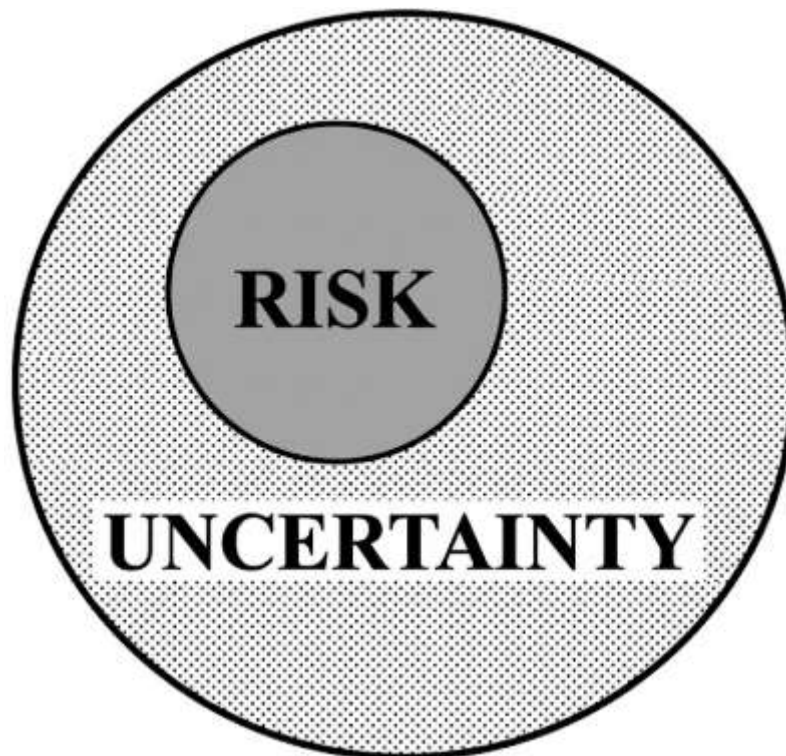


Uncertainty and Risk in LCCA

Uncertainty and risk are fundamental considerations in Life-Cycle Cost [Analysis \(LCCA\)](#) because transportation infrastructure decisions involve long analysis periods during which future costs, asset performance, traffic conditions, and economic conditions cannot be predicted with complete certainty. Pavements and bridges may remain in service for several decades, meaning that assumptions concerning construction prices, deterioration rates, treatment effectiveness, traffic growth, discount rates, maintenance schedules, and service life can substantially influence estimated life-cycle costs and the economic ranking of competing alternatives. The [Federal Highway Administration \(FHWA\)](#) recognizes the importance of uncertainty in LCCA and recommends sensitivity analysis and other analytical techniques to evaluate how changes in key assumptions affect economic results (Federal Highway Administration [\[FHWA\], 1998, 2017](#)). [Traditional LCCA](#) commonly uses deterministic inputs, assigning a single value to each variable and producing one estimated present-value cost for each alternative; however, this approach may create a false impression of precision because actual infrastructure performance and future economic conditions are rarely known with certainty. One major source of uncertainty is construction and rehabilitation cost, which can vary because of changes in material prices, labor costs, equipment costs, energy prices, inflation, supply-chain conditions, and market fluctuations. An alternative that appears economically attractive under current prices may become less favorable if future asphalt, concrete, steel, or labor costs increase substantially. Deterioration-rate uncertainty is equally important because pavement and bridge performance is influenced by traffic loading, material properties, construction quality, environmental exposure, drainage, temperature, precipitation, corrosion, maintenance history, and other factors. Even infrastructure assets with similar designs and construction specifications can experience significantly different deterioration trajectories. If deterioration is underestimated, future rehabilitation and reconstruction costs may be delayed unrealistically, resulting in an underestimated life-cycle cost, whereas overly conservative deterioration assumptions may make an alternative appear unnecessarily expensive. Treatment effectiveness introduces additional uncertainty because maintenance and

rehabilitation treatments do not produce identical results in all conditions. The effectiveness and durability of pavement preservation, overlays, bridge rehabilitation, strengthening, and other treatments depend on existing condition, construction quality, environmental exposure, traffic loading, materials, and maintenance practices.

Figure 9 : Uncertainty and Risk in LCCA

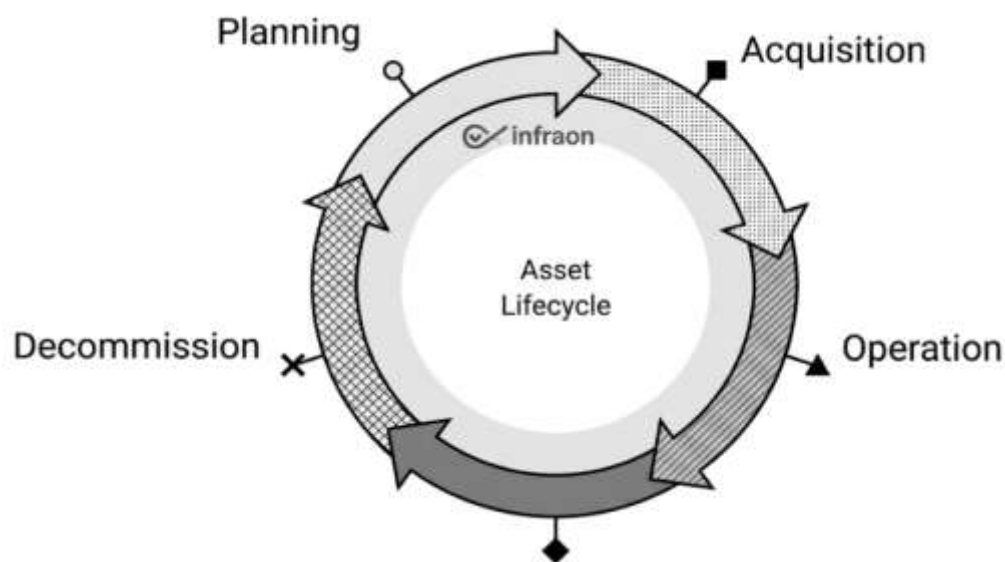


LCCA and Transportation Asset Management

Life-Cycle Cost Analysis (LCCA) is closely connected to modern transportation asset management because both approaches seek to support long-term, economically efficient, and performance-oriented decisions concerning infrastructure investment, maintenance, rehabilitation, and replacement. While LCCA primarily evaluates the economic consequences of alternative strategies over an asset's life cycle, transportation asset management provides a broader framework for managing infrastructure portfolios under financial, operational, performance, risk, and policy constraints. The integration of LCCA with Transportation Asset Management Plans (TAMPs), Pavement Management Systems (PMS), Bridge Management Systems (BMS), performance management, and risk-based asset management allows transportation agencies to move beyond project-level cost comparisons toward coordinated network-level investment planning. The Federal Highway Administration ([FHWA](#)) identifies asset management as a systematic process for maintaining and improving transportation assets in a cost-effective manner while managing risk and achieving established performance objectives ([FHWA, 2012, 2017](#)). Within this broader framework, LCCA provides an important economic foundation by estimating the long-term financial implications of alternative intervention strategies rather than focusing exclusively on initial project expenditures. Transportation Asset Management Plans (TAMPs) represent an important institutional mechanism through which LCCA principles can be incorporated into agency-wide investment decisions. TAMPs establish strategies for managing assets such as pavements and bridges and typically consider asset condition, performance targets, investment strategies, life-cycle planning, risk, and available financial resources. [LCCA](#) can support TAMP development by estimating the long-term costs associated with alternative preservation, rehabilitation, and replacement strategies and by identifying strategies that provide acceptable performance at the lowest reasonable life-cycle cost.

