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A Historical Review of Pavement Management Approaches Employed in Nepal

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Abstract

Pavement management in Nepal has evolved over the past several decades through intertwined technical, institutional, and technological developments. This paper presents a comprehensive historical review of Nepal's pavement management approaches, highlighting: (1) technical advancements in performance modelling from simple empirical deterioration models to Markovian hazard-based models and modern AI/ML techniques alongside the use of pavement condition indices (SDI, IRI, PCI) in the Nepali context; (2) institutional and policy evolution, including the establishment of Roads Board Nepal (RBN) in 2002 to ensure sustainable maintenance funding, development of planning guidelines focusing on a Surface Distress Index (SDI) rating, and the crucial role of international donors (World Bank, JICA) in capacity building and system development; and (3) technology adoption trends, from the introduction of the Highway Development and Management (HDM-4) tool and a Highway Management Information System (HMIS) for data-driven planning, to recent integration of GIS-based Road Asset Management Systems (RAMS) and innovative data collection via smartphone applications like RoadRoid. Through extensive literature survey, we synthesize how technical methodologies have improved, how policies and institutions have adapted, and how new technologies are being embraced. The findings reveal a trajectory of progress: from subjective visual indices and ad-hoc repairs towards data-driven, long-term asset management planning. Nonetheless, challenges remain in fully institutionalizing advanced models and tools amid resource constraints. Recommendations are provided for strengthening pavement management in Nepal by integrating modern predictive models, enhancing institutional capacity, and leveraging appropriate technologies for sustainable road network performance.

***Keywords*:** Pavement Management System, Road Asset Management System, Highway Management Information System, Surface Distress Index, Road Roid

1. Introduction

Nepal's road network, spanning the high Himalayas to the Terai plains, is critical to the country's mobility and economic development. Shah et.al(2019) highlighted that the urbanization in Nepal has several drawbacks(Shah et al., 2019), one of which is the deterioration in the condition of the pavement. Therefore, maintaining pavement quality in this diverse terrain poses significant challenges. Pavements deteriorate due to traffic loading and aggressive environmental conditions, especially the annual monsoons that bring intense rainfall and cause widespread surface distress(Shakya et al., 2025a).

Historically, Nepal's road agencies struggled with limited maintenance funding, inadequate data, and basic planning methods (DOR, 1995). Over time, conscious efforts have been made to introduce systematic pavement management approaches, balancing technical rigor with the realities of Nepal's institutional capacity and resource constraints (DOR, 2015). There have been several technical developments that answer how pavement performance modeling and condition monitoring techniques have advanced in Nepal. This includes the use of performance prediction models (from empirical regressions and Markov models to Artificial Intelligence/Machine

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Learning approaches), and the adoption of pavement condition indices such as the International Roughness Index (IRI), Surface Distress Index (SDI), and Pavement Condition Index (PCI) in maintenance decision-making(Alnaqbi et al., 2024).

There have been several institutional and policy evolution in Nepal with regards to the pavement management system. Nepal's institutional framework and policies for road maintenance have evolved (DOR,2013). Key milestones include the establishment of dedicated funding mechanisms (notably the creation of Roads Board Nepal in 2002) and the influence of government programs and international donors like World Bank and JICA in shaping maintenance planning, standards, and practices (Road Board Nepal, 2002).

Different tools and technologies for pavement management have been introduced and adopted over the past few decades. This ranges from the implementation of Highway Development and Management Model (HDM-4) and development of a Highway Management Information System in the 2000s, to recent moves toward GIS-based Road Asset Management Systems (RAMS) and innovative data collection via smartphones through RoadRoid and Road Bump apps for roughness measurement.

By integrating these dimensions, we aim to chronicle the progression of Nepal's pavement management from its early stages to the present state-of-the-art, highlighting both achievements and remaining gaps. These works provide insight into the Nepal-specific context of pavement performance modeling, condition index correlations, and technology evaluation. The rest of the paper is organized as follows. The Literature Review discusses prior studies and documented practices across the technical, institutional, and technological aspects of pavement management in Nepal. The Methodology section explains how this review was conducted. The Results section then synthesizes key findings, often in chronological order, demonstrating how the three dimensions have co-evolved over time. A Discussion section interprets these findings, examining the interplay between technical approaches, policy decisions, and technology uptake, and comparing Nepal's trajectory with international trends. We then outline specific Challenges that have impeded pavement management effectiveness in Nepal, followed by Recommendations for future improvements. Finally, the Conclusion summarizes the historical evolution and emphasizes the importance of integrated efforts to ensure durable and serviceable road pavements in Nepal.

2. Literature Review

2.1 Technical Developments in Pavement Performance Modeling and Indices

Poor condition of pavement causes delays and unreliable travel times within routes, which may cause a significant loss in economy as well as value of time, therefore requiring effective strategy for pavement management at the earliest (Thapa et al., 2024). The pavement in Nepal is offen used by pedestrians along with motor vehicles (Thapaliya et al., 2024), especially due to lack of sidewalk and mandatorily on crosswalks which is also affected by the condition of the pavement. Early pavement management efforts in Nepal relied on simple empirical approaches and visual condition ratings. The Surface Distress Index (SDI) became the cornerstone of pavement condition assessment. SDI is a subjective index on a 0–5 scale (0 = no distress, 5 = extremely distressed pavement) used by the Department of Roads (DOR) to rate surface condition (Shrestha et al., 2024a). This six-level rating system was originally recommended by the World Bank and then adapted to Nepal's needs. Historically, SDI has been the primary performance indicator for planning maintenance in Nepal, due to its simplicity and the ease of visual data collection by engineers. An SDI of 0 indicates a pavement in good condition with no defects, whereas an SDI 5 represents a poor road with extensive potholes and exposed base on significant portions of the surface (Shakya et al., 2025b). In parallel, the International Roughness Index (IRI), an objective measure of ride quality and surface roughness, was introduced globally in the 1980s and gradually adopted in Nepal.

