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Reliability-Based Optimization of Flexible Pavement Maintenance Using Nonlinear Deterioration Models: A Case Study from Al-Najaf, Iraq

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ABSTRACT

This research proposes a reliability-based methodology to optimize maintenance planning for flexible pavements by employing nonlinear deterioration modelling. The study focuses on Al-Najaf, Iraq, where pavement infrastructure faces compounded stresses due to high temperatures and substantial traffic volumes. Traditional linear models are insufficient for capturing the real-time progression of pavement degradation in such environments, resulting in suboptimal maintenance interventions. To address this gap, the study calibrates two nonlinear models—the Weibull and exponential functions, using performance data gathered between 2016 and 2024 across three representative road corridors. The Weibull model outperformed its counterpart, with a coefficient of determination (R^2) of 0.946, as well as lower Root Mean Square Error (RMSE) and Akaike Information Criterion (AIC) values, indicating better predictive capacity. Reliability analysis was integrated into the modelling process to estimate the probability of pavement failure over time, aiding in the determination of optimal intervention points. Five maintenance strategies were evaluated: preventive, condition-based, hybrid, risk-based, and no-maintenance. Among these, the hybrid strategy emerged as the most efficient in terms of lifecycle cost-effectiveness and service life extension, achieving a pavement lifespan of 12.5 years while maintaining a balanced overall cost. An economic evaluation using Net Present Value (NPV) and Monte Carlo simulation highlighted the system's sensitivity to environmental and operational variables, including increased axle loads and temperature fluctuations. The study concludes with policy-oriented recommendations, advocating for the integration of nonlinear and reliability models into national Pavement Management Systems (PMSs), and proposing the pilot implementation of hybrid strategies in cities with similar climatic and loading conditions.

1. INTRODUCTION

Flexible pavements are a foundational element of transportation infrastructure, facilitating mobility, commerce, and socio-economic progress. In rapidly developing and climatically harsh regions like Al-Najaf, Iraq, these pavements face accelerating degradation due to extreme heat, overloaded traffic, insufficient drainage, and erratic traffic flow. Such factors intensify pavement distress mechanisms, including rutting, fatigue cracking, and thermal shrinkage, prompting the need for predictive maintenance strategies that can optimise pavement lifespan and minimise financial waste [1]. According to AASHTO standards and modern pavement engineering research, the deterioration of pavements due to repeated loading and environmental stressors does not follow a linear pattern; instead, it tends to accelerate over time in a nonlinear manner [2, 3]. The case of Al-Najaf represents a particularly complex example of pavement deterioration, making it an appropriate context for assessing advanced modelling approaches. Over 12 million religious tourists come in and go out of the city annually; as a result, the city experiences seasonal peaks in traffic [4], in addition to bearing a daily ESAL in excess of 23,000 on its main roads, such as the Al-Kufa-Najaf Road [5]. These conditions are exacerbated by extreme climatic conditions, summer temperatures frequently exceed 47°C, and normal precipitation is less than 100 mm per year, with regular sandstorms. Together, these climatic stresses degrade the asphalt layers and the sub-base materials, causing the road to fail prematurely [6, 7]. In such a complex setting, traditional linear deterioration models fall short. Nonlinear modelling tools like Weibull and exponential functions provide better accuracy in predicting pavement performance under highly variable environmental and operational conditions [8, 9]. This study conducts an in-depth evaluation of such nonlinear deterioration models, utilising extensive field data gathered over eight years in Al-Najaf. By applying reliability analysis techniques, the research estimates the probability of failure and identifies long-term maintenance requirements. These insights are essential for infrastructure planners aiming to optimise rehabilitation timing, set investment priorities, and align maintenance efforts with budget constraints [10, 11]. The integration of empirical data and probabilistic risk analysis contributes to the advancement of pavement management practices, particularly in arid, high-demand urban environments.

2. RESEARCH OBJECTIVES

The objective of this research is to develop and calibrate nonlinear pavement deterioration models using field data from Al-Najaf and to evaluate their accuracy through statistical indicators such as coefficient of determination (R^2), Root Mean Square Error (RMSE), and Akaike Information Criterion (AIC). Reliability functions are integrated to estimate failure probability over time, and several maintenance strategies are simulated to assess their cost-effectiveness. Ultimately, the study provides policy-oriented recommendations aimed at enhancing Pavement Management Systems (PMSs) and supporting long-term infrastructure planning.