However, TAMP decision-making differs from conventional project-level LCCA because agencies must allocate limited resources across large networks rather than optimize a single asset independently. A treatment that produces the lowest life-cycle cost for an individual pavement section may not necessarily be the best network-level decision if funding limitations, geographic priorities, safety requirements, freight importance, or equity considerations require resources to be distributed differently. Consequently, LCCA within TAMPs must be combined with performance targets, budget constraints, risk considerations, and strategic priorities. Pavement Management Systems (PMS) provide another important platform for integrating LCCA with transportation asset management. PMS typically collect pavement condition information, monitor deterioration, forecast future performance, identify candidate maintenance and rehabilitation treatments, and support prioritization under budget constraints. LCCA contributes to the economic component of this process by comparing the long-term costs and expected performance of alternative pavement treatments.

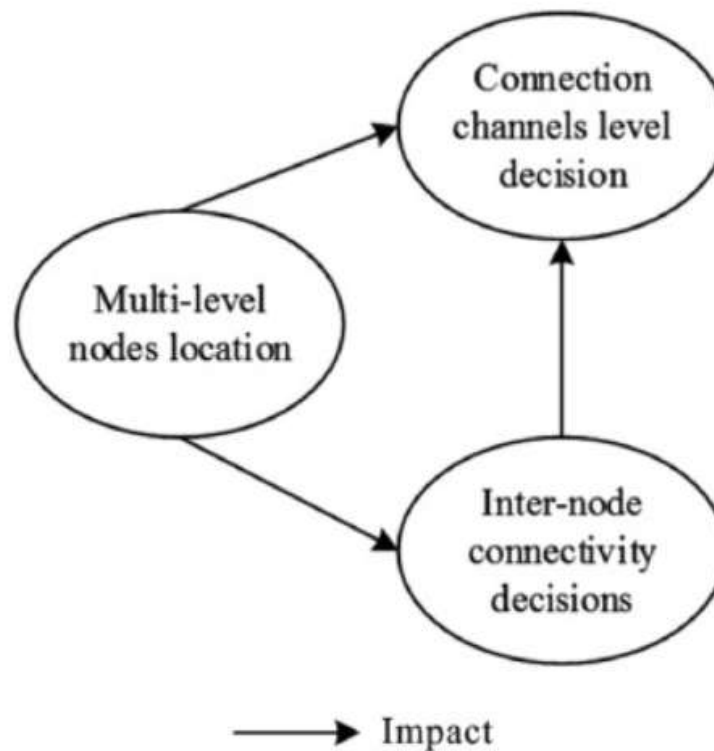
Figure 10 : Asset Lifecycle



Project-Level and Network-Level LCCA

Project-level and network-level Life-Cycle Cost Analysis (LCCA) represent two complementary but distinct approaches to transportation infrastructure investment decision-making. At the project level, LCCA focuses on identifying the most economically advantageous alternative for an individual pavement, bridge, or infrastructure project by comparing the discounted agency and user costs of competing design, preservation, rehabilitation, strengthening, or replacement strategies over a defined analysis period. The objective is generally to select the alternative that satisfies required performance and service-life criteria while minimizing total life-cycle cost. However, the strategy that is economically optimal for an individual asset may not necessarily be optimal for an entire transportation network because agencies operate under constrained budgets, limited construction capacity, and competing performance, safety, mobility, and risk priorities. Network-level LCCA therefore expands the analysis from individual project optimization to the allocation of limited resources across multiple assets, seeking to maximize overall network performance or minimize total long-term cost while satisfying budgetary and policy constraints. This requires consideration of asset condition, deterioration rates, treatment timing, traffic importance, risk, geographic distribution, user impacts, and the consequences of delaying interventions.