By the early 2010s, the Department of Roads began collecting IRI data annually on the Strategic Road Network (SRN) as part of its Highway Management Information System (HMIS). IRI is measured using instrumented vehicles (e.g., laser profilers) or other devices, and it quantifies road roughness in terms of vehicle suspension motion. However, Nepal's maintenance decisions did not heavily utilize IRI data initially. DOR's standard practice remained centered on SDI for prioritizing works, with IRI recorded but "not used to make extensive maintenance decisions" in most cases (Shrestha et al., 2023). One reason is that SDI, though subjective, directly captures observable surface distresses and has an established threshold-based planning framework (especially for routine and periodic maintenance). By contrast, IRI-based planning could recommend costlier interventions like overlays to improve smoothness, which may be impractical under budget constraints (Zhu et.al, 2020). Researchers have noted that in a low-budget context like Nepal, where many roads are in poor condition, exclusive reliance on IRI could trigger expensive rehabilitation needs, whereas distress-focused indices (SDI/PCI) allow targeting of localized repairs to fit limited budgets (Shrestha & Khadka, 2021). Ojha and Joshi (2020) also played a key role in the assessment of pavement condition in a tropical region of Nepal in Pokhara using various metrics that were currently in practice in Nepal. The operational speed, level of service, capacity and delay on the road is also influenced by the condition of the pavement along with other factors as indicated in a study (Kunwar et al., 2025).

To introduce a more comprehensive index, some studies have evaluated the Pavement Condition Index (PCI) in Nepal (Shrestha, 2023; Shrestha et al., 2024b). PCI is a 0–100 rating of pavement health based on detailed visual surveys of distress types, severities, and extents, commonly used in US (Greene et al., 2004). PCI is more labor-intensive to obtain than SDI, but it provides a nuanced picture of pavement condition. PCI is not routinely used in Nepal due to the "cumbersome procedure" of field surveys and calculations (Chandanshive et al., 2024). Nonetheless, Researchers have conducted a study to assess the relationship between pavement condition indicators whether in form of SDI PCI and IRI on Nepali roads, to explore whether one index could substitute or predict the other (Shrestha et al., 2024a). In that study, asphalt concrete road sections were surveyed to compute PCI (ASTM-6433, 2007)and IRI was measured using a smartphone-based tool (RoadRoid) calibrated against a Class I laser profiler. The researchers developed regression models correlating PCI and IRI; the best-fit was a polynomial model ($R^2 \approx 0.79$) showing a negative correlation, as roughness (IRI) increases, PCI (overall condition) decreases. This finding is intuitive and reinforces that ride quality degrades as surface distress worsens. The significance of this work is that it suggests either index could be used to infer the other to some extent, which is useful if only one type of data is available. Moreover, the authors argue that PCI could be advantageous for maintenance planning under budget constraints, because PCI reflects specific distress contributions and can guide more targeted repairs. This research further exemplifies the increasing technical focus on integrating multiple performance indicators in Nepal's pavement management. Vidya et. al,(2013) conducted some of the pioneer research to estimate the values of IRI from the calculated value of PCI and found promising results.

Another technical development has been the modeling of pavement deterioration and performance trends. In 2012, one of the first local studies on pavement performance was by Maharjan (2012), who developed an SDI-based deterioration model. Maharjan's model used time as the sole independent variable to predict SDI over a pavement's life, essentially estimating how long before a road reaches a certain distress level. Separate models were calibrated for the Terai plains vs. the Hill regions, acknowledging different climate and traffic conditions.

The study found that in the hot, humid Terai region, traffic loading was the dominant factor in pavement deterioration, whereas in the cooler Hill region, climatic factors (e.g., moisture) had greater influence. Maharjan also established a preliminary correlation between SDI and IRI, signaling an early attempt to relate Nepal's traditional index (SDI) with the international roughness standard. However, the Maharjan model was limited by considering only time progression and not explicitly incorporating traffic volume or environmental variables. This highlights a progression in technical sophistication: initial models were simplistic due to data limitations, but they set the stage for more complex models.

By the 2020s, researchers in Nepal began employing advanced statistical and machine-learning techniques for pavement performance modeling (Negi et al., 2024). Sigdel and Pradhananga (2021) developed an IRI prediction model for national highways. Their work was expanded by Sigdel et al. (2024) to include Artificial Neural Networks (ANN). In a peer-reviewed study, they built an ANN model to predict the evolution of IRI over time on Nepal's highways. The model used a comprehensive dataset (1,745 road sections, 3,710 observations) from DOR's HMIS covering five years of annual surveys. Input parameters included initial pavement roughness, annual traffic (AADT, including commercial vehicle counts), and climatic factors (rainfall and temperature) for each section. The ANN-based model achieved a high predictive accuracy (overall $R^2 \approx 0.82$), outperforming a traditional multiple linear regression model on the same data ($R^2 \approx 0.76$). When the data was stratified by region, the ANN's fit was even better, e.g., R^2 ~0.91 for Hill region and ~0.87–0.88 for Terai regions, capturing the different deterioration patterns in different climates and traffic regimes. Notably, sensitivity analysis of the ANN model revealed that the initial IRI of a pavement segment is the most influential predictor of future roughness, underscoring the importance of initial construction quality or condition. The second most important factors were climatic conditions (especially the number of high-temperature days) in most regions, and traffic intensity (commercial vehicle count) in high-volume highways. These findings are significant for Nepal, they quantitatively confirm that both environment and traffic load affect pavement longevity, and that data-driven machine learning models can improve prediction accuracy in the context of Nepal's roads (Sigdel et al., 2024). In parallel with ANN techniques, other advanced modeling approaches have been explored. Similarly, pavement condition index was explored and evaluated which provided with a general representation and model the condition of airport in Nepal (Kalika, 2021).