3. SCOPE AND LIMITATIONS

The study focuses on three road corridors in Al-Najaf: urban arterials, airport highway, and religious access roads. While extensive performance data was collected between 2016 and 2024, certain subgrade and layer thickness values were estimated based on standard construction reports, which may introduce potential biases in calibration accuracy. Moreover, traffic measurement errors and the lack of spatially distributed data could affect the reliability of the models. Although sensitivity analysis was used to mitigate these issues, the limitations of relying solely on Weibull and exponential models without incorporating spatial variability should also be acknowledged.

4. LITERATURE REVIEW

Flexible pavements degrade progressively due to cumulative traffic loading, material ageing, and exposure to environmental factors such as temperature gradients, precipitation variability, and UV radiation. Performance indicators like the International Roughness Index (IRI), rutting depth, cracking intensity, and Crack Severity Index (CSI) are widely used in PMSs to monitor condition and inform maintenance planning [12, 13]. These indicators, standardised through protocols such as ASTM D6433, provide a consistent basis for modelling deterioration trajectories and estimating service life. Historically, pavement deterioration has been modelled using linear regression techniques that assume uniform degradation over time. However, empirical studies have repeatedly shown that pavement damage follows a nonlinear pattern, characterised by early-stage stability, mid-life acceleration, and late-stage exponential failure [14, 15]. Madanat et al. [16] stressed the fact that linear models commonly underestimate the late-stage of degradation, causing them to make mistimed maintenance strategies that result in overall life cycle cost increase. These limitations have been controlled by proposing nonlinear experimental models like Weibull, Gompertz, logistic regressions, etc. These functions provide parameters that can be adapted to calibrate according to different climates, texture materials, and traffic conditions [17, 18]. In infrastructure engineering, Weibull-based deterioration models are widely used to characterise pavement performance over time [19]. Comparative studies of exponential and Weibull lifetime models indicate that nonlinear probabilistic approaches yield more reliable deterioration estimates than linear models [20]. Such formulations align with reliability analysis to estimate failure probability over the service life and, in similar climates, have been shown to lower maintenance costs; Weibull-based planning has reduced lifecycle cost in empirical applications [21]. Reliability-based Pavement Maintenance and Rehabilitation (RPMC) utilises reliability-centred intervals to optimise intervention timing, minimise unexpected failures, and contain maintenance budgets [22, 23].

Despite these advancements, the adoption of such models in Iraq remains limited. The majority of domestic research has concentrated on mix design, material testing, or basic condition assessment using visual surveys. Recent work shows that embedding reliability theory in PMS remains emerging, limited by fragmented data and weak calibration [24]. Pilot nonlinear modelling in academia has not shaped municipal practice because of capacity constraints and the absence of implementation standards [25]. In the broader international context, the integration of reliability theory into infrastructure management has become a central theme. ISO 55000 emphasises risk-informed decision-making as a core principle of asset management, advocating for predictive frameworks that account for uncertainty and variability [26]. Recent contributions by Haas et al. and ARA Inc. have reiterated the importance of linking deterioration modelling with financial planning to develop more resilient infrastructure systems [27, 28]. Monte Carlo simulations and probabilistic sensitivity analyses are now routinely used in advanced PMS models across North America, Europe, and Asia, where they support the prioritisation of investments based on performance thresholds, risk tolerance, and economic return [28, 29]. In conclusion, the literature reflects a paradigm shift in pavement management from static, deterministic models toward dynamic, data-driven, and probabilistic approaches. This evolution is especially critical for cities like Al-Najaf, where environmental volatility and traffic intensity create unique stress profiles that cannot be captured by conventional methods. Bridging the gap between international best practices and local implementation requires calibrated modelling, reliable data, and policy integration objectives that this study seeks to advance.

In summary, the reviewed literature highlights significant progress in nonlinear and reliability-based modelling approaches for pavement management. However, their application in Iraq remains limited, with most domestic studies focused on material properties or basic condition assessment. This study addresses this gap by integrating nonlinear deterioration models with reliability analysis to optimize maintenance strategies under the specific climatic and operational conditions of Al-Najaf.