Figure 11: Project Level And Network Level LCCA

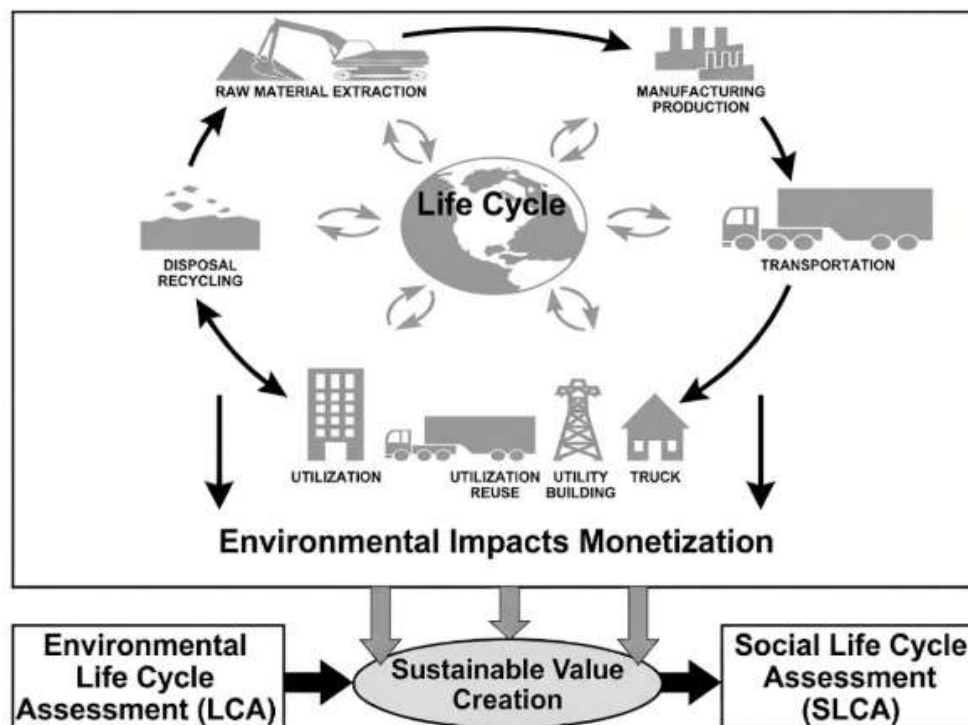


Environmental Sustainability and Life-Cycle Assessment

Environmental sustainability has become an increasingly important dimension of transportation infrastructure decision-making, complementing the traditional economic focus of Life-Cycle Cost Analysis (LCCA). Conventional LCCA primarily evaluates the discounted financial costs incurred by agencies and users over an infrastructure asset's service life, whereas environmental Life-Cycle Assessment (LCA) evaluates environmental impacts associated with material production, transportation, construction, maintenance, rehabilitation, operation, and end-of-life activities. Integrating LCA with LCCA can provide a more comprehensive basis for comparing pavement preservation, bridge rehabilitation, strengthening, and replacement alternatives because strategies with similar financial costs may have substantially different environmental consequences. Pavement construction and rehabilitation, for example, can generate significant greenhouse-gas emissions through the production and transportation of asphalt, cement, aggregates, and other materials, while repeated maintenance activities may increase cumulative energy consumption and emissions over the analysis period. Similarly, bridge rehabilitation and replacement can involve substantial quantities of steel, concrete, and other materials, making embodied carbon and resource consumption important considerations in long-term investment decisions. LCA can also account for benefits associated with recycling, material reuse, reduced construction frequency, extended service life, and lower transportation requirements. Integrating environmental indicators such as greenhouse-gas emissions, energy consumption, material use, waste generation, and resource depletion with LCCA enables agencies to identify alternatives that provide economic value while reducing environmental impacts. This integration is particularly relevant to preventive preservation because extending infrastructure service life can potentially reduce the frequency of major reconstruction and thereby decrease cumulative material and energy requirements. However, environmental LCA introduces methodological challenges related to system boundaries, functional units, emission factors, regional conditions, future energy mixes, recycling assumptions, and uncertainty in long-term environmental performance. Consequently, environmental impacts should be evaluated consistently with the economic analysis period and service-life assumptions used in LCCA. Increasingly, researchers

advocate integrated life-cycle sustainability assessment, in which economic cost, environmental impact, social consequences, resilience, and infrastructure performance are evaluated together rather than independently. Such an approach can help transportation agencies address climate-change objectives while maintaining fiscal responsibility and required infrastructure performance. Future research should therefore strengthen the integration of LCCA and LCA through standardized methodologies, reliable environmental databases, probabilistic assessment, carbon pricing or shadow-cost approaches, circular-economy principles, and climate-resilience considerations, enabling transportation agencies to make investment decisions that are not only economically efficient but also environmentally sustainable and resilient over the entire life cycle of transportation infrastructure.

Figure 12 : Environmental Sustainability and Life-Cycle Assessment



Methodological Limitations in Existing Studies

Despite the extensive application of Life-Cycle Cost Analysis (LCCA) in transportation infrastructure planning, the existing literature contains several methodological limitations that reduce the comparability, reliability, and generalizability of reported findings. One major limitation is the inconsistent selection of discount rates, as studies may use different real or nominal rates and economic assumptions, causing substantially different present-value estimates for alternatives with different patterns of initial and future expenditures. Similarly, differences in analysis periods make direct comparison difficult because some studies evaluate alternatives over relatively short periods while others consider the full expected service life of pavements or bridges. The literature is also constrained by limited and inconsistent data, particularly for bridge deterioration, treatment effectiveness, construction costs, maintenance histories, and long-term performance observations. Although pavement research benefits from extensive datasets such as the Long-Term Pavement Performance (LTPP) program, many studies still rely on regional or agency-specific data that may not be transferable to other geographic or climatic conditions (Federal Highway Administration [FHWA], 2015). Another important limitation is the continued reliance on deterministic assumptions, in which deterioration rates, service lives, treatment effectiveness, traffic growth, and future costs are represented by single values despite considerable uncertainty. Such assumptions can produce overly precise estimates and may fail to capture the range of possible future outcomes. User-cost estimation is also inconsistent

across the literature, with some studies incorporating travel delay, vehicle operating costs, detours, work-zone impacts, and freight disruption while others focus primarily on agency expenditures. This is particularly problematic for bridge projects where denial-of-use and detour effects can represent a substantial proportion of total societal costs. Furthermore, existing deterioration models may not adequately capture nonlinear deterioration, component-specific behavior, climate effects, unexpected failures, or uncertainty associated with inspection and condition assessment. Bridge applications are particularly affected because different structural components can deteriorate at different rates and may require separate intervention strategies. Another significant limitation is the relatively limited integration of environmental and social impacts into conventional LCCA. Traditional analyses generally emphasize financial agency and user costs while giving insufficient attention to greenhouse-gas emissions, embodied carbon, energy consumption, material use, environmental disruption, equity, accessibility, community impacts, and broader social consequences. Although environmental Life-Cycle Assessment (LCA), resilience analysis, and social sustainability approaches are increasingly being incorporated into transportation research, these dimensions are not yet consistently integrated into standard LCCA frameworks. In addition, many studies evaluate alternatives at the project level without fully considering network-level budget constraints, asset interdependencies, risk exposure, and the opportunity costs associated with allocating limited resources among competing projects. The treatment of climate change and extreme events is also relatively limited in traditional LCCA, with many models relying on historical deterioration and cost conditions that may not adequately represent future flooding, extreme precipitation, temperature changes, scour, corrosion, and other climate-related risks. Finally, differences in modeling assumptions, cost categories, performance measures, data sources, and reporting practices can make it difficult to reproduce or directly compare findings across studies. These limitations indicate a need for more standardized and transparent LCCA methodologies that combine consistent discounting and analysis-period conventions with probabilistic deterioration modeling, comprehensive agency and user-cost estimation, advanced data analytics, environmental LCA, social-impact assessment, climate-risk analysis, and network-level optimization. Addressing these methodological gaps would improve the robustness, comparability, and practical usefulness of LCCA and enable transportation agencies to make more economically efficient, sustainable, resilient, and socially responsible long-term infrastructure investment decisions.

Research Gap

Although [Life-Cycle Cost Analysis \(LCCA\)](#) has been extensively applied to transportation infrastructure, the existing literature remains fragmented across individual asset classes and decision-making levels, creating an important research gap. A substantial body of research has examined pavement preservation through preventive maintenance, overlays, rehabilitation, and reconstruction, while another stream has focused on bridge rehabilitation, strengthening, maintenance, and replacement; however, comparatively limited research provides an integrated framework that systematically connects pavement and bridge LCCA with long-term transportation investment planning. Existing studies also differ considerably in their treatment of discount rates, analysis periods, deterioration models, treatment effectiveness, service-life assumptions, and cost categories, making cross-study comparison difficult. Furthermore, many conventional LCCA applications remain predominantly deterministic and emphasize agency expenditures, with incomplete consideration of uncertainty, user costs, environmental impacts, social consequences, and climate-related risks. User impacts such as travel delay, vehicle operating costs, freight disruption, detours, and bridge denial-of-use costs are not consistently incorporated, despite their potential significance in determining the true societal cost of infrastructure interventions. Similarly, environmental sustainability is often evaluated separately through Life-Cycle Assessment rather than being systematically integrated with economic LCCA, while climate change and resilience considerations are frequently treated as supplementary rather than fundamental components of long-term investment decisions. Another important gap concerns the transition from project-level economic optimization to network-level resource allocation.