The study by Basnet et.al,(2025) developed a multiple linear regression (MLR) model to estimate pavement deterioration on a national highway in Nepal, using data collected over a 10-year period (2012–2022). The model considered five key variables: International Roughness Index (IRI), pavement age, annual rainfall, temperature fluctuations, and traffic load (ESAL). Results showed that the model could predict the Surface Distress Index (SDI) with reasonable accuracy, achieving an R^2 value of 0.73 and a mean absolute percentage error (MAPE) of 20.12%. Among the variables, pavement age and IRI had the greatest influence on SDI. This approach offers a practical and data-driven tool to support more efficient and cost-effective road maintenance planning. The study by Joni further aimed to develop a predictive model for pavement roughness, measured by the International Roughness Index (IRI), based on surface distresses in flexible pavements. A total of 83 road sections, each 250 meters long, were selected in Al-Diwaniyah, Iraq. Distress data were manually recorded by type and severity, while IRI values were obtained using the Dynatest Road Surface Profiler. Using stepwise multiple linear regression in SPSS, a model was created linking IRI to distress types such as polished aggregate, potholes, alligator cracking, patching, raveling, and corrugation. The results showed a strong correlation, confirming the model's reliability for predicting IRI from visible surface distresses (Joni et al., 2020).

A recent study by Shakya et al. (2025) introduced a Markov deterioration hazard model for Nepal's national highways. This probabilistic approach differs from deterministic models like HDM-4 or simple regressions. Shakya et al. utilized two years of SDI inspection data (2021–2022) from DOR's HMIS and incorporated cumulative monsoon rainfall as an explanatory variable in a hazard-based Markov chain model. The model computes transition probabilities of pavement condition states (SDI ratings) year-to-year, considering traffic and rainfall exposure. To obtain accurate rainfall inputs for each road segment, the study employed GIS-based spatial interpolation of meteorological data, comparing Inverse Distance Weighted (IDW) vs. Empirical Bayesian Kriging (EBK3D) methods for mapping monsoon rainfall across Nepal's road network. The EBK3D method yielded more accurate rainfall estimates (lower interpolation errors) than IDW, and those rainfall values were used in the Markov hazard model. The results demonstrated that integrating an environmental factor (rain) into the deterioration modeling significantly enhances predictive capability for a monsoon-prone country like Nepal(Shakya et al., 2025b). This aligns with global research emphasizing that moisture and poor drainage accelerate pavement damage. Shakya et al. also highlight that Markovian and Bayesian approaches are well-suited for developing countries where variability is high and data might be uncertain. Such probabilistic models can complement or offer an alternative to HDM-4's deterministic models, with potentially lower data requirements for calibration (Kobayashi et al., 2012).

A study summarizes reviews current approaches to predictive analytics in road condition forecasting, pointing out existing gaps and limitations. It discusses how these issues can affect the accuracy and usefulness of the predictions, and how newer, more advanced methods could help address them. While most researchers agree that predictive models are effective when factors like traffic, pavement age, and weather are considered, selecting the right model is key to getting reliable results. Understanding the pros and cons of each model helps ensure they're used appropriately. As predictive tools and technologies continue to improve, they hold great potential for better road maintenance and safer, more comfortable travel experiences (Basnet et al., 2023).

In summary, the technical toolkit for pavement management in Nepal has expanded from simplistic indices to sophisticated models like regression, ANN, and Markov that leverage increasing data availability and computational methods. Lastly, smartphone-based data collection represents a notable technical and technological innovation. The RoadRoid application, which uses a smartphone's accelerometer and GPS to estimate IRI, has been studied in Nepal as a low-cost alternative to expensive laser profilers. Shrestha & Pradhananga (2023) performed a calibration of RoadRoid on Nepali roads by comparing its IRI measurements against a high-grade laser profiler ROMDAS Z-250) over the same road sections. Using statistical goodness-of-fit tests, they found no significant difference between the RoadRoid-derived roughness distributions and the reference measurements. In other words, a properly calibrated smartphone can produce IRI values correlating at about 81% with class-1 profiler readings. This validation implies that road agencies in Nepal could utilize smartphone apps for routine roughness monitoring, dramatically cutting survey costs while still obtaining objective data (Shrestha et al., 2024b).

RoadRoid and similar apps (e.g., RoadBump) have even been used by the U.S. Federal Highway Administration for roughness analysis (Akinmade & Cinfwat, 2017). Embracing such technologies can particularly benefit countries like Nepal by increasing data coverage on secondary or local roads, where deploying expensive instruments are not feasible. The integration of these technical developments, improved indices, predictive models, and innovative data collection, is gradually enabling Nepal to transition from reactive maintenance to a more data-driven, proactive pavement management strategy.

A study which focused on creating a rutting prediction model that uses minimal input data, making it suitable for regions with limited resources and data availability, such as developing countries was carried out. Sensitivity analysis showed that traffic load and climate conditions have the most significant impact on rutting. To support broader application, the study also developed generalized rutting curves tailored to different traffic, climate, and performance scenarios, allowing road agencies to make reliable rutting forecasts even with limited data. (Hadad et al., 2021)

The study by Issa et.al, (2021) introduced an optimized hybrid model designed to estimate the Pavement Condition Index (PCI) using data from the FHWA Long-Term Pavement Performance (LTPP) database. The model uses a two-stage cascade approach, starting with three traditional machine learning models whose outputs are then fed into a neural network. This setup allows the neural network to focus on capturing complex nonlinear patterns, helping to improve prediction accuracy. To ensure the model's reliability, both cross-validation and out-of-sample performance tests were conducted. The results show that the hybrid model can predict PCI with a high level of accuracy and consistency (Issa et al., 2021).

