

A Techno-Economic Framework for Resilient Pavement Infrastructure: A Mechanistic-Empirical Approach for Overload Conditions

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Abstract

Premature failure of flexible pavements in developing nations, such as Pakistan, is a critical issue exacerbated by uncontrolled vehicle overloading and the limitations of traditional empirical design methods. This study presents a Mechanistic-Empirical (M-E) framework to address this challenge. Using the Michigan Flexible Pavement Design System (MFPDS), a comprehensive parametric analysis of 144 unique flexible pavement cross-sections was conducted by systematically varying the thickness of the Asphalt wearing course (2–10 cm) and binder course (10–25 cm). Pavement performance was evaluated based on critical mechanistic responses, including tensile strain at the bottom of the AC layer and compressive strain at the top of the subgrade, to predict fatigue and rutting life. A techno-economic optimisation was performed using a Cost-Benefit Ratio that links initial construction cost to predicted design life. Results indicate that the existing local design is critically inadequate, with a predicted service life of only 0.02 years. In contrast, the proposed M-E designs demonstrate that increasing AC layer thickness significantly enhances pavement life, with an optimal design achieving over 15 years of service. A key finding is that the Cost-Benefit Ratio decreases non-linearly, identifying an economic "sweet spot" beyond which further investment in thickness yields diminishing returns. Furthermore, the M-E framework highlights the high sensitivity of pavement life to the AC elastic modulus, indicating that improvements in material quality can yield significantly greater increases in durability than simply increasing material quantity. This study provides a validated M-E design framework tailored to local conditions, offering economically optimised solutions that are resilient to severe loading and making a data-driven case for a paradigm shift toward performance-based design and advanced material selection.

Keywords: Flexible Pavement; Mechanistic-Empirical Design; Vehicle Overloading; Techno-Economic Analysis; Pavement Performance; Cost-Benefit Ratio

1 Introduction

1.1 The Critical Role of Road Infrastructure and the Challenge of Premature Failure

Road networks are the arteries of economic development, facilitating the movement of goods, services, and people essential for national growth and social cohesion (Shaikh et al., 2023). In developing nations, this infrastructure is particularly vital, yet it often suffers from accelerated deterioration, leading to significant economic losses, increased transportation costs, and public safety concerns (Ekwulo & Eme, 2013). The situation in Pakistan is particularly acute, with a national survey revealing that over 62% of the road network

exhibits significant surface cracking and more than 30% is afflicted by severe permanent deformation, or rutting (Rind et al., 2017). This widespread premature failure of flexible pavements points to a systemic issue in design and analysis that warrants immediate and rigorous investigation. The consequence of this degradation is not merely an inconvenience but a substantial impediment to economic progress, as funds are diverted from new projects to the recurring and costly cycle of premature rehabilitation (Huang, 2004; Miftahulkhair et al., 2024).

1.2 The Primary Catalyst: Uncontrolled Vehicle Overloading

The principal driver of this rapid degradation is the pervasive and uncontrolled overloading of commercial vehicles, a phenomenon common in many developing regions. While Pakistani regulations enforce a maximum single axle load of 118 kN, field studies have documented actual loads reaching as high as 200 kN, representing an overload of nearly 70% (Muhammad et al., 2015). This overloading is not a minor infraction but a fundamental change in the loading conditions for which the pavements were designed. The overloading condition is shown in Figure 1.



Figure 1. Overloading and Accidental scenarios on Pakistani Roads

The relationship between axle load and pavement damage is highly non-linear, famously described by the "fourth-power law." This principle dictates that the damage inflicted by an axle is approximately proportional to the fourth power of its load relative to a standard axle load.¹ Consequently, a doubling of the axle load can increase the damage by a factor of sixteen ($2^4=16$) (Thom, 2014). This exponential damage accumulation means that even a small percentage of severely overloaded vehicles can consume a disproportionately large portion of a pavement's design life. Studies have shown that a mere 1% increase in overweight trucks can cause a 1.8% reduction in pavement service life, while a 20% increase in vehicle weight can amplify the Vehicle Damage Factor by three to four times (Ameri & Khavandi, 2009; El-Ashwah et al., 2021; Goehl & Nyamuhokya, 2022). In some cases, overloading has been shown to reduce a pavement's design life from 15 years to just over 3 years. This compounding damage renders pavements designed for legal loads catastrophically under-designed for the real-world traffic they must endure.