Selecting the lowest-cost life-cycle alternative for an individual pavement or bridge does not necessarily produce the most beneficial investment portfolio when transportation agencies face limited budgets, competing infrastructure needs, performance targets, and varying levels of network risk. Existing research therefore provides insufficient integration among project-level LCCA, pavement and bridge management systems, transportation asset management plans, probabilistic deterioration forecasting, risk assessment, and multi-year budget optimization. In particular, there is a need for a systematic synthesis that compares pavement and bridge applications while simultaneously examining economic cost, user impacts, uncertainty, sustainability, climate resilience, and network-level investment priorities. Addressing this gap would contribute to a more comprehensive understanding of how LCCA can evolve from a conventional project-selection technique into an integrated, risk-informed, sustainable, and network-oriented decision-support framework for transportation infrastructure management. This study therefore seeks to synthesize the existing evidence across pavement preservation, bridge rehabilitation, and long-term investment planning and identify methodological directions for integrating uncertainty analysis, user-cost estimation, environmental sustainability, climate resilience, and resource allocation within future LCCA practice.

Future Research Directions

Future research on Life-Cycle Cost Analysis (LCCA) should focus on developing more comprehensive, dynamic, and integrated approaches that overcome the methodological limitations identified in the existing literature. A major opportunity lies in the expanded use of probabilistic modeling, which can explicitly represent uncertainty in construction costs, deterioration rates, treatment effectiveness, traffic growth, discount rates, maintenance schedules, and service life rather than relying on deterministic assumptions. Probabilistic LCCA combined with Monte Carlo simulation, reliability analysis, and scenario-based approaches could provide transportation agencies with not only expected life-cycle costs but also the probability and consequences of unfavorable outcomes. Another important direction is the integration of artificial intelligence (AI) and machine-learning (ML) techniques for deterioration and performance prediction. AI/ML models can process large and complex datasets to identify nonlinear relationships among traffic, environmental conditions, material characteristics, structural properties, maintenance history, and infrastructure condition, potentially improving predictions of remaining service life and treatment timing. The increasing availability of real-time asset data from Internet of Things (IoT) sensors, structural health-monitoring systems, automated inspections, drones, remote sensing, and mobile data-collection technologies also creates opportunities to transform LCCA from a static analysis into a continuously updated decision-support system. Real-time condition information could allow agencies to revise deterioration forecasts, maintenance schedules, treatment effectiveness, and cost estimates as infrastructure conditions change. Climate-change scenarios should also be incorporated more systematically into future LCCA because changing temperature patterns, flooding, extreme precipitation, storms, scour, corrosion, and other hazards may substantially influence infrastructure deterioration and service life. Scenario-based climate LCCA can help agencies compare conventional and climate-adapted alternatives and determine whether additional investment in resilient infrastructure can reduce expected future damage and disruption costs. Closely related to this is the need for stronger resilience assessment, particularly for bridges and other critical transportation assets where failure or closure can generate significant safety, mobility, freight, and economic consequences. Future models should therefore consider both the probability of infrastructure damage and the consequences of service disruption, including detour and denial-of-use costs. Another important research direction is the integration of environmental sustainability and Life-Cycle Assessment (LCA) with conventional economic LCCA. Future frameworks should simultaneously evaluate financial costs, greenhouse-gas emissions, embodied carbon, energy consumption, material use, waste generation, and resource efficiency so that agencies can identify alternatives that provide long-term economic and environmental value. Finally, greater emphasis should be placed on network-level optimization, linking project-level LCCA with Transportation Asset Management Plans (TAMPs),

Pavement Management Systems (PMS), Bridge Management Systems (BMS), performance targets, risk-based prioritization, and multi-year budget allocation. Such integration would enable agencies to move beyond selecting the least-cost alternative for individual projects and instead identify investment portfolios that maximize network performance and resilience under limited financial resources. Overall, future LCCA research should move toward an integrated, probabilistic, data-driven, climate-informed, environmentally sustainable, and network-oriented framework that combines economic evaluation with performance, risk, resilience, and sustainability considerations. Such advancement would strengthen the ability of transportation agencies to make transparent and evidence-based decisions concerning pavement preservation, bridge rehabilitation, and long-term infrastructure investment while improving the efficiency, resilience, and sustainability of transportation systems over their entire life cycles.

METHODOLOGY

This review follows the general logic of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, which has itself been used by prior reviewers of pavement life-cycle literature, adapted for a narrative-synthesis format appropriate to a heterogeneous, cross-disciplinary body of engineering, economics, and public-policy literature.

Search Strategy

Literature was identified through structured searches of major academic databases and scholarly repositories, including ScienceDirect, SpringerLink, Wiley Online Library, Transportation Research Board (TRB) publications, and institutional repositories, to ensure broad coverage of peer-reviewed research and transportation engineering studies. The academic search was supplemented with authoritative technical and policy documents produced by organizations such as the Federal Highway Administration (FHWA), National Cooperative Highway Research Program (NCHRP), American Association of State Highway and Transportation Officials (AASHTO), and state departments of transportation, as these sources provide important methodological guidance, agency practices, cost-estimation procedures, and transportation asset-management frameworks that are not always captured in journal literature. The search strategy employed combinations of keywords and Boolean operators, including “life-cycle cost analysis,” “life-cycle cost,” and “LCCA” in combination with terms such as “pavement,” “pavement preservation,” “bridge,” “bridge rehabilitation,” “maintenance,” “asset management,” “transportation infrastructure,” “infrastructure investment,” “budget allocation,” and “long-term infrastructure planning.” Additional searches incorporated terms related to the major analytical dimensions of the review, including “deterioration modeling,” “user costs,” “uncertainty,” “risk,” “sustainability,” “climate resilience,” “life-cycle assessment,” “network-level optimization,” and “transportation asset management.” Search strings were adapted to the syntax and indexing characteristics of each database to maximize retrieval while maintaining consistency with the research objectives. The search process considered publications addressing both project-level and network-level LCCA, with particular attention to studies evaluating pavement preservation, bridge rehabilitation, and long-term investment planning. Reference lists of highly relevant studies and major review articles were also examined through backward citation searching to identify additional influential publications, while forward citation tracking was used where appropriate to locate subsequent research building on established LCCA methodologies. Grey literature, including technical reports, guidelines, research-program publications, and agency manuals, was included where it provided substantial methodological or practical evidence relevant to transportation LCCA. Following the initial retrieval process, all identified records were compiled, duplicates were removed, and titles and abstracts were screened against predefined inclusion and exclusion criteria. Potentially relevant studies were then subjected to full-text assessment before final inclusion in the systematic review. This structured search and supplementary citation-tracking approach was designed to provide comprehensive coverage of the literature while maintaining transparency, reproducibility, and alignment with the PRISMA 2020 systematic-review framework.