A realistic prediction of pavement deterioration was recognized as essential for ensuring effective maintenance and smooth operation of road networks. In this study, pavement deterioration models were developed specifically for low-volume roads using a system dynamics approach. Pavement condition data from 14 low-volume roads in the state of Kerala, India, were utilized. The models were created using Powersim Studio version 10, allowing for a dynamic simulation of how pavement conditions changed over time and helping support more informed maintenance strategies (Sudhan et al., 2020).

The study by Sidess developed a model to predict pavement roughness deterioration using the International Roughness Index (IRI), based on structural factors like asphalt thickness, subgrade strength, and environmental conditions. Combining empirical-mechanistic and regression methods, the model was validated using data from different climate zones in Israel. The results showed strong agreement with actual IRI measurements, confirming its reliability for use in pavement management systems (Sidess et al., 2020).

2.2 Institutional and Policy Evolution in Road Maintenance Management

Institutional reforms and policy initiatives in Nepal have been fundamental in enabling more systematic pavement management. Before the 2000s, road maintenance was funded and executed traditionally, through general government budgets and project-specific allocations, often resulting in chronic under-funding of maintenance. There was a recognized need for a stable funding mechanism and better management of maintenance activities. This led to the establishment of the Roads Board Nepal (RBN) under the Roads Board Act of 2002 (2058 B.S.). RBN's creation was a pivotal institutional milestone, heavily influenced by collaboration between the Government of Nepal and the World Bank. The RBN was conceived as a dedicated road fund to provide sustainable financing for road maintenance, insulated from annual political budget fluctuations. Under the RBN Act, funding is secured through earmarked revenue streams, chiefly a fuel levy, road tolls, and vehicle registration fees. The Roads Board collects and manages these funds and allocates them to road agencies for maintenance works on a needs basis. This model was designed to ensure a stable, adequate flow of maintenance funds and to introduce accountability in their utilization. The Department of Roads (DoR) was designated as the main implementing agency for maintaining the Strategic Road Network (national highways and feeder roads), while local roads' maintenance is handled via the Department of Local Infrastructure (for rural roads, with coordination through local governments). Importantly, the RBN structure brings multiple stakeholders into decision-making, including government, private sector, and road users, aiming to foster a sense of ownership and transparency in maintenance management. In essence, the establishment of RBN in 2002 marked Nepal's shift towards a "second-generation" road maintenance regime, following models successfully applied in other countries. It addressed the earlier lack of institutional mechanism for sustained maintenance funding and signified recognition that maintenance must be treated as a continuous program rather than an intermittent project (*Road Maintenance Funds*, 2005).

Following RBN's formation, policy and planning tools were developed to effectively use the new funding. In 2005, the Department of Roads issued the "Standard Procedure for Periodic Maintenance Planning", a guideline document (prepared by the Maintenance Branch of DoR) that standardized how road condition data would be collected and used to prioritize maintenance on the Strategic Road Network. This policy explicitly adopted the Surface Distress Index (SDI) as the key parameter for maintenance decisions. Each year, with RBN financing, DOR carries out network-wide road condition surveys (recording SDI and IRI for each 1 km segment) and compiles an Annual Road Maintenance Plan (ARMP). The ARMP ranks road sections for maintenance (routine, recurrent, periodic, or rehabilitation) based primarily on their SDI ratings, along with traffic levels and economic considerations, as per the 2005 guideline. This one-year planning horizon, while useful, was acknowledged to have limitations (it focuses on immediate needs rather than multi-year optimization) (DOR, 2024).

Nonetheless, the institutionalization of annual condition surveys and planning was a major step forward, moving Nepal from reactive, ad-hoc repairs to a more systematic, data-informed maintenance programming. International donor agencies have played a significant role in Nepal's pavement management evolution. The World Bank not only aided the creation of RBN but also supported capacity building in data systems and planning tools. For instance, the World Bank's Road sector projects in Nepal introduced the use of the Highway Development and Management Model (HDM-4) (Thube, 2013) . HDM-4 is a software tool for analyzing pavement deterioration, maintenance effects, and life-cycle economics; it was developed under World Bank auspices and disseminated globally in the early 2000s. By the mid-2000s, Nepal's DOR had begun experimenting with HDM-4 for strategic planning (Jain et al., 2005) . However, full adoption of HDM-4 proved challenging. Calibration of the model's deterioration equations to Nepal's specific conditions (terrain, traffic, materials) is resource-intensive, and the data requirements (detailed inventory, condition history, costs) are high. Developing countries often face hurdles in sustaining such complex systems without continuous donor support. Indeed, neighboring countries like Bangladesh and India also use HDM-4, but typically as part of larger Road Management Systems supported by external funding and technical assistance (Caroff et al., 2001).

In Nepal, while HDM-4 has been used in feasibility studies and multi-year program development, its routine application in yearly planning was limited. The current practice, as noted, relies on simpler indices (SDI) and economic ranking formulas for short-term plans. Recognizing this, recent initiatives aim to integrate HDM-4 into a more user-friendly asset management framework (discussed in the next section on technology). Another key donor, JICA (Japan International Cooperation Agency), has contributed significantly, especially in capacity development. JICA has a long history in Nepal's road sector, from constructing major highways to technical cooperation in maintenance. One notable example is the Sindhuli Road project, after whose completion JICA provided technical assistance for maintenance management on that and other roads(Kamie, 2019). This included training DoR staff in maintenance planning and introducing Japanese best practices, resulting in "significant improvements in road administration in Nepal". JICA also initiated a Road Asset Management Platform in 2017, aimed at sharing knowledge and supporting road asset management across several countries, including potentially Nepal (JICA, 2017).