1.3 The Methodological Flaw: The Limits of Empirical Design

Compounding the physical failure caused by overloading is a fundamental methodological failure: the continued reliance on traditional empirical design methods, such as the AASHTO 1993 guide and the California Bearing Ratio (CBR) method (American Association of State Highway and Transportation Officials [AASHTO], 1993). These methods are derived from historical road tests, most notably the AASHO Road Test of the late 1950s, which were conducted under specific and controlled loading, material, and environmental conditions unique to their time and location. When these empirical relationships are extrapolated and applied in contexts like modern-day Pakistan, where the actual conditions, particularly the magnitude and frequency of axle loads, fall far outside their original calibration range, their predictive power collapses (Ekwulo & Eme, 2013). The resulting pavement failures are not merely a consequence of insufficient layer thickness but a result of a "fundamental methodological mismatch" (AASHTO, 2020). The empirical approach, by its nature, cannot rationally account for loading scenarios it has never "seen" in its historical database, leading to designs that are structurally inadequate from their inception.

1.4 Study Objectives and Contribution

While the advantages of modern design approaches are well-established globally, a significant research gap exists in their practical application and validation within developing countries like Pakistan, where the unique challenges of extreme vehicle overloading and continued reliance on outdated empirical methods persist.³ This study aims to bridge the gap between advanced theory and local practice by validating and applying a comprehensive M-E design framework, using the MFPDS, tailored to the material properties and severe overloading conditions prevalent in Pakistan. It will also systematically quantify the non-linear relationships between AC layer thickness, pavement service life, and economic efficiency through a parametric analysis of 144 unique pavement cross-sections. Finally, the study will develop an actionable techno-economic framework that identifies economically optimal pavement designs, providing a quantitative tool for policymakers and transportation agencies to justify higher initial investments for superior long-term value and resilience.

2 Research Method

To overcome the limitations of outdated empirical methods, a transition to a performance-based M-E design philosophy is imperative. The M-E approach is a hybrid framework that integrates the principles of engineering mechanics with empirically calibrated performance models to provide a rational and robust basis for pavement design (Ameri & Khavandi, 2009). The comprehensive methodology employed in this study follows a systematic, multi-stage process, ensuring that the analysis is rigorous, the tools are validated, and the conclusions are grounded in both mechanistic principles and economic realities.

2.1 M-E Design Principles

The "mechanistic" component of the M-E framework involves modelling the pavement as a multi-layered elastic system to calculate its physical responses, stresses, strains, and deflections at critical locations under a defined wheel load. This allows for a fundamental understanding of how the pavement structure behaves under load. The "empirical" component consists of transfer functions, which are regression models developed from extensive field performance data. These functions correlate the calculated mechanistic responses to the cumulative damage and observable distresses, such as cracking and rutting, over the pavement's life (Carvalho, 2006; El-Ashwah et al., 2021; Goehl & Nyamuhokya, 2022). This study focuses on the two primary distress modes that govern the design life of flexible pavements:

Fatigue Cracking: This distress, often seen as "alligator" cracking, originates from the repeated application of horizontal tensile strain (ϵ_t) at the bottom of the lowest AC layer. The allowable number of load repetitions to failure (N_f) is predicted using a transfer function that considers both the magnitude of the tensile strain and the stiffness of the asphalt mixture, represented by its elastic modulus (E). The model is expressed as $N_f = k_1(1/\epsilon_t)^{k_2}(1/E)^{k_3}$, where k_1 , k_2 , and k_3 are material and model calibration constants (Harichandran, 2000; Harichandran et al., 1990).