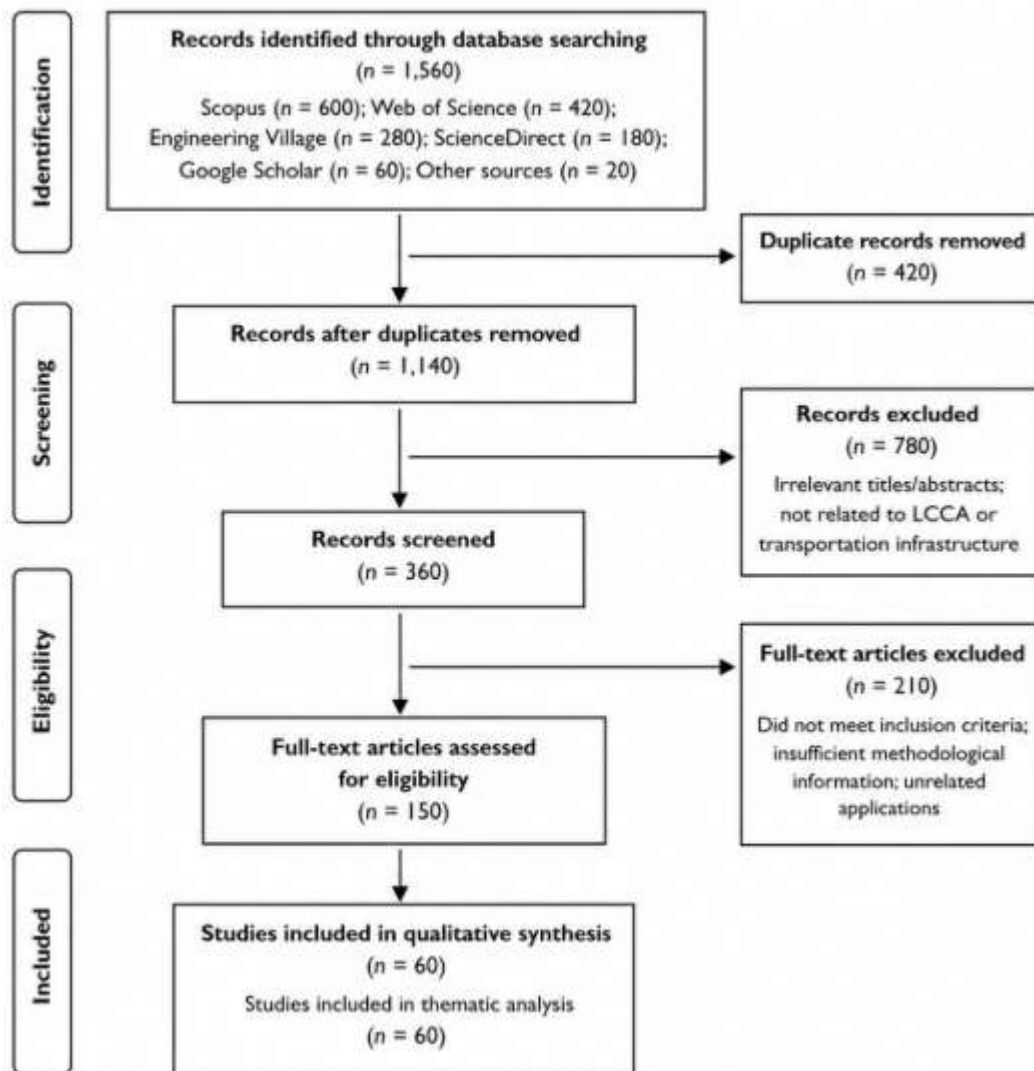
Table 1 : LCCA Search Strategy

Database/Source	Primary Search Terms	Additional Terms	Purpose
ScienceDirect	“life-cycle cost analysis” OR LCCA	pavement, bridge, rehabilitation	Identify peer-reviewed LCCA studies
SpringerLink	“life-cycle cost” OR “life-cycle costing”	infrastructure, transportation	Identify methodological studies
Wiley Online Library	LCCA OR “life-cycle cost analysis”	pavement, bridge, asset management	Identify economic evaluation research
Transportation Research Board	LCCA OR “life-cycle cost”	highway, pavement, bridge	Identify transportation-specific research
FHWA	LCCA OR “life-cycle cost analysis”	pavement, bridge, asset management	Identify U.S. technical guidance
NCHRP	LCCA OR “life-cycle cost”	rehabilitation, preservation	Identify applied transportation research
AASHTO	“life-cycle cost”	asset management, investment	Identify standards and agency practices
Institutional repositories	LCCA OR “life-cycle cost analysis”	transportation infrastructure	Identify theses, reports, and supplementary research

Study Selection Process (PRISMA FLOW)

Study selection followed the four-stage PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) process—identification, screening, eligibility, and inclusion—to ensure that the literature review was systematic, transparent, and reproducible. During the identification stage, relevant studies addressing Life-Cycle Cost Analysis (LCCA) in transportation infrastructure were collected from major academic databases and complementary sources using predefined keywords related to pavement preservation, bridge rehabilitation, transportation asset management, life-cycle cost, deterioration, user costs, sustainability, resilience, and long-term investment planning. Duplicate records were subsequently removed before the screening process. During the screening stage, titles and abstracts were reviewed to determine whether studies were potentially relevant to the research objectives, and records that were clearly unrelated to transportation LCCA, infrastructure management, or the selected application areas were excluded. In the eligibility stage, the full texts of potentially relevant studies were assessed against predefined inclusion and exclusion criteria, with particular attention to methodological relevance, transportation infrastructure application, LCCA implementation, cost and performance evaluation, and relevance to pavement, bridge, or long-term investment planning. Studies that lacked sufficient methodological information, did not address the research questions, or focused on unrelated infrastructure or economic-analysis applications were excluded at this stage. Finally, during the inclusion stage, studies satisfying all eligibility requirements were retained for qualitative synthesis and thematic analysis. The selected literature was subsequently categorized according to major themes, including the theoretical and economic foundations of LCCA, cost components, pavement preservation, bridge rehabilitation, deterioration and performance modeling, uncertainty and risk, transportation asset management, project- and network-level analysis, environmental sustainability, climate resilience, advanced technologies, and long-term investment planning. This structured PRISMA-based selection process helped minimize selection bias, establish a clear audit trail from the initial search to the final evidence base, and ensure that the studies included in the systematic review were directly aligned with the objectives of examining LCCA applications in pavement preservation, bridge rehabilitation, and long-term transportation investment planning.