2.3 Technology Adoption Trends: RAMS, GIS, HDM-4, and Smart Tools

The progression of pavement management in Nepal has been closely linked with the adoption of new technologies and systems for data handling and decision support. One of the earliest such systems was the Highway Management Information System (HMIS) established within the Department of Roads. HMIS functions as a database for the Strategic Road Network, recording road inventory, traffic, and annual condition data (SDI, IRI, etc. (DOR 1995). By digitizing and centralizing this information, HMIS has been the backbone for analysis and planning. For example, data from HMIS was used to develop the regression and ANN models for IRI prediction in recent research, covering thousands of km of highways and several years of observations. Having such a repository was a prerequisite for Nepal's researchers and planners to move beyond anecdotal assessment to network-level performance modeling. Building on HMIS, there is a current drive to implement a more comprehensive Road Asset Management System (RAMS) that integrates GIS (Geographic Information System) mapping and analytical tools like HDM-4 (Thube, 2013). In 2024, under the World Bank-funded Strategic Road Connectivity and Trade Improvement Project (SRCTIP), the DoR launched a procurement for the development of a web-based RAMS integrating HDM-4 with the existing Annual Road Maintenance Plan process (*The Consultancy Service for the Developing and Imp...*,2024). The objective is to create a modern platform where road network data, including geospatial information, is combined with HDM-4's modeling capabilities to improve multi-year maintenance programming. The tender for this RAMS explicitly mentions using DOR's current ARMP system as the foundation and building a web-based interface around it. This indicates that while the annual planning mechanism (ARMP) is in place, the tools to extend it into a multi-year, scenario-based analysis (which HDM-4 offers) and to visualize results on a map are being added. The RAMS is expected to allow GIS-based visualization of road conditions and maintenance plans, enabling planners to see the spatial distribution of pavement conditions and works. It should also help optimize resource allocation over a longer horizon by analyzing different maintenance strategies' impacts on network condition and user costs (HDM-4's forte). The inclusion of GIS is significant, Nepal's topography and climate vary sharply by location, and GIS layers (such as rainfall, terrain, or subgrade types) can be overlapped with the road network to inform maintenance needs (Krivoruchko, 2012). Recent research underscores this benefit: for instance, Shakya et al. (2025) used GIS interpolation of rainfall data to assign climate exposure values to each road link, which was vital in their deterioration model.

Another technology trend is the growing use of mobile and sensor technology for pavement data collection. The Roadroid smartphone app, as noted earlier, is one such tool that has garnered interest (Lars Forslöf & Hans Jones, 2015) . In Nepal, traditional road condition data collection involved teams of engineers conducting visual surveys for SDI (and manual roughness measurements like riding quality, before profilers were available). This is laborious and can be inconsistent due to subjective judgment. The introduction of laser-based roughness profilers provided objective IRI data, but the cost of those devices and operation limits their use to major highways on an infrequent basis. Smartphone-based roughness measurement offers a leap in coverage and frequency (Putra & Suprapto, 2018).

The fact that even the U.S. FHWA has experimented with RoadRoid attests to its viability (FHWA, 2019). Nepal's context makes such low-cost innovation extremely attractive for scaling up pavement monitoring. It is conceivable that soon, each Division Road Office could be equipped with a smartphone or two and tasked to survey their network's roughness annually, feeding data into the central RAMS. This would vastly improve the data pool for planning, allowing trend analysis of deterioration rates on various routes. In addition to roughness, other mobile-based tools and GIS mapping of distress are being explored. While specific studies in Nepal on those are not yet prominent, the infrastructure is being laid. Improved internet connectivity and GPS coverage in Nepal make it feasible to crowdsource some pavement condition information in the future (through driver feedback apps, etc.)(Negi et al., 2024). Already, DOR's use of GIS in mapping the road network is evident, the HMIS "road register" is now available online with geographic referencing. A noteworthy adoption has been in contracting practices: Nepal has piloted performance-based road contracts that use IRI as a performance indicator. As Shrestha et al. (2024) report, IRI-based contracts have been implemented on some major highway projects, such as an improvement project on the East–West Highway with a 4-year maintenance period. In such contracts, the contractor is responsible not only for construction but also for maintaining the road at or below a certain IRI level for several years. This pushes for better initial quality and timely repairs. The fact that Nepal undertook IRI-based contracting shows an appreciation for outcome-driven maintenance and the necessity of measurable service levels. However, scaling this model broadly is challenging when many roads already have poor ride quality and the maintenance budget is limited (Shrestha, 2023). The relationship of different distresses with IRI was initially explored by Prasad et.al, (2013).

This study is organized as a narrative review of available literature and documented practices concerning pavement management in Nepal. We adopted a multi-step methodology to ensure a comprehensive and rigorous review:

3. Results

This section presents the synthesized findings of our review, detailing how pavement management approaches in Nepal have changed over time across the three dimensions: technical methods, institutional framework, and technology tools. For clarity, we organize the results partly in chronological order, highlighting key phases and milestones. Table 1 provides an overview of major developments, and the subsequent text elaborates on each.