5. METHODOLOGY

This paper uses a systematic approach to model pavement deterioration and to optimise corresponding maintenance policies of the Al-Kufa-Najaf Road in southern Iraq. The method starts with a detailed study of the project area and moves on to the organised aggregation and treatment of performance information for the period of 2016-2024. The effect of environment and structural conditions on the pavement is then explained. Indicators of performance (IRI, rutting, cracking) are adjusted for calibration of the nonlinear models of deterioration (Weibull and Exponential). A reliability analysis is incorporated to predict the failure probability and to provide maintenance timings. The approach additionally involves a comparative simulation of five maintenance options and is then complemented with a sensitivity analysis based on the Monte Carlo method to assess the effect of uncertainty in traffic, climate, and maintenance interruptions.

5.1 Study area description

The study area is identified as Al-Kufa-Najaf Road, a major urban arterial in Al-Najaf Governorate, southern Iraq. The area has an arid climate characterised by extremely high summer temperatures (over 47°C), low annual rainfall (< 100 mm), and frequent sandstorms, which exacerbate the condition of roads. This corridor is heavily used, featuring roughly 23,000 ESALs/day due to its role in daily commuting purposes and religious tourism. The asphalt section structure of the pavement is divided into 5–6 cm of wearing layer, 12 cm of binder layer, and 25–30 cm of base layer supported by the natural roadbed.

5.2 Data collection and processing

In this study, we collected a comprehensive set of engineering and environmental data over eight years to monitor pavement performance among selected corridors in Al-Najaf. These parameters were then gathered using standardised methods of collection to ensure high levels of precision and temporal consistency. Measuring parameters:

- IRI was evaluated using the Automated Road Analyser (ARAN) longitudinal surface profiles and provided surface roughness quantifications.
- Rutting depth was measured by 3D high-precision laser Profiling, which recorded permanent deformations in the wheel paths.
- Surface cracking is manually monitored, may include photometric image analysis to obtain the CSI according to ASTM D6433 standards.
- Resilient modulus determined by the Falling Weight Deflectometer (FWD) test has an average value of about 65 MPa and shows subgrade strength.
- Traffic loads (ESALs/day) were estimated through a combination of manual vehicle counts and fixed inductive loop detectors to calculate the Equivalent Single Axle Loads (ESALs).
- Climatic data, sourced from the Iraqi Meteorological Organisation, includes the main types of environment-stress factors on pavements: annual temperature ranges and their extremes (including rainfall levels), and frequency data for sandstorms. Meeting the needs of incomplete and inconsistent data records (less than 5 per cent of all data), interpolation techniques such as cubic spline and second-order polynomial fitting were used. Finally, all data were transformed into normalised annual flat intervals for use in model development work calibration.

5.3 Engineering and environmental context

The performance of flexible pavements in Al-Najaf is heavily influenced by the region's extreme environmental conditions and structural pavement configurations. Over the past decade, Al-Najaf has experienced a marked shift in climate, which has directly impacted the durability of road surfaces and accelerated the degradation of pavement materials.

As shown in Table 1, climatic data collected between 2016 and 2024 indicate a progressive increase in maximum summer temperatures from 46.1°C in 2016 to 47.9°C in 2024, paired with a consistent decline in annual rainfall, dropping from 101.4 mm to just 86.3 mm. In parallel, the number of sandstorms per year has risen sharply, increasing from 14 to 22 events over the same period. These shifts are visualised in Figure 1, which highlights the dual climatic stressors: rising temperatures and diminishing precipitation. Together, these factors intensify pavement fatigue, accelerate oxidative ageing of asphalt binders, and promote thermal cracking and surface ravelling, particularly in unshaded or poorly drained segments of the network. This environmental background necessitates the use of durable pavement structures that can withstand thermal stress and surface erosion.

