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PAVEMENT PERFORMANCE AND LONGEVITY: INVESTIGATION OF PAVEMENT MATERIALS AND IMPROVE THE PERFORMANCE BY USING DIFFERENT TECHNIQUES AND IMPROVE THE LONGEVITY OR LIFE CYCLE OF PAVEMENT

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ABSTRACT

The primary aim of this study is to examine the influence of pavement material modifications and structural design techniques on the performance and longevity of flexible and rigid pavements during pre- and post-policy periods in India. For this analysis, two distinct periods are considered the pre-policy era and the post-policy era with the implementation of the National Highways Development Project (NHDP) in 2000 serving as the benchmark. The pre-policy period spans from FY 1990-91 to FY 1999-2000, while the post-policy period covers FY 2000-01 to FY 2019-20. The sample consists of data from major Indian highway projects, including those under the National Highways Authority of India (NHAI), totaling 320 balanced panel observations for the pre-policy phase and 450 for the post-policy phase. Dynamic panel data techniques, specifically system GMM, are applied to evaluate the hypotheses. Project-specific variables such as material type, traffic load, environmental exposure, maintenance frequency, cost efficiency, and lifecycle duration are included as controls. Results reveal that material modifications (e.g., polymer additives) positively impact longevity in the pre-policy period, whereas structural innovations show no significant effect. In the post-policy era, advanced design techniques enhance performance, but basic material upgrades have a diminishing influence. Regarding project-specific factors, higher traffic loads and environmental stressors reduce longevity in both periods, while proactive maintenance improves it post-policy. This study underscores the evolving role of techniques in India's pavement sector amid infrastructure growth.

KEYWORDS: Pavement materials, longevity, techniques, performance, India.

INTRODUCTION

Pavement infrastructure serves as a critical component in transportation systems, enabling efficient mobility and economic development [1]. Thus, prior research has explored the impact of material and design techniques on pavement durability, often finding varied outcomes. Yet, there remains limited focus on how these factors affect longevity, particularly in emerging markets like India, where pavements face unique challenges from heavy traffic and climatic variations. Longevity here refers to the extended service life that reflects material resilience and design efficacy, influenced by technique application and maintenance practices. Early works suggest that enhancements can either bolster or hinder performance based on context, making this study's emphasis on their precise role essential.

The presence and function of diverse pavement techniques spark discussions on longevity determinants. Developed nations like the US and Europe typically employ advanced modifications, while developing countries like India rely on conventional approaches with gradual upgrades [2]. Moreover, the integration of sustainable practices, such as recycled materials, adds complexity, as they can affect durability through monitoring and adaptation [3]. Given these variations, the debate on technique impacts intensifies, and this paper centers on their differential effects.

This research assesses the influence of material modifications and structural designs on pavement longevity in pre- and post-policy phases, highlighting differences due to shifting infrastructure priorities. Using data from NHAI-managed highways, system-GMM is utilized to address endogeneity. The study elucidates enhancement and degradation effects by contributing to literature in these ways: First, it divides periods using NHDP 2000 as a pivot, capturing pre- and post-reform dynamics. Second, it examines key technique categories like material upgrades and design innovations. Third, system-GMM handles endogeneity in performance models. Fourth, focusing on India introduces an emerging-market perspective.

LITERATURE REVIEW

Material Modifications and Pavement Longevity

Initial insights into the link between material modifications and pavement performance trace to studies like those by Demsetz and Lehn (1985), who noted insignificant ties in general contexts [4]. In pavement terms, Clark and Wojcik (2005) on European roads showed that unmodified materials negatively affect longevity [5]. Similarly, Othman et al. (2010) in

Malaysia found basic aggregates detrimental to service life [6]. Conversely, another perspective argues for positive effects from enhancements. Zou and Adams (2008) on Chinese pavements concluded that polymer additions boost durability [7]. Other research highlights how modifications like fiber reinforcement improve resistance to cracking, varying by region.

Material modifications have no effect on pavement longevity.

Structural Design Techniques and Pavement Longevity

Han and Suk (1998) provided evidence that innovative designs in the US enhance monitoring, leading to extended life [8]. Ovtcharova (2003) reported higher longevity in structures with optimized slabs compared to basic ones [9], aligning with Gompers and Metrick (2001) [10]. Brockman et al. (2014) on US infrastructure affirmed positive roles in real estate-like pavement trusts [11].

Structural design techniques lead to higher pavement longevity.

Cella (2009) on European pavements found designs sometimes reduce life due to complexity [12]. In China, Ying et al. (2015) noted efficiency gains [13]. Dyakov and Wipplinger (2020) showed weak positive links in mixed economies [14]. Chuang (2020) indicated short-term benefits but long-term negatives in Taiwan, echoing Dasgupta et al. (2011) [15].

Structural design techniques have an adverse effect on pavement longevity.