Table 1. Chronology of Key Developments in Pavement Management in Nepal

Year/Period	Development/Initiative	Description & Significance
Mid-1990s	Maintenance & Rehabilitation Coordination Unit (MRCU) and initial guidelines	DoR established MRCU and drafted early pavement management documents (e.g., 1995 discussion paper). Introduced the concept of SDI (0–5 rating) under World Bank guidance, laying groundwork for standardized condition assessment.
2002	**Roads Board Nepal (RBN)** established	Created under Roads Board Act 2058 with World Bank support. Provides sustainable maintenance funding via fuel levy, tolls, etc. Marks shift to a dedicated road fund and stakeholder-inclusive governance of road maintenance.
2005	**Periodic Maintenance Planning Standard** issued	DoR Maintenance Branch published standard procedure focusing on SDI as the key criterion for annual maintenance planning. Instituted annual road condition surveys (SDI & IRI) and preparation of Annual Road Maintenance Plans (ARMP). Formalized data-driven prioritization for the Strategic Road Network.
Mid-2000s	Introduction of **HDM-4** tool	Through donor projects, HDM-4 (Highway Development & Management Model) was introduced for evaluating pavement strategies. Used in strategic analyses, but full integration limited by calibration and data challenges. Highlighted need for long-term planning beyond 1-year ARMP.
~2010–2012	**Highway Management Information System (HMIS)** enhancement & IRI data collection	DoR's HMIS began systematic yearly roughness (IRI) measurements on national highways. Acquired laser profilers (e.g., ROMDAS) enabling objective condition data. IRI data (2012–2016) archived for ~3,397 km of highways. However, IRI not yet used in routine decision-making.
2012	SDI Deterioration Models	First known local research on pavement performance: regression model of SDI vs. time for Terai and Hill roads. Found traffic dominates Terai deterioration, climate more in Hills. Also noted correlation between SDI and IRI. Provided initial analytical insight, though lacking multivariate factors.
2017	JICA's Road Asset Management Platform (JRAMP) & Training	JICA launched a platform to support road asset management and initiated capacity-building programs for Nepali engineers. Continued technical cooperation (e.g., maintenance management training on Sindhuli Road) leading to improved practices.
2019–2021	Performance-Based Contracts and Preliminary IRI Models	Nepal experimented with IRI-based performance contracts (e.g., East–West Highway 4-year maintenance). Sigdel & Pradhananga (2021) developed an initial IRI prediction model (regression) using HMIS data (presented at IOE Conference). Signaled rising use of IRI in both contracting and academic modeling.
2023	Shrestha & Pradhananga – **Roughness vs. Distress Model**	Study calibrated **Roadroid** smartphone app with laser profiler, confirming its accuracy for IRI measurement in Nepal. Developed a model relating road distresses (visual survey data) to IRI, bridging subjective and objective measures. Demonstrated feasibility of low-cost roughness monitoring and linking PCI/SDI with IRI (Shrestha, et al., 2025).
2024	Sigdel, Pradhananga, Shrestha – **ANN IRI Prediction**	Published in *Transportation Research Interdisciplinary Perspectives*, this work built an ANN model for IRI progression on 1,745 sections (2012–2016 data). ANN achieved R^2=0.82 (vs 0.76 for linear model) for overall network; region-specific models R^2 up to 0.91. Highlighted importance of initial condition, climate (temperature, rainfall), and traffic in roughness performance. Established state-of-art predictive capability for Nepal's pavements.
2024	Shrestha et al. – **PCI vs IRI Correlation**	Published in *Int. Journal of Engineering Technology*, investigated correlation between PCI (0–100) and RoadRoid-derived IRI on Nepali roads. Found strong negative correlation (best-fit polynomial R^2≈0.79). Concluded PCI (detailing distress types) can

Year/Period	Development/Initiative	Description & Significance
		complement IRI and that using PCI could be advantageous for budget-limited maintenance planning. Introduced PCI methodology to Nepali context as a more objective alternative to SDI.
Late 2024	**Web-GIS Road Asset Management System (RAMS)** project	Under World Bank SRCTIP, DoR tendered consultancy to develop a web-based RAMS integrating **HDM-4** with its ARMP process. Financed by WB, due for implementation 2024–25. Aims to provide GIS visualization of road conditions and optimal multi-year maintenance planning. Marks a significant institutional adoption of modern RAMS software.
2025	Shakya et al. – **Markov Deterioration Model with Climate**	Published in *Infrastructures (MDPI)*, applied a Markov hazard model to SDI transition for 2021–22 data. Incorporated **cumulative monsoon rainfall** via GIS-based interpolation (EBK3D) as a predictor. Demonstrated improved modeling of pavement deterioration by including environmental factors and using Bayesian updating. Suggests probabilistic models for long-term planning under uncertainty.

As Table 1 and the preceding literature review indicate, Nepal's pavement management journey can be broadly divided into phases:

3.1 Initiation and Standardization (1990s–mid 2000s): During this phase, Nepal recognized the need for systematic maintenance management. With input from international experts, the Surface Distress Index was adopted and a dedicated road fund (RBN) established in 2002 to ensure regular maintenance financing. The 2005 maintenance planning guidelines cemented SDI-based annual planning as a standard. By the end of this phase, institutional structures like RBN, Maintenance Branch, HMIS beginnings and basic policies were in place to manage pavement upkeep more proactively than before.

3.2 Data Collection and System Building (mid 2000s–2010s): This phase saw the ramp-up of data and tools. The HMIS was populated with inventory and condition data across the Strategic Road Network. Annual surveys measuring SDI (and later IRI) became routine. DOR divisions were conducting these surveys and forwarding data to the center, supported by RBN funds. Technologically, Nepal tested HDM-4 for planning, though not fully operationalized due to complexity. Importantly, the culture of relying on data, even if just SDI, for maintenance decisions took root in DOR during this time. By 2012, the availability of several years of consistent data (including roughness) allowed the first analytical studies to emerge, as well as internal assessments of network condition trends which likely informed budgeting and policy dialogues (Maharjan, 2012).

3.3 Analytical and Pilot Innovations (2010s): With data in hand, researchers and the DOR experimented with improving practices. The idea of combining IRI with SDI for decisions was floated; some large projects introduced IRI-based performance contracts to guarantee smoother roads. Although SDI remained the principal index for routine planning, there was growing awareness of its subjectivity and limitations. This led to pilot studies: e.g., calibrating smartphone apps for roughness (to supplement expensive profilers), and computing PCI for sample roads to compare against SDI. International collaboration increased – Nepalese professionals attended training in pavement management (often in Japan or other countries via JICA/World Bank programs), bringing back knowledge of GIS, RAMS, and advanced models. Institutionally, RBN had been operating for over a decade by 2015, and its impact was seen in somewhat improved road maintenance outcomes, though challenges of adequate funding persisted.

