

AI-DRIVEN CLIMATE-RESILIENT PAVEMENT DETERIORATION PREDICTION FOR SUSTAINABLE ROAD INFRASTRUCTURE IN PAKISTAN

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Abstract

Climate change, increasing traffic loading, and aging road infrastructure create growing challenges for pavement management in Pakistan. This study developed an artificial intelligence (AI)-driven framework for predicting pavement deterioration by integrating pavement condition, traffic loading, maintenance history, and climatic variables, including temperature, precipitation, and flood exposure. A quantitative longitudinal design was used at the road-section level. Random Forest, Support Vector Regression, Gradient Boosting, XGBoost, and Artificial Neural Network models were evaluated using R^2 , RMSE, MAE, and MAPE. The reported analysis identified XGBoost as the strongest-performing model and showed that the climate-sensitive model outperformed the conventional pavement-and-traffic model. Pavement age, traffic loading, previous pavement condition, maximum temperature, flood exposure, and maintenance interval were important predictors. SHAP-based explainability further indicated the direction and contribution of major predictors. The framework supports earlier identification of vulnerable road sections and a transition from reactive maintenance toward predictive, climate-resilient, and sustainability-oriented pavement management.

1. INTRODUCTION

Road pavements are essential for economic activity, connectivity, mobility, and social welfare, but their performance is increasingly affected by traffic growth, aging, inadequate maintenance, extreme weather, and climate change. Temperature variation, intense precipitation, flooding, and moisture can accelerate rutting, cracking, roughness, potholes, and structural deterioration (Golalipour et al., 2025). These challenges are particularly important in Pakistan

because road networks experience substantial climatic and geographic variability.

Conventional deterioration models are useful but may be constrained when deterioration involves nonlinear interactions among traffic, pavement characteristics, maintenance, and climate. Machine learning can represent such interactions and has increasingly been applied to pavement condition assessment, deterioration prediction, and maintenance planning (Tamagusko et al., 2024). Climate-sensitive studies further indicate

that temperature, precipitation, and flood exposure can improve pavement-performance prediction (Bhat et al., 2022; Cui & Wang, 2025). A key gap is the limited integration of pavement condition, traffic, maintenance, and multiple climatic stressors within Pakistan-specific predictive models. International models may not transfer directly because materials, construction practices, traffic composition, drainage, maintenance, and climatic conditions differ. The present study addresses this gap by developing an interpretable AI framework for climate-sensitive pavement deterioration prediction and maintenance support.

2. Problem Statement

Pakistan's road infrastructure faces combined pressures from traffic growth, aging assets, limited maintenance resources, extreme temperatures, intense rainfall, and flooding. Periodic inspections and historical deterioration patterns may be insufficient for anticipating future pavement performance when climate conditions change. Pavement deterioration also results from interacting factors, including pavement age, traffic loading, structural characteristics, maintenance, temperature, precipitation, drainage, and moisture.

The central problem is the lack of an integrated, data-driven, climate-sensitive framework capable of predicting pavement deterioration under Pakistan's operational and climatic conditions and translating those predictions into preventive maintenance decisions.

3. Research Questions

- RQ1: How accurately can AI models predict pavement deterioration using pavement, traffic, maintenance, and climatic variables?
- RQ2: Which climatic and infrastructure variables most strongly influence deterioration?
- RQ3: How does adding climate variables affect predictive performance?
- RQ4: Which AI algorithm provides the most accurate prediction?
- RQ5: How can AI predictions support climate-resilient and sustainable maintenance?

4. Research Objectives

The study aimed to develop and evaluate an AI-driven, climate-sensitive framework for pavement deterioration prediction and sustainable road infrastructure management in Pakistan.

- Develop AI models using pavement, traffic, maintenance, and climatic variables.
- Compare the predictive performance of alternative machine-learning algorithms.
- Determine the contribution of temperature, precipitation, and flood exposure.
- Compare conventional and climate-sensitive models.
- Identify road sections with elevated deterioration risk.
- Support preventive maintenance and climate-resilience prioritization.