Table 1. Climatic and environmental conditions in Al-Najaf (2016–2024)

Year	Max Temp. (°C)	Rainfall (mm/year)	Sandstorms (annual)
2016	46.1	101.4	14
2018	46.8	97.2	16
2020	47.2	92.5	17
2022	47.6	89.1	20
2024	47.9	86.3	22

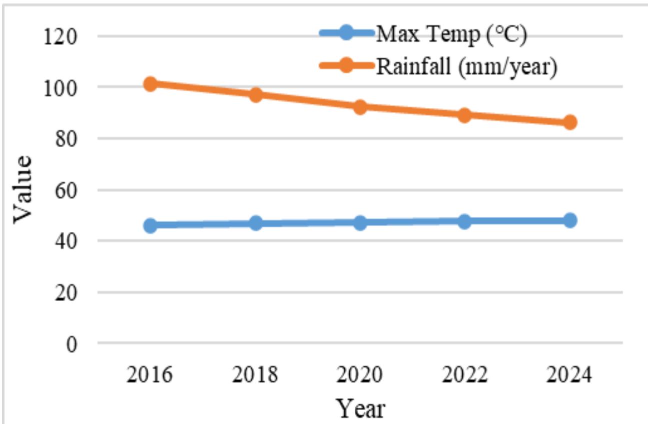

Figure 1. Max temperature and rainfall of the climatic trend in Al-Najaf (2016–2024)

Table 2. Structural design of pavement layers (typical cross-section)

Layer Type	Material Type	Thickness (cm)
Surface Course	Asphalt Concrete (Hot Mix)	5–6
Binder Course	Dense Bituminous Base	12
Base Course	Crushed Aggregate	25
Subbase	Granular Fill	30

Table 2 summarises the typical cross-section of flexible pavements deployed in Al-Najaf's main corridors. The surface course generally consists of a 5–6 cm layer of hot mix asphalt (HMA), which is prone to oxidation under elevated temperatures. Beneath this lies a 12 cm binder course composed of dense bituminous material that provides intermediate structural support. The load distribution is handled by a 25 cm crushed aggregate base and a 30 cm subbase of compacted granular fill resting over natural subgrade. This layered design is intended to manage the significant traffic loading typical of the region while mitigating environmental impacts.

However, as thermal gradients steepen and sandstorm frequency increases, even well-engineered pavements require advanced performance monitoring and predictive maintenance strategies. Together, Table 1, Table 2, and Figure 1 frame the environmental and structural constraints facing pavement engineers in Al-Najaf. These inputs serve as a critical foundation for the subsequent modelling of deterioration behaviour and the selection of context-appropriate maintenance strategies.

5.4 Pavement performance monitoring

Observation of pavement performance over long periods of time provides an important basis for recognising the degradation process of road structure under combined traffic-environmental action. For the Al-Kufa-Najaf corridor, 2016–2024 performance measurements indicate deterioration that is gradual, as in the stress history example, although not in a strictly linear or even manner for ride quality and structural durability.

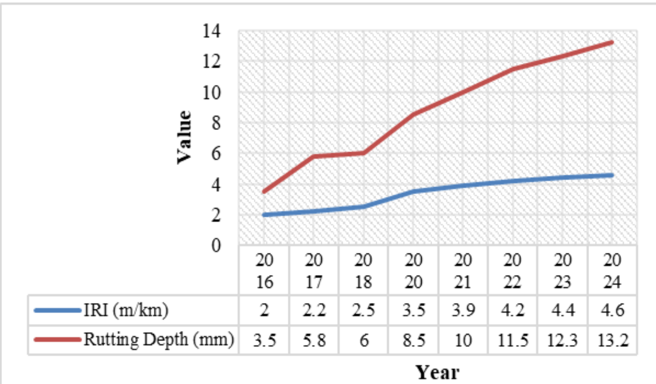

Figure 2. Pavement deterioration trend (IRI and rutting)

Table 3. Pavement surface performance indicators (Al-Kufa-Najaf Road)

Year	IRI (m/km)	Rutting Depth (mm)	Cracking (%)	Structural Rating (0-10)	CSI
2016	1.8	3.1	2.2	9.2	12
2018	2.4	6.0	4.8	8.4	22
2020	3.6	8.9	9.5	7.1	36
2022	4.2	11.7	14.2	6.1	48
2024	4.7	13.3	18.4	5.3	61

Table 4. Traffic and load data (ESALs/day)

Year	Average ESALs/Day	Source of Measurement
2016	18,500	Pneumatic tube counters
2018	21,300	Inductive loop detectors
2020	22,000	Manual + automatic observation
2022	23,100	Transport Directorate estimates
2024	23,000	Najaf municipality traffic report

A time-series plot containing the two most important performance measures, the IRI and rut depth, is shown in Figure 2. It can be seen from the table that IRI increased from 1.8 m/km in 2016 to 4.7 m/km in 2024, which meant that the surface smoothness was worsening and the comfort of the users became poorer. At the same time, rutting depth increased from 3.1 to 13.3 mm, which indicated that wheel paths were progressively deforming under repeated axle loads and high temperatures. Parallel increases in the two measures highlight how early intervention is required to avoid a rapid degradation path beyond affordable levels.