3.4 Modernization and Integration (2020s): Nepal is currently in this phase. Academic research by often in partnership with universities, has provided cutting-edge insights (ANN models, Markov models) tailored to Nepali roads. The government, on its part, is investing in modern systems: the upcoming web-based GIS-enabled RAMS will institutionalize many advances (multi-year analysis, HDM-4 optimization, interactive mapping). The incorporation of climate factors, as seen in recent research, is likely to influence future policy (e.g., prioritizing maintenance in high-rainfall areas, designing climate-resilient pavement structures). Data collection is also being enhanced: if smartphone roughness measurements and perhaps even automated distress surveys (via drones or vehicle-mounted cameras) are embraced, the volume and frequency of pavement condition data will increase dramatically. This, combined with AI/ML analytical tools, sets the stage for Nepal to implement a true Pavement

Management System (Shrestha, et al., 2025) approaching international standards, albeit adapted for local constraints(FHWA, 2001; Hawks & Teng, 1993; Hossain et al., 2019; McGhee, 2004). Crucially, throughout these phases, one can see the interplay of the three dimensions: technical knowledge grew (from SDI to PCI, from linear models to ANN) often spurred by institutional support and policies (RBN funding surveys, donor projects pushing new methods), and enabled by technology acquisition (profilers, HMIS software, GIS, etc.). The results highlight that progress was not linear or without setbacks, but overall, the trajectory has been towards more sophisticated, data-driven, and forward-looking pavement management in Nepal.

4. Discussion

The historical trajectory outlined in the Results reveals how Nepal's pavement management approaches have matured by mutually reinforcing advances in technology, policy, and analytical techniques. In this section, we discuss the implications of these findings, analyze the interconnections between the three dimensions, and compare Nepal's experience with global practices. We also interpret how these developments have translated into real-world outcomes (e.g., road network conditions) and what lessons can be drawn. Integration of Technical and Institutional Advances: One clear pattern is that institutional reforms often paved the way for technical improvements. The establishment of Roads Board Nepal (RBN) in 2002 created not just a funding source but also a mandate for systematic maintenance management. With stable funds, the DOR could institutionalize annual condition surveys and adopt data-driven planning in 2005. In turn, the data collected (SDI, and later IRI) enabled technical analysis.

Had RBN and the planning policy not been in place, such data might not exist or be reliable. Conversely, technical findings have begun to influence policy. The realization that SDI alone might be insufficient – being subjective and coarse-scaled – has led to calls for including other indices like IRI or PCI in decision-making. We see early adoption of this in performance-based contracts using IRI targets, a policy shift recognizing roughness as a serviceability measure. Additionally, research demonstrating the impact of climate on pavement life (Shakya et al., 2025b) may well prompt policy moves towards climate-adaptive maintenance planning (e.g., considering resilience measures or adjusting intervention criteria in monsoon-prone areas). Thus, the technical and institutional dimensions in Nepal have a feedback loop: institutions facilitate data and trials, which produce evidence that institutions can use to refine strategies. Initially, deterministic models (like regressions or HDM-4) were the main tools. HDM-4 itself, used worldwide, is deterministic and requires tailoring to local conditions. Nepal faced difficulties with this, like other developing countries, due to calibration challenges and resource needs. The recent turn to probabilistic models (Markov chains with hazard modeling) by Shakya et al. shows Nepal exploring alternative approaches that can explicitly handle uncertainty and variability. Probabilistic PMS models (often implemented via Markov processes) have been used in countries like the USA or Japan for long-term network predictions under uncertainty. Nepal's application of a Markov hazard model, especially integrating Bayesian updating, is quite advanced and suggests that the country's researchers are aligning with state-of-the-art practices. The benefit of such models is their ability to work with limited or variable data by treating deterioration as a probability distribution rather than a fixed progression (*Forecasting the Unseen: Enhancing Tsunami Occurrence Predictions with Machine-Learning-Driven Analytics*, 2021.; Raftery et al., 2013; Sun et al., 2025).

This can be more forgiving of the data quality issues that are common in developing contexts. It is noteworthy that the Markov model study was in collaboration with Japanese academia, hinting at technology transfer and capacity building through international partnerships. The discussion point here is that Nepal is diversifying its analytical toolkit, and the eventual PMS might well combine deterministic methods (e.g., HDM-4 for economic analysis of alternatives) with probabilistic forecasting (for long-term condition predictions and risk assessment). Use of Composite Indices vs. Simpler Indices: Historically, Nepal stuck with a simple index (SDI) that is easy to measure but is somewhat subjective. Many countries use composite indices like PCI, which are more informative but also more labor-intensive(Basnet et al., 2023; Shrestha, 2023; Shrestha et al., 2024b; Sigdel et al., 2024) . The review of these works shows a nuance: in a developing country context, a highly detailed index like PCI might not always be practical or even necessary for every situation, especially if budgets only allow modest interventions. Shrestha et al. argue that PCI, by identifying specific distress types, could help target maintenance better under tight budgets. However, they also found a decent correlation between PCI and IRI, and given that IRI is already being measured, one could leverage IRI) as a proxy for general condition while using SDI to flag specific issues. In practice, Nepal's approach might evolve towards a dual-index system: using IRI as a network-level screening tool and SDI/PCI as a project-level diagnostic tool.This would mirror practices in some countries where roughness triggers a closer look, and a pavement condition index then informs the maintenance action. The ongoing RAMS development could institutionalize this by storing multiple indices for each road segment and providing decision rules on how to use them. For example, a high IRI and a moderate SDI might indicate a structurally sound but uneven surface, possibly requiring an overlay, whereas a high SDI with low IRI might indicate localized failures needing patching. The integration of indices is a key discussion point, and Nepal's researchers are pushing for it. Role of Funding and Donor Dependency: The case of Nepal highlights how critical funding is in pavement management. The Roads Board Nepal has been a linchpin, but even RBN's resources have often been described as "much too small to meet maintenance needs" in policy discussions. The backlog of maintenance, exacerbated by years of underfunding pre-RBN, means Nepal is in a catch-up game. This context explains some of the choices: for instance, why IRI wasn't used extensively, because if most roads are in poor shape, an IRI-based analysis might suggest reconstruction or heavy rehab that simply can't be funded (*Introduction | Road Board Nepal*, 2021; *Source Of Revenue | Road Board Nepal*, 2021).