Rutting (Permanent Deformation): This distress, characterised by longitudinal depressions in the wheel paths, is controlled by limiting the vertical compressive strain (ϵ_c) at the top of the subgrade. The following model determines the allowable number of load repetitions (N_r) before rutting failure: $N_r = k_4(1/\epsilon_c)^{k_5}$, where k_4 and k_5 are calibration parameters. The final design life of the pavement is conservatively taken as the minimum of the fatigue life (N_f) and the rutting life (N_r) (Harichandran, 2000; Harichandran et al., 1990).

2.2 Pavement Modelling and Parametric Study

The complex, iterative calculations required for M-E analysis were performed using the MFPDS, a comprehensive software package based on the finite element method (Harichandran, 2000; Harichandran et al., 1990). To establish the credibility of the software for this specific application, a validation exercise was performed. The critical tensile strain at the bottom of the AC layer calculated by MFPDS for a standard pavement structure was compared against a manually calculated value using layered elastic theory. The results differed by only 0.37%, confirming the software's accuracy and reliability for this research. The schematic of the research methodology is presented in Figure 2.

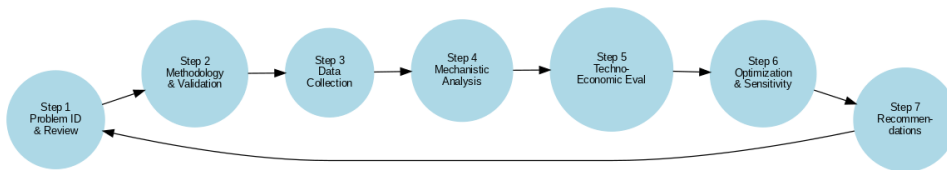


Figure 2. Research Methodology

A matrix of 144 unique pavement cross-sections was generated to evaluate the impact of AC layer thickness on performance. The thickness of the AC Wearing Course was varied from 2 cm to 10 cm in 1 cm increments, and the AC Binder Course was varied from 10 cm to 25 cm in 1 cm increments. The material properties used in the analysis, detailed in Table 1, are based on the existing design of the Talty to Dadu (N-55) road cross-section presented in Figure 3, ensuring the analysis is grounded in local conditions.

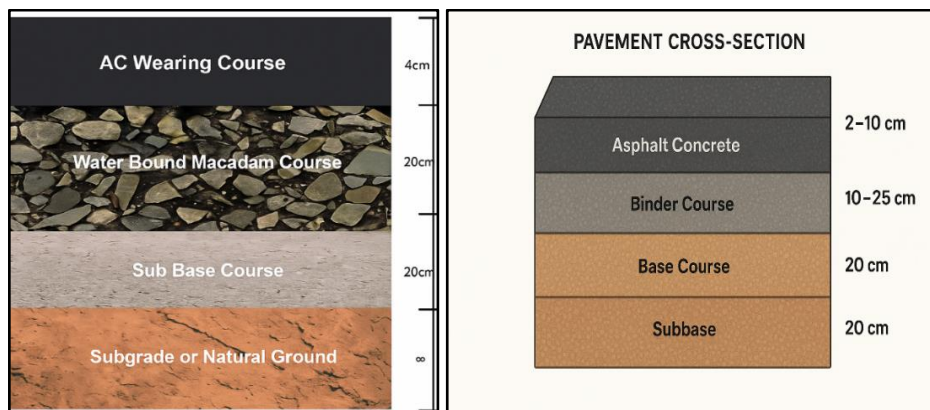


Figure 3. Design for the Talty to Dadu (N-55) road

Table 1 provides the fundamental input parameters for the Mechanistic-Empirical model used in this study, ensuring the replicability of the analysis. The properties are based on materials typically used in the case study region.