Figure 15 : Selection Process PRISMA Flow



Inclusion And Exclusion Criteria

Sources were included if they (a) presented, applied, or critically evaluated an LCCA or closely related life-cycle costing methodology; (b) addressed transportation infrastructure – principally roadway pavements, highway bridges, or multi-asset transportation networks; and (c) were peer-reviewed journal articles, conference papers, national research syntheses (e.g., NCHRP reports), or agency technical guidance documents with methodological substance. Sources limited to life-cycle assessment (LCA) of environmental impacts without a cost dimension, or to unrelated infrastructure sectors (buildings, water systems) without transferable transportation relevance, were excluded unless they provided methodological insight applicable to LCCA more broadly. Table 1 summarizes these criteria.

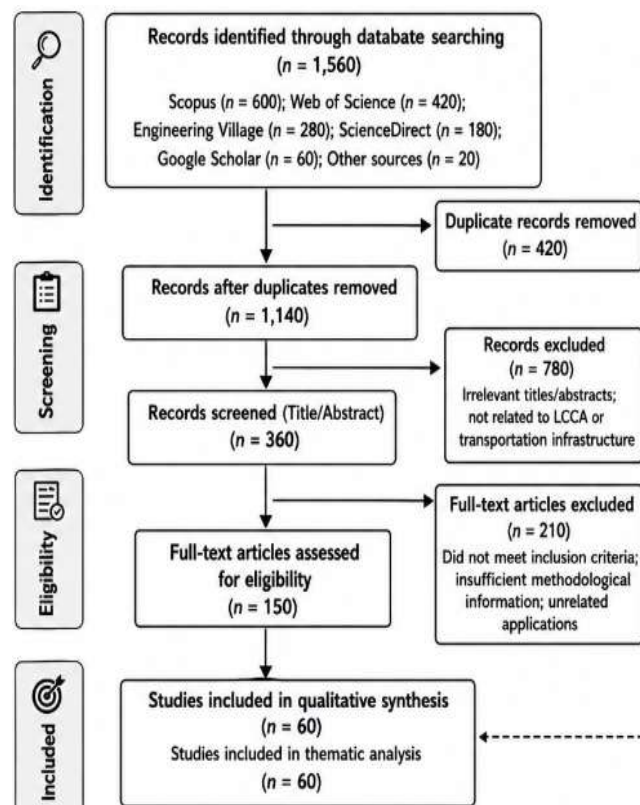
Table 2 : Inclusion And Exclusion For LCCA

Criterion	Included	Excluded
Topic focus	LCCA, BLCCA, or closely related life-cycle costing methodology applied or critically reviewed	Environmental LCA presented with no cost dimension; general cost-estimating studies unrelated to life-cycle framing
Sector	Roadway pavements, highway bridges, multi-asset transportation networks	Buildings, water/wastewater systems, and other non-transportation infrastructure with no transferable methodological content
Publication type	Peer-reviewed journal articles, conference papers, NCHRP/TRB reports, agency (FHWA, state DOT, AASHTO) technical guidance	Non-technical news items, opinion pieces, vendor marketing material
Content depth	Reports a methodology, model, case application, or critical synthesis with identifiable inputs, assumptions, or findings	Abstracts or listings with no accessible methodological detail
Language / era	English-language sources; no lower date bound given the long institutional history of LCCA	Non-English sources without an available translation

Synthesis Approach

Because the underlying studies vary widely in scope, analysis period, discount-rate assumptions, and reported metrics, a quantitative meta-analysis was not feasible. Instead, this review employs a narrative and thematic synthesis, organizing findings around (i) the shared conceptual and mathematical core of LCCA, (ii) domain-specific adaptations for pavements and bridges, (iii) network- and program-level investment planning applications, and (iv) cross-cutting methodological themes uncertainty treatment, user-cost estimation, and sustainability integration that recur across all three domains.

Figure 16 : Synthesis Approach



Data Extraction

A standardized data-extraction framework was developed to systematically collect, organize, and compare relevant information from all studies included in the systematic literature review, ensuring consistency, transparency, and comparability while minimizing subjective interpretation. For each selected publication, bibliographic and contextual information, including author(s), publication year, journal or conference, country or geographical region, research context, and type of transportation infrastructure, was recorded, with particular attention to flexible and rigid pavements, highways, bridges, tunnels, and other transportation assets. The methodological characteristics of each study were also extracted, including the type of Life-Cycle Cost Analysis (LCCA), analytical framework, evaluation period, discount rate, economic assumptions, maintenance and rehabilitation strategies, and decision criteria. The extraction process further documented the individual cost components considered, including initial construction, routine maintenance, periodic rehabilitation, reconstruction, agency costs, user costs, vehicle operating costs, travel-delay costs, detours, work-zone impacts, and, where applicable, environmental and social costs. Information regarding data sources was also recorded, including historical infrastructure records, government databases, field observations, engineering estimates, traffic data, cost databases, and simulation-based datasets. For studies incorporating uncertainty or risk, the extraction framework captured the techniques applied, including sensitivity analysis, scenario analysis, probabilistic modeling, Monte Carlo simulation, stochastic LCCA, and other risk-based approaches. In addition, information concerning analytical and computational tools was collected, including spreadsheet-based models, specialized LCCA software, statistical packages, optimization models, simulation platforms, artificial intelligence, machine-learning techniques, and predictive analytics. The principal findings, recommended maintenance strategies, economic rankings of alternatives, reported limitations, and identified research gaps were also recorded. To support the thematic-comparative synthesis, the extracted information was organized into structured evidence tables and coded according to recurring methodological and substantive themes, enabling systematic comparison of how different studies define life-cycle costs, establish analysis periods, incorporate agency and user impacts, address uncertainty, and evaluate alternative infrastructure management strategies. The resulting dataset served as the foundation for descriptive and analytical synthesis by facilitating the identification of methodological trends, differences in assumptions, areas of convergence and disagreement, and emerging research directions, with particular emphasis on differences between pavement and bridge LCCA applications, the treatment of agency versus user costs, the integration of sustainability considerations, and the growing application of predictive analytics and advanced computational methods. Overall, the data-extraction procedure provided a transparent and structured evidence base for the subsequent quality assessment, thematic classification, comparative synthesis, and identification of research gaps.