For additional context to these results, Table 3 summarises the yearly field data for the Al-Kufa-Najaf section. They are IRI, rutting depth, percentage cracking, structural condition rating, CSI, and subgrade modulus. Together, these parameters directly relate to the long-term physical health and function of the pavement system. From Table 3, it can be seen that structural ratings have declined from 9.2 in 2016 to 5.3 in 2024, in parallel with the increasing CSI, indicating worsening surface condition. The degradation is further confirmed by a steady drop in subgrade modulus, highlighting the impact of underlying soil resilience on surface performance.

Table 4 presents the increasing trend in traffic loading, represented by ESALs, which rose from 18,500 to over 23,000 vehicles per day. The high traffic density, especially during religious events, exerts continuous stress on pavement layers, contributing significantly to rutting and cracking.

5.5 Modelling and calibration results

In such weather and traffic conditions, nonlinear models, for the deterioration of both advanced models, were employed to predict pavement condition more accurately. These models were selected as they are sufficiently flexible to model realistic pavement deterioration processes that accelerate over time, e.g., as a result of cumulative loading and environmental ageing.

The Weibull Model: The first model considered in the analysis was the Weibull Model, whose mathematical expression is:

$$IRI(t) = a \cdot t^{b}$$

In this study, the calibration process yielded the parameters a = 1.42 and b = 1.63, indicating that the deterioration rate increases progressively over time. This makes the Weibull model particularly useful in simulating later-stage pavement distress.

The second model used was the Exponential Model, represented as:

$$IRI(t) = a \cdot e^{b \cdot t}$$

This model with the estimated parameters a = 1.81 and b = 0.257 describes a stable growth of pavement roughness IRI in time. However, it is less sophisticated and may not completely reflect the accelerated ageing behaviours in all cases. Hence, the reliability-based analysis was used to estimate the probability of the pavement's survival over a required period. The Weibull Reliability Function used to calculate the idea may be defined as follows:

$$R(t) = \exp\left(-(t/\eta)^{\beta}\right)$$

where, η = 8.5 (scale parameter representing the characteristic life of the pavement before accelerated deterioration begins), and β = 2.1 (shape parameter that indicates how quickly deterioration accelerates over time). This expression calculates the probability that a pavement will be in service for a given time "t" to enable engineers to select a suitable time for maintenance or rehabilitation.

Furthermore, the Hazard Function corresponding to it was computed to illustrate the rate of the increasing hazard of failure:

$$H(t) = (t/\eta)^{\beta}$$

This one is key in the prediction of imminent fast decline. For practical use, the intervention level was set at R(t) < 70%, indicating that the maintenance practice is recommended when the survival probability is < 70%.

Table 5. Calibrated model parameters and fit statistics

Model	a	b	R^2	RMSE	MAE	AIC
Weibull	1.42	1.63	0.946	0.176	0.174	34.8
Exponential	1.81	0.257	0.874	0.312	0.298	42.1