Table 1. Material Properties and Layer Configuration for M-E Analysis

Pavement Layer	Thickness (cm)	Elastic Modulus (MPa)	Poisson's Ratio
AC Wearing Course	Variable (2 to 10)	3500	0.35
AC Binder Course	Variable (10 to 25)	2400	0.35
WBM Base Course	20	350	0.40
Granular Sub-base	20	70	0.40
Subgrade	Semi-infinite	35	0.45

2.3 Techno-Economic Evaluation

To integrate the economic dimension, this study utilises a Cost-Benefit Ratio to evaluate the economic efficiency of each design alternative. The analysis is based on standard project appraisal practices for Pakistan. A 20-year appraisal period was used to capture long-term structural benefits, with a 12% discount rate applied to reflect the social opportunity cost of capital. Financial costs were converted to economic prices using a shadow exchange rate factor of 1.039 and a shadow wage rate of 0.85 for labour. A residual value of approximately 27% was included at the end of the appraisal period to account for the remaining serviceable life of the asset. Annual routine maintenance was assumed to be equivalent to 10.7% of the cost of the pavement layers (surface, base, and sub-base).

$$\text{Cost-Benefit Ratio} = \text{Initial Construction Cost (Million Rs/km)} / \text{Predicted Design Life (Years)}$$

This metric serves as a practical proxy for the annualised cost of the pavement structure, a central concept in formal Life-Cycle Cost Analysis (LCCA) that facilitates the comparison of alternatives with different service lives and initial costs. A design with a lower Cost-Benefit Ratio is considered more economically efficient over its lifespan. The initial construction costs were derived from the local schedule of rates and project data, reflecting the economic realities of the study region (Shah, 2022).

3 Results

The core of this research involved the systematic M-E analysis of 144 pavement cross-sections to quantify the impact of structural design choices on pavement performance and economic viability. The results are presented objectively below, with interpretation reserved for the Discussion section.

3.1 Performance of the Existing Empirically Designed Pavement

The analysis began with an evaluation of the existing pavement design for the Talty to Dadu (N-55) road, which consists of a 4 cm AC Wearing Course, no AC Binder Course, a 20 cm WBM Base, and a 20 cm Sub-base. When subjected to the rigorous M-E analysis under the region's heavy loading conditions, this design is predicted to have a catastrophic service life of just 0.02 years. The associated initial construction cost of 2.98 Million Rs/km results in an astronomical Cost-Benefit Ratio of 148.85 Million Rs/km per year of service. This finding provides a quantitative validation of the rapid, real-world deterioration observed on such roads and serves as a critical baseline for comparing alternative designs.

3.2 Influence of AC Thickness on Pavement Response and Service Life

The parametric study revealed strong, predictable relationships between the total thickness of the asphalt concrete layers (Wearing Course + Binder Course) and the pavement's structural performance. The detailed comparison is presented in Figure 4.

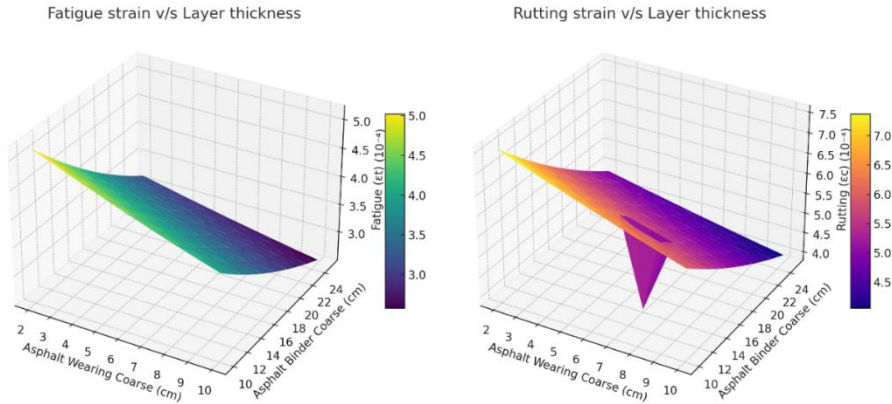


Figure 4. Relationship between the Layer thickness and the pavement structural performance

A consistent and near-linear inverse relationship was observed between the total AC thickness and the critical pavement responses. As the thickness of the asphalt layers increased, the surface deflection, the tensile strain at the bottom of the AC layer (ϵ_t), and the compressive strain at the top of the subgrade (ϵ_c) all decreased systematically. Linear regression analyses of these relationships yielded coefficients of determination (R^2) greater than 0.95, confirming the strength and predictability of this effect (Kumar & Suman, 2025). This empirically validates a fundamental principle of flexible pavement mechanics: thicker and stiffer upper layers are more effective at distributing traffic loads, thereby reducing the magnitude of stresses and strains transmitted to the weaker, unbound underlying layers. The data for this relationship is presented in Figure 5, which is intended for conversion into a figure as described below.