Quality Assessment

A systematic quality assessment was conducted to evaluate the methodological rigor, transparency, reliability, and relevance of the studies included in the review. Given the diversity of research designs, data sources, analytical techniques, and economic assumptions used in Life-Cycle Cost Analysis (LCCA) research, the assessment applied consistent criteria across the selected studies, including clarity of research objectives, adequacy and reliability of data, transparency of methodological procedures, appropriateness of the LCCA framework, justification of economic assumptions, treatment of uncertainty and risk, reproducibility of analysis, and relevance to transportation infrastructure decision-making. Each study was also examined to determine whether it clearly defined the analysis period, discount rate, cost components, maintenance and rehabilitation alternatives, and evaluation criteria. Particular attention was given to the distinction between agency and user costs because transportation interventions may generate significant indirect impacts through travel delays, vehicle operating costs, detours, work-zone disruptions, freight interruptions, and temporary denial of

infrastructure use; therefore, studies incorporating these impacts were assessed according to the transparency and validity of their assumptions, estimation procedures, and data sources. Similarly, studies incorporating environmental, social, or sustainability-related costs were evaluated based on the clarity, consistency, and validity of their measurement approaches. The treatment of uncertainty and risk was considered another important quality dimension, with particular attention to studies employing sensitivity analysis, scenario analysis, probabilistic modeling, Monte Carlo simulation, stochastic LCCA, or other uncertainty-analysis techniques to address variations in construction costs, maintenance timing, deterioration rates, traffic growth, discount rates, material prices, and infrastructure service life. Studies based primarily on deterministic assumptions were not automatically excluded, but their limitations were considered during the interpretation and comparison of findings. A structured quality-assessment matrix was used to classify the methodological strength of each study, with higher-quality studies characterized by clearly defined objectives, reliable and transparent data sources, justified assumptions, appropriate LCCA methodologies, comprehensive cost considerations, explicit treatment of uncertainty, and sufficient methodological detail to support replication; moderate-quality studies provided relevant empirical or methodological evidence but contained limitations in areas such as data transparency, uncertainty analysis, or cost coverage; and lower-quality studies were identified where substantial methodological information was missing or assumptions and analytical procedures were inadequately justified. The quality assessment was primarily used to determine the strength and reliability of the evidence rather than to exclude studies solely because of methodological differences. It also supported the subsequent thematic-comparative synthesis by allowing greater emphasis to be placed on findings supported by robust and transparent methodologies and by considering study quality when interpreting conflicting results arising from differences in discount rates, analysis periods, cost definitions, deterioration assumptions, traffic conditions, or geographical contexts. Overall, this quality-assessment process strengthened the credibility and reliability of the systematic review by ensuring that the conclusions reflected not only the frequency of reported findings but also the methodological quality and evidentiary strength of the underlying studies.

Thematic-Comparative Synthesis

The findings of the selected studies were synthesized using a thematic-comparative approach to identify major research themes, methodological patterns, areas of agreement and disagreement, and emerging directions in Life-Cycle Cost Analysis (LCCA) for transportation infrastructure. Unlike a purely descriptive review, this approach examined both the substantive focus of individual studies and the methodological differences that may explain variations in their findings. The included studies were categorized according to major application areas, including pavement preservation, bridge rehabilitation, maintenance and rehabilitation optimization, infrastructure replacement, long-term investment planning, sustainability-oriented LCCA, and risk and uncertainty analysis, while additional themes were developed when recurring concepts emerged during the coding process. Within each thematic category, studies were compared according to infrastructure type, geographical context, analytical framework, evaluation period, discount rate, cost components, maintenance strategies, data sources, uncertainty treatment, and decision-making criteria, recognizing that LCCA outcomes can vary considerably according to researchers' assumptions and methodological choices. For example, pavement studies commonly emphasize preventive maintenance, resurfacing, rehabilitation, and reconstruction cycles, whereas bridge studies may focus more strongly on component-level deterioration, structural rehabilitation, strengthening, replacement, and service-life extension; therefore, the synthesis considered the distinctive characteristics of each infrastructure type rather than treating transportation assets as methodologically identical. The analysis also examined how studies defined and measured agency and user costs, with agency costs generally including construction, routine maintenance, rehabilitation, reconstruction, inspection, and management expenditures, while user costs included travel delays, vehicle operating costs, detours, work-zone impacts, freight

disruption, and denial-of-use costs. Comparisons were made according to the extent to which these direct and indirect costs were incorporated into LCCA frameworks, thereby identifying whether existing research primarily emphasizes agency expenditures or provides a broader assessment of societal impacts and whether the inclusion of user costs changes the economic ranking of alternative maintenance and rehabilitation strategies. Another important comparative dimension was the treatment of uncertainty and risk, with studies grouped according to their use of deterministic LCCA, sensitivity analysis, scenario analysis, probabilistic approaches, Monte Carlo simulation, stochastic models, and other advanced techniques. Particular attention was given to how uncertainty in construction prices, deterioration rates, traffic demand, maintenance timing, discount rates, material performance, and infrastructure service life influenced estimated life-cycle costs and to the extent that research has progressed from traditional deterministic approaches toward dynamic, probabilistic, predictive, and data-driven LCCA frameworks. The synthesis further examined the growing integration of sustainability and advanced technologies into transportation LCCA, including environmental impacts, carbon emissions, resource consumption, social costs, resilience, climate-related risks, artificial intelligence, machine learning, predictive analytics, digital asset-management systems, and real-time infrastructure data, with emphasis on their potential contributions to deterioration prediction, maintenance scheduling, cost forecasting, and investment optimization. Finally, the comparative synthesis identified methodological convergence, inconsistencies, and research deficiencies by examining whether studies reached similar conclusions across different geographical and methodological settings and whether divergent findings could be explained by differences in assumptions, datasets, analytical horizons, infrastructure conditions, or economic parameters. Overall, the thematic-comparative synthesis provides a structured interpretation of the existing evidence and establishes a robust basis for identifying research gaps, improving LCCA methodologies, and developing more integrated, uncertainty-aware, sustainable, and data-driven approaches to transportation infrastructure management and long-term investment planning.

Gap Analysis

The gap analysis was conducted to identify limitations, inconsistencies, and underdeveloped areas within the existing literature on Life-Cycle Cost Analysis (LCCA) for transportation infrastructure based on the thematic and comparative findings of the selected studies, with particular emphasis on methodological, data-related, geographical, technological, and practical gaps. Although LCCA has been extensively applied to pavement management, bridge rehabilitation, maintenance planning, and long-term infrastructure investment, substantial variation remains in how researchers define cost components, establish analysis periods, select discount rates, estimate deterioration and service life, and incorporate uncertainty, thereby limiting direct comparison across studies and making it difficult to establish universally applicable LCCA benchmarks and decision rules. A major gap concerns the inconsistent treatment of agency and user costs, as many studies primarily focus on agency expenditures related to construction, maintenance, rehabilitation, and reconstruction while giving comparatively limited attention to indirect user impacts such as travel delays, vehicle operating costs, detours, work-zone disruptions, freight delays, and denial-of-use costs, despite their potential to substantially influence the overall economic consequences of infrastructure interventions. This highlights the need for integrated LCCA frameworks capable of simultaneously evaluating direct agency expenditures and broader user and societal impacts using transparent and standardized measurement approaches. Another important gap involves the treatment of uncertainty and risk, as many traditional LCCA studies continue to rely on deterministic assumptions concerning construction costs, deterioration rates, maintenance timing, traffic growth, discount rates, material performance, and service life, even though transportation infrastructure performance is inherently uncertain because future deterioration, climate conditions, traffic demand, economic conditions, and material behavior cannot be predicted with complete certainty. Although probabilistic LCCA, sensitivity analysis, scenario analysis, Monte Carlo simulation, and stochastic approaches are increasingly being applied,