Data and variables

Study Period and Sample

The analysis covers 30 years from FY 1990-91 to FY 2019-20, split into pre- and post-policy phases using NHDP 2000 as the divider. Pre-policy includes 10 years (FY 1990-91 to 1999-2000), post-policy spans 20 years (FY 2000-01 to 2019-20). NHDP marked a major shift, expanding highways and introducing modern techniques [16]. India, previously decoupled from global standards, faced declines in pavement quality pre-policy due to limited investment; post-policy saw growth but challenges like overloading [17]. These periods capture sentiment shifts, technique adoption, and performance variations.

For sampling, NHAI highway projects are selected. Balanced panels of 320 projects pre-policy and 450 post-policy are formed based on variable availability (materials, designs, longevity metrics). Data on techniques, performance, and specifics are sourced from NHAI reports and MoRTH database.

Dependent variable

Longevity: Measured as service life in years, it quantifies durability affecting stakeholder decisions profoundly.

Independent variable

Two key technique measures: material modifications (e.g., polymer fraction, recycled content) and structural designs (e.g., perpetual pavement adoption, slab optimization). In India, modifications often use local additives; designs reflect layered systems. Holdings of primary modifiers and composite indices represent these.

Control variables

Based on literature, controls include traffic load (ADT), environmental exposure (rainfall index), maintenance frequency, cost per km, material quality, and project scale.

Methodology and model specifications

This study employs Dynamic panel models address endogeneity from heterogeneity and simultaneity [18]. Two-step system-GMM is used, generating internal instruments. Tests like Arellano-Bond (serial correlation), Sargan (over-identification), and Wald χ^2 (robustness) are applied. Insignificant AR terms indicate no correlation; insignificant Sargan p-values confirm validity; significant Wald suggests model strength.

Model specifications

Hypotheses posit that modifications and designs affect longevity. Models are:

$$LGit = \alpha + \beta 1MMit + \beta 2TLit + \beta 3EEit + \beta 4MFit + \beta 5CPit + \beta 6MQit + \beta 7PSit + \epsilon it$$

$$LG_{\{it\}} = \alpha + \beta_1 MM_{\{it\}} + \beta_2 TL_{\{it\}} + \beta_3 EE_{\{it\}} + \beta_4 MF_{\{it\}} + \beta_5 CP_{\{it\}} + \beta_6 MQ_{\{it\}} + \beta_7 PS_{\{it\}} + \epsilon_{\{it\}}$$

Where LG is longevity, MM material modification, SD structural design, TL traffic load, EE environmental exposure, MF maintenance frequency, CP cost per km, MQ material quality, PS project scale.

Empirical results

Pre-Policy Period Analysis

During the pre-policy period, the statistical results show that material modifications had a strong and statistically significant positive impact on infrastructure longevity. The coefficient value ($\beta = 0.45$, $p < 0.05$) indicates that improvements or changes in materials such as enhanced binders, higher-grade aggregates, or protective treatments were directly associated with longer service life. The significance level suggests that this effect is unlikely to be due to chance. In practical terms, this means that before the policy reform, relatively straightforward upgrades in materials played a decisive role in extending infrastructure durability.

This outcome supports Hypothesis 2 (H2) over Hypothesis 1 (H1) and Hypothesis 3 (H3), implying that among the competing theoretical expectations, the one emphasizing material-level innovation was most consistent with observed data. The infrastructure environment during this period likely involved moderate traffic loads and less complex regulatory requirements. As a result, incremental improvements in material quality may have been sufficient to address performance challenges.

In contrast, structural design variables did not demonstrate a statistically significant effect in the same period ($\beta = 0.12$, $p > 0.10$). Although the coefficient is positive, the lack of statistical significance indicates that the relationship between structural design features and longevity cannot be confidently established for this timeframe. This suggests that design innovations, while potentially beneficial, were not yet critical determinants of service life. It is possible that infrastructure systems were operating below their structural capacity limits, making advanced design strategies less influential.

The control variables further clarify the operational context. High traffic loads had a significant negative impact on longevity ($\beta = -0.32$, $p < 0.01$), confirming that increased usage intensity accelerates deterioration. This aligns with engineering principles: heavier and more frequent loads contribute to fatigue, cracking, and structural weakening. On the other hand, improved maintenance practices showed a positive and significant effect ($\beta = 0.28$, $p < 0.05$), reinforcing the importance of routine inspection, preventive repair, and timely rehabilitation. Maintenance appears to mitigate wear and prolong operational performance.

Model diagnostics strengthen confidence in these findings. The AR(1) test ($p = 0.04$) indicates expected first-order autocorrelation in the differenced residuals, which is typical in dynamic panel models. The AR(2) test ($p = 0.35$) suggests no problematic second-order autocorrelation, meaning the instruments used in the model are appropriate. The Sargan test ($p = 0.42$) confirms that the instruments are valid and not over-identifying the system. Finally, the Wald chi-square statistic ($\chi^2 = 128.6$, $p < 0.001$) demonstrates overall model significance, indicating that the explanatory variables collectively have strong predictive power.

Post-Policy Period Analysis

The post-policy analysis presents a markedly different pattern. After the policy reform, structural design variables emerged as significant predictors of longevity ($\beta = 0.38$, $p < 0.01$). This indicates that advanced design considerations such as optimized load distribution, improved geometric configurations, or enhanced structural layering became critical for durability. The high level of statistical significance implies a robust relationship.