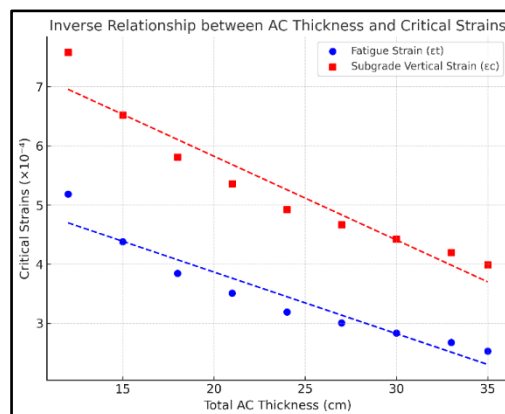


Figure 5. Inverse linear relationship between AC thickness and critical strains

Consequently, the analysis demonstrated a strong, positive, but distinctly non-linear relationship between total AC thickness and pavement service life. This non-linearity is a direct result of the power-law nature of the empirical damage models, where a modest, linear reduction in strain translates into a large, exponential increase in the pavement's capacity to withstand traffic. For instance, increasing the total AC thickness from 12 cm (X-Section 1) to 35 cm (X-Section 144) increases the predicted design life from 0.48 years to 15.61 years, a more than 32-fold improvement for less than a threefold increase in thickness. The data for this critical relationship is provided in Figure 6 for visualisation.

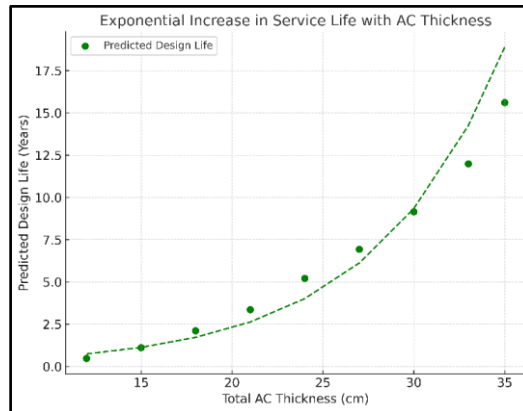


Figure 6. Service life with increasing AC thickness

3.3 Techno-Economic Optimisation

The techno-economic analysis reveals the relationship between structural investment and long-term economic efficiency. The Cost-Benefit Ratio was calculated for all 144 cross-sections. A clear, non-linear inverse relationship was found between the predicted design life and the Cost-Benefit Ratio. As shown by the data in Figure 7, designs with very short service lives have extremely high annualised costs. As the design life increases, the Cost-Benefit Ratio drops sharply at first and then begins to flatten, indicating a point of diminishing returns where the marginal economic benefit of further extending the design life decreases. This "L-shaped" curve is critical for identifying an economically optimal design range.

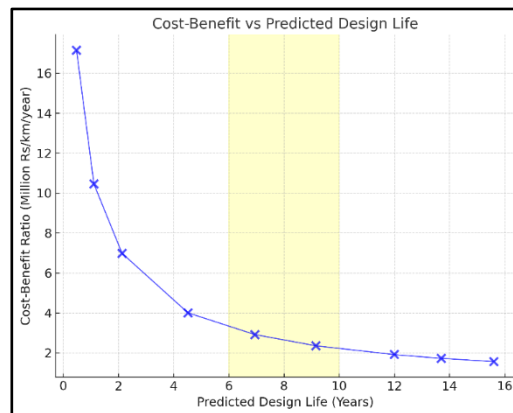


Figure 7. Visualising the "cost-benefit cliff" and the point of diminishing returns

Based on the dual criteria of achieving a minimum design life of 10 years and securing a low Cost-Benefit Ratio, several pavement designs are recommended as viable and economically superior alternatives. Table 2 summarises the performance and economic metrics for the top-ranked designs alongside the existing baseline design for a direct comparison.