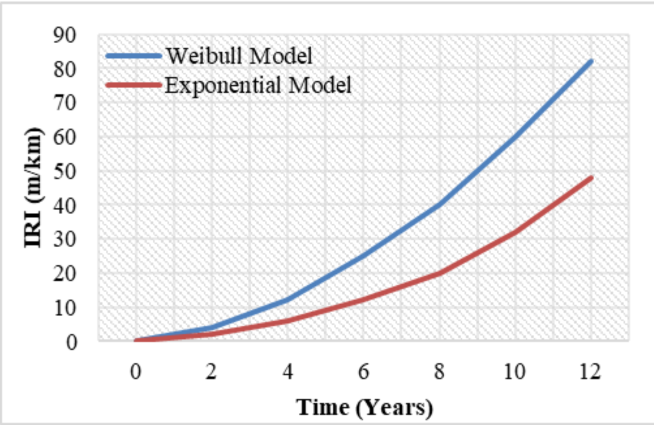

Figure 3. Model fit comparison: Weibull vs. Exponential

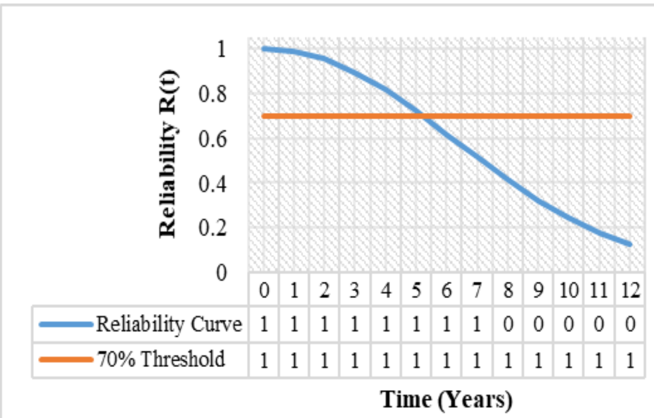

Figure 4. Risk-adjusted degradation projection

Incorporating distress modelling within reliability analysis establishes a comprehensive and systematic framework for proactive, cost-efficient pavement management. The calibration process underwent rigorous robustness checks and cross-validation, employing MATLAB (infit function), R (nls and lm packages), and Excel Solver to ensure methodological accuracy and consistency of results. As already depicted in Table 5, the performance comparison of the two models against observed pavement deterioration data is shown in Figure 3.

This is because the empirical measurements seem to converge on important periods of the object's life, and the Weibull seems preferable for predictive purposes, especially towards the end of the object's life.

Figure 4 illustrates the risk-adjusted degradation projection based on the Weibull reliability function. The curve demonstrates a steep drop in reliability after year 8, emphasizing the critical importance of timely maintenance actions to prevent sudden performance failure. This projection provides decision-makers with a quantitative basis for intervention planning based on acceptable levels of service reliability.

5.6 Maintenance strategy simulation

Design and application of pavement maintenance strategies are crucial to achieving sustainable and cost-effective road asset management. Under the specific environmental and operating conditions in Al-Najaf, Iraq, the choice of the most appropriate maintenance strategy is becoming more and more important. This section describes a holistic model for five different maintenance approaches over 10 years (2025–2035) of planning. The assessed policies considered in the experiments are preventive maintenance, condition-based maintenance (CBM), hybrid strategy, risk-based planning, and no-maintenance as a baseline.

The comparison is conducted with four performance measurements, i.e., cumulative cost, surface condition measured by the IRI, the anticipated service life, and the probability of structural failure. Together, these metrics provide an overall assessment of the long-term survivability of each strategy.

As shown in Table 6, the hybrid option proved to be the most efficient with the highest projected service life (12.5 years) and the lowest average IRI (3.8) at a modest cost of $450,000. This approach is based on the use of scheduled and condition-based maintenance, allowing intervention when field conditions are observed. Likewise, the CBM model showed quite effectiveness, leading to extending the service life to 11.2 years, based on the range of the lowest accumulated cost, which was $390,000, by carrying out the necessary maintenance at the time that it passed the performance thresholds.

Conversely, not maintaining resulted in the highest cost burden ($690,000) and significantly higher failure rates of 85% emphasising the negative outcomes associated with delaying or disregarding maintenance. The findings emphasise that proactive maintenance programs should be put in place as part of the PMS, as shown in Figure 5.