5. Significance of the Study

The study integrates AI, pavement deterioration modeling, and climate resilience within one framework. Practically, it can help road authorities identify high-risk sections, prioritize limited maintenance budgets, and improve intervention timing. Environmentally, better prediction may extend pavement service life and reduce premature reconstruction and resource consumption. At the policy level, the framework supports incorporating climate exposure and predictive risk assessment into pavement-management strategies. Its principal contextual contribution is a Pakistan-focused approach that recognizes local climatic, traffic, pavement, and maintenance conditions.

6. Literature Review

6.1 AI and Pavement Deterioration

Pavement deterioration is cumulative and influenced by traffic, age, structural characteristics, drainage, maintenance, and environmental exposure. Machine-learning models—including random forests, support vector machines, gradient boosting, ensemble methods, and neural networks—can capture nonlinear relationships and have been increasingly used for pavement prediction and maintenance planning (Tamagusko et al., 2024).

6.2 Climate Change and Pavement Performance
Climate change affects pavement stiffness, rutting, cracking, moisture damage, drainage performance, and subgrade behavior. Higher temperatures can increase asphalt softening and deformation, while intense precipitation and flooding can increase water infiltration, weaken supporting layers, and accelerate deterioration (Golalipour et al., 2025).

6.3 Climate-Sensitive and Explainable AI

Climate-sensitive machine learning extends conventional prediction by incorporating environmental exposure. Bhat et al. (2022) demonstrated the feasibility of climate variables in pavement condition prediction, while Cui and Wang (2025) showed that climate uncertainty can materially affect future deterioration estimates. Explainable AI, particularly SHAP, can identify the variables driving individual predictions and improve the usefulness of AI for engineering decisions.

6.4 Research Gaps

- Limited Pakistan-specific evidence on climate-sensitive AI pavement prediction.
- Insufficient integration of pavement, traffic, climate, and maintenance information.
- Limited longitudinal datasets in developing-country contexts.
- Potential underestimation of future deterioration when only historical climate is used.
- Limited interpretability of some high-performing AI models.
- Insufficient linkage between prediction, sustainability, and maintenance prioritization.

7. Underpinning Theory

The study is grounded in Resilience Theory, which views resilience as the capacity of a system to withstand disturbances, maintain essential functions, and adapt to changing conditions. For road infrastructure, climate and operational stressors create exposure and vulnerability, while AI-based deterioration prediction can provide an anticipatory mechanism for preventive adaptation. Conceptually: Climate and operational stressors → Pavement vulnerability → AI-predicted

deterioration → Preventive adaptation → Improved resilience and sustainability.

8. Hypotheses

- H1: Pavement age positively affects deterioration.
- H2: Traffic loading positively affects deterioration.
- H3: Higher temperature exposure positively affects deterioration.
- H4: Higher precipitation intensity positively affects deterioration.
- H5: Flood exposure positively affects deterioration.
- H6: Longer maintenance intervals are associated with greater deterioration.
- H7: Climate-sensitive AI predicts deterioration more accurately than the conventional model.

The source manuscript also proposed H8–H10 concerning maintenance prioritization, sustainability performance, and decision-support capability; these should be retained only when the corresponding outcomes are directly measured in the final dataset. [filecite\turn1file0\L550-L583]

9. Methodology

9.1 Research Design and Population

A quantitative, predictive, longitudinal design was used. The unit of analysis was the individual paved road section. The target population comprised road sections for which pavement condition, traffic, climate, maintenance, and geographic information were available.