Table 2. Comparative Analysis of Recommended Pavement Designs vs. Existing Design

Section ID	Wearing Course (cm)	Binder Course (cm)	Total AC Thickness (cm)	Predicted Design Life (Years)	Initial Cost (Million Rs/km)	Cost-Benefit Ratio
Existing X-Section	4	0	4	0.02	2.98	148.85
X-Section 144	10	25	35	15.61	24.30	1.56
X-Section 143	10	24	34	13.70	23.62	1.72
X-Section 128	9	25	34	13.69	23.55	1.72
X-Section 142	10	23	33	12.00	22.95	1.91
X-Section 127	9	24	33	11.99	22.88	1.91
X-Section 111	8	24	32	10.48	22.13	2.11

4 Discussion

The results of this study have profound implications for pavement design philosophy and practice, particularly in developing regions grappling with severe traffic loading and limited infrastructure budgets. The findings provide a quantitative basis for a necessary paradigm shift, moving away from outdated methods toward a modern, performance-based approach.

4.1 The Imperative for a Paradigm Shift from Empirical to M-E Design

The findings present an unequivocal case for abandoning outdated empirical design methods in environments for which they were not calibrated. The predicted 0.02-year service life of the existing, empirically based design is not an anomaly but a quantitative confirmation of the widespread premature failures observed in the field (Loulizi et al., 2006). The M-E analysis provides a clear, mechanistic explanation for these failures, directly linking them to the inadequacy of the design to handle the high tensile and compressive strains induced by real-world traffic loads.

This study reinforces the growing international consensus that a transition to M-E design is a practical necessity for building durable road networks (Mamlouk et al., 2000). Unlike empirical methods that are constrained by their historical databases, M-E frameworks can rationally characterise local materials, accommodate new and heavier load types, and provide more reliable performance predictions, making them inherently more adaptable and scientifically sound. The successful validation and application of the MFPDS software in this study demonstrate that the tools for this transition are readily available and can be effectively localised to address specific regional challenges.

The predicted failure of the existing design is not an anomaly but a quantitative confirmation of widespread premature failures seen internationally. Benchmarking these results against global datasets validates the findings; for example, in Saudi Arabia, transitioning to M-E design reduced prediction bias from 4.90 to 0.03 for rutting. Similarly, studies in Egypt and Nepal show that empirical designs consistently under-predict distress in hot climates and overloaded conditions, where rutting is often the predominant failure mode. Evidence from Indonesia further supports that overloaded trucks can reduce service life by 50% to 70% if designs are not adjusted for real-world spectra.

4.2 The Economic Fallacy of Minimising Initial Cost

The techno-economic analysis provides a decisive refutation of the false economy of minimising initial construction costs. A contrast between the existing design and the recommended M-E alternatives is presented in Figure 8.

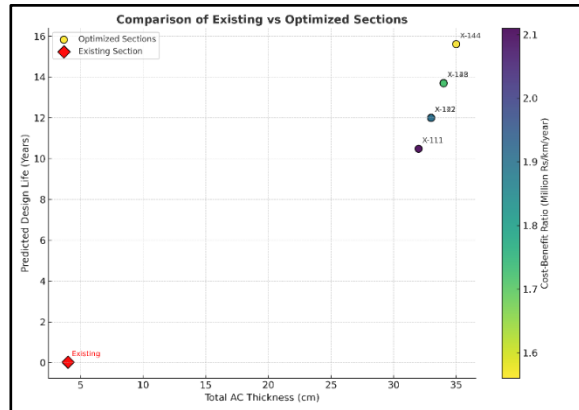


Figure 8. Contrast between the existing design and the recommended M-E alternatives

The existing design, with its astronomical Cost-Benefit Ratio of 148.85, represents a near-total loss on investment, creating a recurring liability rather than a long-term asset. The data reveals a critical "economic tipping point." Even the weakest M-E alternative analysed, X-Section 1, with a predicted life of only 0.48 years, has a Cost-Benefit Ratio of 17.15, an 88% reduction in the annualised cost compared to the existing design for a modest increase in initial investment. This is not a marginal improvement; it is a fundamental shift in economic viability, demonstrating that any design falling below a minimum structural threshold represents a guaranteed misallocation of public funds (Langer, 2011; Santos & Ferreira, 2012).