Table 6. Maintenance scenarios (2025–2035)

Strategy	Cost (USD)	Avg. IRI	Service Life	Prob. of Failure
Preventive	$460,000	4.2	10.0 yrs	35%
CBM	$390,000	4.0	11.2 yrs	22%
Hybrid	$450,000	3.8	12.5 yrs	18%
Risk-based	$400,000	4.1	10.8 yrs	21%
No maintenance	$690,000	>6.0	7.6 yrs	85%

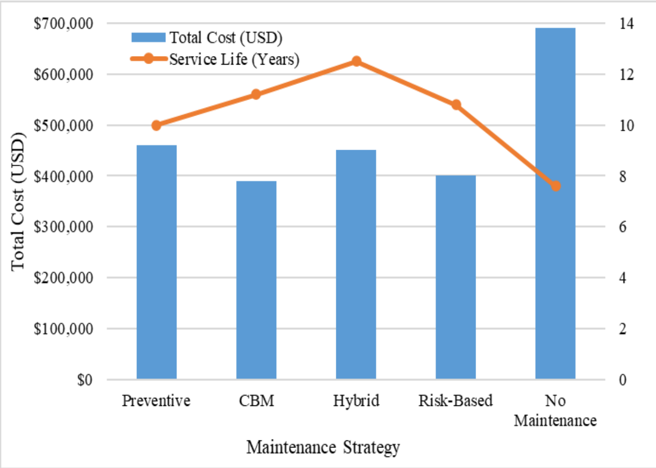

Figure 5. Maintenance strategy - cost vs. service life (updated)

The cost and the lifetime of each maintenance policy are compared in terms of graphs in Figure 5. The bar chart shows the cost of each alternative, and overlaid with the dotted line series is the 20-year life span for each alternative. Such a visualisation of dual axes can present policy-makers with a more sophisticated view of the cost-efficiency effect, aiding more rational policy-making.

The economic analysis was supplemented by Net Present Value (NPV) analysis. NPV is very common in infrastructure management to account for the time value of money so that future rehabilitation and failure-related costs are discounted properly. The NPV for each strategy was calculated using the following formula:

$$NPV = \Sigma(Ci + Pf(i) \cdot Crehab) / (1+r)^i, i = 1, 2, \ldots, n$$

where, Ci is the annual maintenance cost in year i, $Pf(i)$ is the probability of failure in year i, Crehab is the cost of full rehabilitation (USD 110,000), and r is the discount rate (4%). This formulation allows consistent comparison of strategies by incorporating both direct and indirect costs across the analysis period.

5.7 Sensitivity analysis inputs and results

Sensitivity analysis using Monte Carlo simulation methods was performed to examine the validity of the proposed crude and maintenance models under uncertainties of a real-world situation. Overall, 1,000 simulation runs were conducted to consider the influence of critical input variables on the pavement performance, risk of failure, and economic consequences. This method allows uncertainty to be quantified and helps with risk-based decision-making in the pavement management area.

The controlled perturbation variables were comprised of the ESALs, the environmental temperature, the time of maintenance intervention, and the binder's ageing rate. All parameters were varied in a physical range using regional traffic and climate data. More precisely, the variation of the traffic loading (ESALs) was ±15%, the temperature was ±2.5°C, the maintenance delay was ±1 year, and that of the binder ageing was ±10%. These values were chosen to encompass realistic changes occurring over an average operating time in Al-Najaf.

These findings underscore the importance of proactive decision-making under uncertainty. For road agencies, the results suggest that even modest delays or climatic shifts can impose substantial financial burdens, reinforcing the need for continuous monitoring and adaptive maintenance planning. An upward adjustment in traffic volume of 15% simulating increased freight movement, elevated the probability of early failure by 22%. Additionally, an increase in average temperature by 2℃ led to an 18% rise in surface cracking, indicating heightened sensitivity to climate-induced degradation.

Table 7 summarises the direct impact of individual parameter changes on the year in which IRI exceeds 4.0 m/km (indicating functional failure), along with the associated increase in lifecycle costs.

As evident from Table 7, the timing of performance degradation shifts forward with each perturbation. Traffic escalation and thermal loading were particularly impactful, accelerating pavement deterioration by nearly two years in some scenarios. These insights emphasize the critical role of proactive data-driven monitoring and intervention planning under conditions of climatic volatility and increased vehicular demand.

Figure 6 presents a dual-axis representation of the sensitivity analysis results. The bar chart displays the estimated increase in lifecycle costs (left axis) for each parameter variation, while the line plot (right axis) tracks the corresponding year when the pavement's IRI exceeds 4.0 m/km, signaling the onset of functional failure. Among the tested parameters, a one-year maintenance delay produced the highest economic burden ($110,000), while increased temperature led to the earliest threshold breach (year 7.4). This figure underscores the interplay between environmental stressors, traffic growth, and delayed intervention—each of which exerts significant influence on long-term pavement performance and cost.