9.2 Sampling and Sample Size

The manuscript specifies purposive stratified sampling based on climatic region, road functional class, traffic intensity, and pavement condition. It specifies 500 road sections with repeated observations and approximately 2,500 section-year observations where five annual observations were available. The source itself notes that the final sample size should be replaced by the actual available records before submission. [filecite\turn1file0\L625-L654]

9.3 Data and Variables

Category	Principal variables
Pavement	PCI, IRI, rut depth, cracking, potholes, pavement age, structure
Traffic	AADT, heavy vehicles, axle loading, cumulative traffic exposure
Climate	Mean/max temperature, extremes, precipitation, heavy-rain events, flood exposure
Maintenance	Treatment type, intervention date, frequency, time since treatment
Environment	Drainage, terrain, geographic exposure

9.4 Data Processing and Modeling

Data were integrated using a road-section identifier and observation year. Duplicate and inconsistent records were addressed, missing values were examined, and the temporal structure was preserved to reduce information leakage. Feature engineering included cumulative traffic, precipitation and heat exposure, and deterioration rates. Five algorithms were evaluated: Random Forest, Gradient Boosting, XGBoost, Support Vector Regression, and Artificial Neural Network. A conventional pavement-and-traffic model was compared with a climate-sensitive model incorporating temperature, precipitation, and flood exposure. The proposed split was 70% training, 15% validation, and 15% testing, with temporal leakage minimized.

9.5 Evaluation and Explainability

Model performance was evaluated using MAE, RMSE, R^2 , and, where appropriate, MAPE. Reliability was assessed through model stability and repeated validation rather than questionnaire-based internal consistency. Predictive and external validity were assessed using unseen observations and geographically diverse sections. SHAP-based explainability was used to identify the contribution and direction of important predictors.

10. Results

Important source note: the manuscript explicitly states that the numerical results were not based on an uploaded empirical dataset and should be replaced with actual dataset/model outputs before submission. Therefore, the values below are retained only as the reported draft results, not independently verified empirical findings.

10.1 Descriptive Statistics

Variable	N	Mean	SD
Pavement deterioration rate	2,500	3.76	1.82
Pavement age (years)	2,500	10.63	5.47
Traffic loading (million ESALs)	2,500	6.28	4.35
Mean annual temperature (°C)	2,500	25.64	3.21
Annual precipitation (mm)	2,500	694.38	341.26
Flood exposure index	2,500	0.27	0.31

Time since maintenance (years)	2,500	5.74	3.61
Previous PCI	2,500	68.42	16.87

10.2 Correlations

The reported draft results showed positive associations between deterioration and pavement age ($r=.61$), traffic loading ($r=.54$), flood exposure

($r=.44$), temperature ($r=.39$), maintenance interval ($r=.47$), and precipitation ($r=.31$), all reported at $p<.01$. These are associations rather than causal estimates.

10.3 AI Model Performance

Model	R ²	RMSE	MAE	MAPE (%)
Random Forest	.86	.78	.57	14.21
Support Vector Regression	.81	.92	.68	17.46
Gradient Boosting	.88	.72	.52	12.87
XGBoost	.91	.61	.44	10.95
Artificial Neural Network	.89	.69	.49	11.84

XGBoost was the strongest reported model, with $R^2=.91$, $RMSE=.61$, $MAE=.44$, and $MAPE=10.95\%$.

10.4 Conventional vs. Climate-Sensitive Model

Model	Predictors	R ²	RMSE	MAE
Conventional	Pavement + traffic	.78	1.02	.76
Climate-sensitive	Pavement + traffic + climate	.91	.61	.44
Improvement	—	+.13	-.41	-.32

The reported climate-sensitive model substantially outperformed the conventional model. R^2 increased from .78 to .91, while RMSE and MAE

decreased, indicating additional predictive value from climate variables. [filecite]turn2file0[L10-L30]

10.5 Feature Importance and SHAP

Predictor	Importance (%)	Rank
Pavement age	21.4	1
Traffic loading	18.7	2
Previous PCI	16.3	3
Maximum temperature	12.8	4
Flood exposure	10.6	5
Maintenance interval	9.4	6
Precipitation	7.2	7
Other variables	3.6	8

Pavement age was the most influential reported predictor. Climate variables—maximum temperature, flood exposure, and precipitation—

collectively accounted for 30.6% of relative feature importance. SHAP interpretation indicated positive contributions from age, traffic,

temperature, flood exposure, and precipitation, while better previous PCI and more timely maintenance reduced predicted deterioration. [filecite]turn2file0[L31-L96]

11. Discussion

The reported findings indicate that pavement deterioration is a multidimensional outcome of infrastructure condition, traffic loading, maintenance, and climate exposure. Pavement age was the strongest predictor, reflecting cumulative deterioration, while traffic loading remained a major operational stressor. Temperature, precipitation, and flood exposure added information beyond conventional pavement and traffic variables.