Furthermore, the analysis quantitatively justifies higher capital investment to achieve significantly lower life-cycle costs (Thom, 2014). For example, X-Section 142, a robust design with 33 cm of total AC thickness, has an initial cost of 22.95 Million Rs/km, approximately double that of a weaker design like X-Section 6 (11.6 Million Rs/km). However, its predicted service life is nearly eleven times as long (12.00 years vs. 1.11 years), resulting in a Cost-Benefit Ratio of just 1.91 compared to 10.45. This demonstrates that doubling the initial investment can improve long-term economic efficiency more than fivefold. The non-linear relationship between design life and Cost-Benefit Ratio (as shown in the data for Figure 7) also reveals a "sweet spot" of diminishing returns. The improvement in Cost-Benefit Ratio is most dramatic in the early years of service life and gradually flattens. This allows an agency to identify an optimal range of designs (e.g., those with 10–14 years of life) that offer an outstanding balance of longevity and economic efficiency, enabling a portfolio-based approach to network-wide upgrades.

The reliability of this techno-economic framework is highlighted by its resilience to market fluctuations. Sensitivity analysis indicates that the recommended designs remain viable even under a 15% increase in construction costs. This is critical in Pakistan, where material price volatility is notably high, and bitumen prices increased by 48.6% recently. Because the annualised cost of M-E optimised sections is so dramatically lower than the empirical baseline, project viability is maintained even when material costs surge or traffic demand exceeds estimates.

4.3 Beyond Quantity: The Overriding Importance of Material Quality

While this study has systematically demonstrated the benefits of increased AC thickness, it is a fundamental principle of Mechanistic-Empirical design that pavement life is also highly sensitive to the material properties of the structural layers. The M-E models used in this analysis show that the predicted service life is exponentially related to the elastic modulus of the asphalt concrete. This reveals a profound insight: material quality is a far more potent lever for enhancing pavement durability than material quantity. A modest increase in the AC elastic modulus can lead to a disproportionately large increase in predicted fatigue and rutting life, often far exceeding the benefits gained from an equivalent investment in additional layer thickness. This indicates that enhancing material stiffness is a more effective and potentially more economical strategy for building long-lasting pavements.

The finding strongly suggests that future efforts should focus on implementing high-modulus asphalt mixes. HMA is an advanced asphalt concrete specifically engineered with hard-grade binders and optimised aggregate structures to achieve high stiffness (dynamic modulus), offering superior resistance to deformation and fatigue. Research shows that HMA can carry significantly more load repetitions before fatigue cracking and can allow for a reduction in pavement thickness for equivalent performance, offering both structural and economic advantages.

This insight reveals a crucial synergy: to truly optimise pavement networks, agencies must combine modern design methodology (M-E analysis) with advanced material technology (high-stiffness asphalt). An empirical design approach cannot properly account for the structural benefits of an advanced material whose performance characteristics fall outside the bounds of its historical database (Goehl & Nyamuhokya, 2022). Only an M-E framework can mechanistically model the improved load distribution from a stiffer layer and allow engineers to fully realise the benefits of these advanced materials (Timm et al., 2006). This study thus provides the quantitative foundation for a powerful policy argument: strategic investment in better materials, guided by rational design, is the most effective strategy for maximising the value and minimising the long-term financial burden of a nation's road infrastructure.