Table 7. Variable impact on pavement performance

Parameter Change	Magnitude	IRI > 4.0 Trigger Year	Cost Impact (USD)
Traffic ↑ 15%	+3,450 ESALs	Year 7.7	+92,000
Temperature ↑ 2°C	Climatic shift	Year 7.4	+103,000
Maintenance Delay	+1 year	Beyond Year 8.0	+110,000

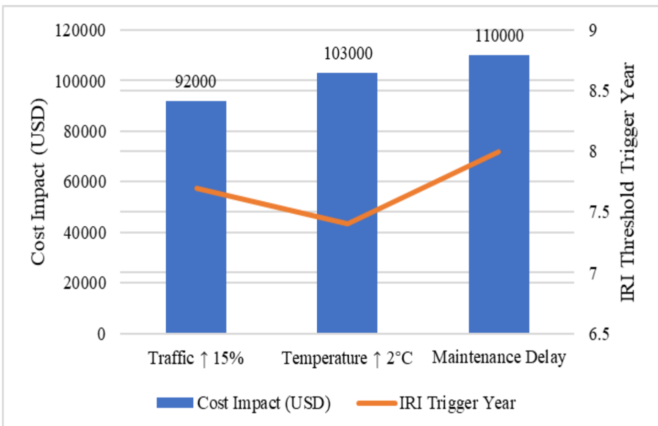

Figure 6. Sensitivity analysis -cost and degradation impact

6. CONCLUSION

This study set out to develop a reliability-based optimisation framework for flexible pavement maintenance in Al-Najaf. By calibrating nonlinear deterioration models with empirical data, the research demonstrates how reliability functions can improve the prediction of pavement failure and guide more effective maintenance planning. Under the unique climatic and operational conditions of Al-Najaf. By incorporating nonlinear deterioration models specifically, the Weibull and exponential functions, and calibrating them with empirical field data from 2016 to 2024, the research underscores the limitations of conventional linear models and emphasises the importance of accurately capturing the accelerated nature of pavement degradation over time.

Adoption of reliability-based modelling has been instrumental in providing insights into probabilities of failure and determination of the most appropriate timing for intervention. These models provide a dynamic, as opposed to static, threshold-based approach to assist municipal agencies in planning maintenance more proactively. In addition, simulation of different maintenance philosophies, i.e., preventive, condition-based, hybrid, and risk-informed, has generated invaluable information concerning the cost-performance trade-offs associated with each implementation.

The cost-effectiveness financing model was further confirmed by the NPV economic evaluation and the Monte Carlo simulation sensitivity testing. These instruments facilitated a rigorous examination of the effects of major uncertainties, such as the increase in traffic and climatic variability, on long-term maintenance planning and infrastructure sustainability. In fact, the hybrid maintenance approach was found to be the most effective with respect to cost, life span, and risk, especially under budget limitations and environmental variances.

Overall, the research makes both methodological and practical contributions to pavement management by providing a data-driven, risk-aware, and economically viable framework. For practitioners, the study offers actionable insights on balancing service life extension with cost efficiency. Future research should focus on integrating GIS-based spatial modelling and expanding the approach to other Iraqi cities, thereby enhancing the scalability and real-world applicability of the proposed framework. The proposed framework supports data-driven, risk-aware, and economically viable decisions, which are essential for enhancing infrastructure resilience in arid regions like Al-Najaf. The findings serve as a foundation for future extensions that may include real-time sensor integration, GIS-based spatial modelling, and broader regional application across other governorates with similar challenges.

7. RECOMMENDATIONS

Based on the findings of this study, several recommendations are proposed to enhance the effectiveness and sustainability of pavement management practices in similar climatic and operational contexts:

- Integrate nonlinear deterioration models, such as Weibull and exponential functions, into PMSs to more accurately represent field behaviour and failure progression.
- Incorporate reliability-based tools and hazard functions in planning and evaluation processes to improve decision-making under uncertainty.
- Establish centralised databases for pavement condition, maintenance history, and environmental data to support evidence-based policy formulation.
- Implement a pilot project to evaluate the hybrid maintenance strategy in a comparable urban setting, such as Karbala, to validate the transferability and scalability of results.

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