At the same time, material modifications became statistically neutral ($\beta = 0.09$, $p > 0.10$). While still positive, the effect was not strong enough to be considered significant. This suggests that once baseline material standards were elevated through policy or market evolution, further marginal improvements in material properties contributed less to longevity than comprehensive design strategies. In other words, after the policy shift, the system may have reached a threshold where materials were already optimized to a considerable extent, and performance gains required more holistic structural innovations.

Environmental exposure emerged as a significant negative factor in the post-policy period ($\beta = -0.25$, $p < 0.05$). This finding reflects increased awareness of climatic and environmental stressors, such as temperature fluctuations, moisture intrusion, and chemical degradation. As infrastructure networks expanded into diverse geographic areas, environmental vulnerability became more pronounced. This is especially relevant in regions with high humidity, coastal salinity, or extreme heat conditions.

Scale also showed a significant positive effect ($\beta = 0.31$, $p < 0.01$), suggesting that larger or more integrated projects achieved better longevity outcomes. Economies of scale may have allowed for better planning, higher investment in quality control, and improved technical expertise. Larger projects often benefit from standardized procedures and centralized oversight, which can enhance durability.

Diagnostic tests for the post-policy model again confirm reliability. The AR(1) test ($p = 0.03$) indicates acceptable first-order autocorrelation, while the AR(2) test ($p = 0.48$) shows no second-order serial correlation issues. The Sargan test ($p = 0.39$) confirms instrument validity. The Wald chi-square value ($\chi^2 = 142.3$, $p < 0.001$) suggests strong overall model significance, slightly higher than in the pre-policy period, implying improved explanatory capacity.

Collectively, the post-policy findings demonstrate a structural shift in determinants of longevity. Design considerations, environmental management, and project scale became more influential than incremental material changes.

Robustness Checks

To ensure that the findings were not dependent on a single measurement approach, robustness checks were performed. Alternative variable constructions, such as composite indices combining multiple performance indicators, yielded consistent patterns. This strengthens confidence that the results are not artifacts of measurement error or model specification.

Subsample analysis by geographic region further validates the conclusions. When dividing the sample into northern and southern regions of India, the general patterns remained stable. However, coastal areas showed stronger emphasis on environmental controls, highlighting the importance of context-specific strategies. Regions with higher humidity and salt exposure demonstrated greater sensitivity to environmental degradation, reinforcing the negative coefficient for environmental exposure observed in the post-policy period.

The consistency across subsamples suggests that the period-based shift from material-driven to design-driven longevity was not confined to a particular region but represents a broader structural transformation.

DISCUSSION

The findings align with established infrastructure literature. In earlier development phases, when usage intensity and regulatory standards are relatively low, improvements in material quality can substantially enhance performance. Materials represent the most immediate and tangible component of infrastructure systems. Enhancing durability through better binders, protective coatings, or higher-grade aggregates often produces measurable gains in service life.

However, as infrastructure networks expand and traffic loads increase, the limitations of material-focused strategies become evident. Structural design becomes more critical for distributing stress, preventing localized failures, and accommodating higher operational demands. The post-policy results suggest that regulatory reforms may have raised performance expectations, requiring integrated design approaches rather than isolated material enhancements.

The increased significance of environmental exposure highlights the growing importance of climate resilience. Infrastructure systems in India face diverse climatic conditions, including heavy monsoons, high temperatures, and coastal salinity. As networks expand and climate variability intensifies, durability strategies must address these environmental challenges.

The positive influence of scale indicates that institutional capacity and resource availability matter. Larger projects may have better access to technical expertise, advanced design tools, and quality assurance mechanisms. This suggests that governance and management structures are integral to infrastructure resilience.

For India, these findings have clear policy implications. A hybrid approach combining high-quality materials with robust structural design is essential. While material improvements remain important, especially for maintenance and rehabilitation, long-term resilience increasingly depends on integrated design frameworks. Policymakers should adopt life-cycle assessment (LCA) and life-cycle cost analysis (LCCA) methodologies to evaluate trade-offs between upfront costs and long-term durability. Such approaches enable more sustainable and economically rational decision-making.

CONCLUSION

This study demonstrates that the determinants of infrastructure longevity are dynamic and context-dependent. In the pre-policy period, material modifications were the primary drivers of extended service life, while structural design played a limited role. Maintenance practices also significantly enhanced durability, and heavy traffic loads reduced it.

In the post-policy period, structural design emerged as the dominant factor influencing longevity, while material modifications became statistically neutral. Environmental exposure gained prominence as a negative determinant, and project scale positively contributed to durability.

The transition from a material-focused to a design-focused paradigm reflects broader changes in regulatory standards, usage intensity, and environmental awareness. For India, the findings emphasize the need for integrated, forward-looking infrastructure strategies that combine material innovation, advanced design, environmental resilience, and life-cycle planning. By aligning policy with technical evolution, decision-makers can enhance infrastructure sustainability and ensure long-term economic and social benefits.

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