5 Conclusion

This study successfully developed and validated a Mechanistic-Empirical framework for the design and analysis of flexible pavements tailored to the severe loading conditions prevalent in Pakistan. The key findings provide a clear, data-driven mandate for a fundamental shift in pavement engineering practice in the region. The primary conclusions are:

- i. The M-E analysis of existing empirically designed pavements confirmed their critical structural inadequacy, providing a quantitative explanation for widespread premature failures and demonstrating the obsolescence of the empirical method for current traffic realities.
- ii. A comprehensive parametric study established strong, predictable, and non-linear relationships between the thickness of AC layers and pavement performance, demonstrating that robust M-E designs can achieve service lives exceeding 15 years, even under severe overloading conditions.
- iii. The integration of a cost-benefit analysis proved that higher initial investment in durable pavement structures leads to substantially lower life-cycle costs, decisively refuting the false economy of minimising upfront costs and representing a more prudent use of public funds.
- iv. A sensitivity analysis revealed that enhancing the elastic modulus (stiffness) of the AC layer is a more potent strategy for improving pavement durability than simply increasing layer thickness, highlighting the immense potential of investing in advanced material technology, such as High-Modulus Asphalt.

Ultimately, this research provides a clear, evidence-based directive for transportation agencies to transition from outdated empirical design practices to a modern, performance-based M-E design philosophy. Adopting this framework, especially when coupled with a strategic focus on advanced, high-quality materials, will enable the construction of more resilient, sustainable, and economically efficient road infrastructure capable of supporting national development for decades to come.

This study provides a data-driven mandate for transitioning to performance-based design. The recommended M-E optimised sections achieve a shift from a 0.02-year failure for the empirical baseline to a predicted service life of 15.61 years. This represents a 780-fold improvement in durability and a 99% gain in economic efficiency, with the Cost-Benefit Ratio dropping from 148.85 to 1.56. Doubling the initial capital investment can improve long-term financial efficiency more than fivefold, proving that a design falling below a minimum structural threshold represents a guaranteed misallocation of public funds.

5.1 Limitations and Future Research

This study, while comprehensive, has limitations that define a clear path for future research. Acknowledging these limitations is crucial for scientific integrity and for guiding the next steps in advancing pavement design in the region.

- i. **Traffic Spectrum:** The analysis used a severe standard axle load; future work should use detailed axle load spectra from weigh-in-motion data (Jihanny et al., 2021; Loulizi et al., 2006; Mamlouk et al., 2000; Pais et al., 2013).
- ii. **Climatic Data:** Static properties were used instead of hourly climatic modeling (e.g., AASHTOWare), which accounts for temperature-induced stiffness changes.
- iii. **User Costs:** The evaluation focused on agency costs; a full Life-Cycle Cost Analysis should include road user delay and vehicle operating costs over 35 to 50 years (Santana et al., 2022; Santos & Ferreira, 2013; Walls & Smith, 1998).
- iv. **Local Calibration:** Models were based on standard transfer functions and require localization for Pakistani materials ([INFORMATION REQUIRED FROM AUTHOR: reference 32 is not in the reference list]; Izaks et al., 2022).

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Declaration of Conflicting Interests

All authors declare that they have no conflicts of interest.

Author Contribution

Naeem Aziz Memon: Conceptualization, methodology, data collection, analysis, and manuscript drafting.
Nur Izzi Yousuf: Supervision, validation, and critical revision of the manuscript.
Warid Wazien: Guidance on methodology, data interpretation, and manuscript review.
Ahmad Ali: Assistance in data analysis, visualization, and literature review.
Awang Mohsin: Support in data compilation, formatting, and proofreading.

All authors have reviewed and approved the final version of the manuscript for publication.

Declaration of Generative Ai in The Writing Process

An AI-based language assistance tool was used to support minor language editing, grammar correction, and improvement of the manuscript's readability. The authors remain fully responsible for the content, scientific analysis, interpretation, and conclusions presented in the manuscript.

Data Availability/Supplementary Materials

All data generated and analysed during this study are presented within the manuscript. Any additional data supporting the findings of this study are available from the corresponding author upon reasonable request.

Ethics Statement

The authors declare that this research did not involve human or animal subjects. All experimental procedures were performed following the institutional Safety, Health, and Environmental (HSE) protocols of Mehran University of Engineering and Technology-Pakistan.

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