The superior performance of the climate-sensitive model supports incorporating climate exposure directly into pavement prediction. The importance of flood exposure also suggests that extreme hydrological events may provide information that annual precipitation totals alone cannot capture. Longer maintenance intervals were associated with greater deterioration, reinforcing the value of preventive intervention. XGBoost achieved the strongest reported predictive performance, consistent with the ability of ensemble tree methods to model nonlinear relationships and interactions. However, the source appropriately notes that algorithm superiority is dataset-dependent and that accuracy should be considered alongside stability, interpretability, computational feasibility, and transferability. SHAP analysis provides a practical bridge between predictive analytics and engineering judgment by explaining the factors underlying high-risk predictions.

The findings align with recent literature showing the growing value of machine learning in pavement management and the importance of climate-sensitive prediction (Tamagusko et al., 2024; Bhat et al., 2022; Cui & Wang, 2025; Golalipour et al., 2025).

12. Conclusion

The study presents an AI-driven framework for climate-resilient pavement deterioration prediction in Pakistan. The reported analysis

identifies pavement age, traffic loading, previous pavement condition, temperature, precipitation, flood exposure, and maintenance history as important predictors. XGBoost showed the strongest reported performance, while the climate-sensitive model outperformed the conventional model. SHAP analysis enhanced interpretability by identifying the principal contributors to deterioration risk.

Overall, the framework supports a shift from reactive to predictive pavement management. Integrating climate exposure with pavement, traffic, and maintenance information can improve identification of vulnerable road sections and support earlier, more targeted interventions. The manuscript's numerical results, however, require validation and replacement with actual empirical outputs before publication.

13. Implications

- Road agencies can use predicted deterioration risk to prioritize inspection and preventive maintenance.
- Climate exposure should be integrated into pavement-management systems and asset planning.
- Explainable AI can improve transparency and engineering acceptance of predictive outputs.
- Digital integration of pavement, traffic, maintenance, meteorological, flood, and geographic data is essential.
- AI should remain a decision-support tool complemented by engineering inspection and professional judgment.

14. Recommendations

- Develop integrated digital pavement databases combining condition, traffic, climate, maintenance, drainage, and geographic information.
- Incorporate temperature extremes, precipitation intensity, and flood exposure into deterioration models.
- Adopt predictive maintenance based on deterioration-risk forecasts.
- Use SHAP and related explainability methods for infrastructure decision-making.

- Develop climate-specific maintenance strategies for flood- and heat-exposed roads.
- Validate models across Pakistan's different climatic and geographic regions.
- Periodically retrain models as new pavement and climate observations become available.
- Connect AI predictions with life-cycle cost, environmental impact, service-life, and resource-efficiency assessment.

15. Limitations and Future Research

The study is limited by dependence on the completeness and consistency of longitudinal pavement records, potential spatial mismatch between weather data and road sections, context-specificity to Pakistan, risks of overfitting, and the distinction between predictive contribution and causal effect. Rare extreme climate events may also be underrepresented, and full uncertainty quantification was not incorporated. A complete sustainability assessment would require direct measurement of life-cycle cost, material use, emissions, energy, and disruption. Future research should develop larger Pakistani longitudinal datasets, incorporate projected climate scenarios and uncertainty-aware methods, investigate temporal deep-learning and physics-informed approaches, integrate remote sensing and computer vision, and link deterioration forecasts directly to maintenance optimization and multi-region field validation.

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