their use remains inconsistent, indicating a need for more robust frameworks capable of explicitly quantifying uncertainty and communicating its implications for infrastructure investment and maintenance decisions. The literature also demonstrates a limited integration of sustainability dimensions into conventional LCCA, with traditional economic approaches often emphasizing monetary costs and benefits while environmental emissions, energy consumption, resource use, climate impacts, resilience, and social consequences are treated separately or omitted. This creates a gap between conventional cost-minimization approaches and contemporary infrastructure planning requirements, which increasingly demand economically efficient, environmentally responsible, socially sustainable, and climate-resilient solutions. Another important gap is the uneven geographical distribution of LCCA research, as existing evidence is concentrated largely in developed transportation systems with comprehensive infrastructure databases, established maintenance standards, and relatively reliable cost information, whereas comparatively fewer studies examine developing and emerging economies where infrastructure deterioration, budget constraints, rapid traffic growth, climatic conditions, institutional capacity, and data availability may differ substantially. This geographical imbalance limits the generalizability of existing LCCA models and emphasizes the need for context-specific research, particularly in South Asian and other rapidly developing transportation systems. A significant data and technological gap is also evident because conventional LCCA models frequently depend on historical averages, engineering assumptions, periodic inspections, and static cost estimates, despite the increasing availability of sensors, intelligent transportation systems, geographic information systems, remote sensing, connected vehicles, and digital asset-management platforms that could support more dynamic and accurate life-cycle evaluations. Although artificial intelligence, machine learning, and predictive analytics offer considerable potential for improving deterioration prediction, maintenance scheduling, cost forecasting, scenario analysis, and investment optimization, their systematic integration with conventional LCCA frameworks remains an emerging research area. The literature further indicates a lack of standardization in methodological assumptions, particularly regarding discount rates, inflation treatment, residual values, service-life assumptions, maintenance intervals, deterioration models, and cost boundaries, which can generate substantially different results even when studies examine similar infrastructure alternatives and consequently reduce reproducibility and complicate cross-study comparison. Future research should therefore promote transparent reporting standards, standardized terminology, clearly documented assumptions, sensitivity testing, and consistent methodological procedures. In addition, a gap exists between LCCA research and practical infrastructure decision-making because relatively few studies investigate how LCCA findings are incorporated into actual agency budgeting, asset-management systems, procurement decisions, policy development, and long-term investment programming. Future research should therefore strengthen the connection between LCCA models and operational decision-support systems by integrating predictive analytics, risk assessment, sustainability indicators, budget constraints, and infrastructure condition information into practical multi-objective frameworks. Overall, the gap analysis demonstrates that the next generation of transportation LCCA research should move beyond conventional deterministic cost comparison toward integrated, probabilistic, sustainable, geographically adaptable, and data-driven decision-support frameworks in which agency and user costs, uncertainty, environmental and social impacts, real-time infrastructure data, artificial intelligence, and long-term asset-management objectives are jointly considered to improve the reliability, comparability, and practical value of LCCA for transportation infrastructure investment, maintenance, rehabilitation, and preservation decisions.

Discussion And Synthesis

Table 3 : Comparison Table Pavement Preservation,Bridge Rehabilitation and Long Term Investment Planning

Dimension	Pavement Preservation	Bridge Rehabilitation	Long-Term Investment Planning
Primary decision unit	Treatment/design alternative for a pavement section	Rehabilitation, retrofit, or replacement alternative for a structure	Multi-year program or portfolio of projects
Dominant user cost	Vehicle operating cost, work-zone delay	Denial-of-use / detour cost during closure or posting	Aggregated network-level delay and safety cost
Typical analysis period	20–50 years	40+ years	10+ years (rolling program horizon)
Maturity of institutional practice	High — standardized software (e.g., RealCost), statutory mandates in several jurisdictions	Moderate — anchored by NCHRP 483 but less standardized across agencies	Emerging — driven by federal TAM regulation since 2016
Principal methodological frontier	LCA–LCCA integration; preventive-maintenance modeling	Reliability-/risk-based LCCA; advanced materials (e.g., UHPC)	Network optimization under budget constraint; P3 evaluation

Several important implications emerge from the synthesis. First, the maturity gradient across domains—where pavement LCCA is relatively standardized, bridge LCCA is less standardized, and portfolio-level life-cycle planning remains an emerging regulatory and management practice—indicates significant opportunities for methodological transfer in both directions. Bridge and network-level applications can benefit from the pavement LCCA literature's experience with standardized software tools, treatment-effectiveness databases, and established maintenance procedures, while pavement practice can draw on the more advanced reliability- and risk-based approaches developed in bridge research, particularly as pavement agencies increasingly address resilience, climate-related risks, and extreme-event impacts. Second, the persistent gap between the theoretical comprehensiveness of LCCA, which can incorporate agency and user costs as well as environmental impacts and failure risks, and the narrower scope of routine agency applications suggests that the primary challenge is increasingly a practice and implementation gap rather than a purely methodological one. The reviewed literature indicates that closing this gap requires not only further methodological refinement but also greater investment in data infrastructure, workforce training, analytical capacity, and standardized default parameters, including unit costs, deterioration curves, discount rates, service-life assumptions, and treatment-effectiveness estimates, which can make comprehensive LCCA approaches more practical for agencies with limited resources. Third, the growing integration of Life-Cycle Assessment (LCA) with LCCA, together with the increasing application of climate-resilience and reliability-based approaches, demonstrates that the concept of “life-cycle cost” is expanding beyond its traditional focus on agency and user costs toward a broader framework of life-cycle sustainability and resilience assessment. This development has important implications for future transportation asset-management practices because agencies will increasingly need to incorporate economic, environmental, social, resilience, and risk considerations into long-term investment decisions. As funding programs and infrastructure policies increasingly emphasize sustainability, climate resilience, and performance-based investment, transportation agencies will need to strengthen their data systems, analytical capabilities, and asset-management frameworks to support more comprehensive and integrated life-cycle decision-making.

Conclusion

Life-cycle cost analysis has evolved from a niche pavement-design technique into a central analytical framework spanning project-level treatment selection, structural rehabilitation decisions, and agency-wide investment planning. Across pavement preservation, bridge rehabilitation, and long-term transportation asset management, the reviewed literature demonstrates that LCCA consistently reveals the limitations of first-cost-driven decision-making and provides a defensible, quantitative basis for prioritizing preventive and preservation-oriented strategies over reactive, deferred-maintenance approaches. At the same time, the review identifies durable methodological and practical gaps – in the treatment of uncertainty, in the integration of environmental and social costs, in the estimation of user costs, and in the underlying data infrastructure needed to support rigorous analysis that continue to separate the theoretical promise of LCCA from its routine application. Future research and agency practice would benefit from continued development of probabilistic and risk-based LCCA methods, deeper integration of environmental life-cycle assessment with cost analysis, and sustained investment in the standardized cost, performance, and deterioration data that make sophisticated life-cycle analysis feasible across agencies of varying size and analytical capacity.

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