Therefore, engineers stuck to patching what they could, guided by SDI which prioritizes worst distresses. As funding improves (if RBN's fuel levy is increased or donor support comes in), the strategy might tilt more towards preventive maintenance on fair roads to stop them becoming poor, which is where IRI can be very useful (maintaining ride quality). Donor influence is a double-edged sword: it has brought in expertise and systems like HDM-4, but it can also lead to stop-start implementations if local ownership is lacking. For example, earlier attempts to use HDM-4 may have dwindled after project completion. The current RAMS effort, being embedded in DOR's own planning process, seems designed to avoid that by fully integrating with what DOR already does (ARMP). This is a positive development, indicating lessons learned: new systems must be assimilated into the agency's workflow rather than run in parallel by consultants. JICA's continued engagement through training and technical assistance has helped with capacity we see senior Nepali officials and young engineers alike being educated in modern infrastructure management, which increases the likelihood that advanced methods will actually be utilized(*Preparatory Survey on Intersection Improvement Project in Kathmandu* ｜ *About JICA - JICA*, 2025.).

Another area is possibly the use of drones for surface imaging; while not documented in this review for Nepal, it's emerging globally and Nepal could adopt it given its difficult terrain. The integration of GIS is a leap from paper maps to digital layers on the web, which will greatly aid multi-criteria decision analysis (considering factors like proximity to markets, social importance of roads, etc., in maintenance planning). In the discussion, it's worth noting that Nepal's small size (in terms of network and institutional structure) can sometimes allow faster adoption of new tech than very large countries, there are fewer bureaucratic layers (*GIS and Pavement Management: A Concrete Relationship*, 2021). If the web-based RAMS is successful, Nepal could become a model for other South Asian countries in how to implement a national-scale road asset management with modern tech on a limited budget. The condition of Nepal's road network today is a result of all these efforts (and gaps). According to some recent reports and anecdotal evidence, the condition of the Strategic Road Network has improved in terms of proportion in "good/fair" condition since the early 2000s, but there is still a significant portion in poor condition due to funding shortfalls and natural disasters (floods, earthquakes). The introduction of planned maintenance reduced the extreme neglect somewhat, but periodic maintenance cycles are still longer than ideal. The discussion can surmise that roads which received regular maintenance through ARMP are performing better (slower deterioration) than those that did not , a validation of the pavement management approach. However, the backlog of rehabilitation (roads already in very bad shape that need reconstruction) remains high, which is beyond the scope of normal maintenance and requires capital projects. This is a common scenario in developing countries: maintenance systems help keep the fair roads fair, but without enough money to fix the bad roads, the network-level indicators improve slowly. In international comparison, Nepal's pavement management system is roughly where many countries were in the 1990s-2000s, i.e., establishing basic PMS functions, but it's rapidly incorporating 2020s technology in doing so. Countries like the United States have had PMS since the 1980s and are now moving into AI and big-data analytics. Nepal is simultaneously grappling with basics (inventorying roads, ensuring routine maintenance is done) and advanced questions (like ML models, climate adaptation). This dual challenge is both an opportunity and a strain on the institutions. The discussion highlights that capacity building is crucial: without enough trained personnel who understand both the fundamentals of pavement engineering and the new tools (ANN, GIS, etc.), the full benefits won't be realized. The literature shows promising signs, young Nepali scholars contributing research, and continuing donor support in training. To sum up the discussion: Nepal's historical experience in pavement management underscores the importance of aligning policy, practice, and science. When these are aligned as in the case of the ARMP process supported by data and funded by RBN, the outcome is a more rational allocation of scarce resources and generally better road conditions

5. Challenges

Despite the progress documented, Nepal faces several challenges in fully implementing effective pavement management. These challenges span technical, institutional, and operational domains:

5.1 Funding Constraints and Backlog: The most persistent challenge is the insufficiency of funding relative to maintenance needs. While Roads Board Nepal has provided a dedicated stream, the budget is still "much too small" to cover all required maintenance. The road network expanded significantly in the last two decades (including many new rural roads and upgraded highways), but maintenance funding did not keep pace with the growing asset base. This results in a backlog where many road sections remain in poor or bad condition, awaiting major rehabilitation. The ARMP process has to prioritize within limited funds, often deferring resurfacing or reconstruction that is needed. Over time, deferred maintenance leads to more rapid deterioration (a classic vicious cycle) and ultimately higher costs. Thus, funding shortfall is both a cause and consequence of deteriorating pavements, a challenge that is as much economic as it is technical. Securing increased funding (through higher fuel levies, government budget allocations, or donor grants) remains a constant struggle. Moreover, RBN's success hinges on political support to maintain or raise these levies, which can be unpopular.

5.2 Data Gaps and Quality Issues: Although Nepal has instituted annual surveys, the quality and consistency of pavement condition data can be a challenge. SDI, being visual, can vary based on the judgment of the surveyor. Training and calibration of survey teams are needed to ensure ratings are uniform across districts and years. IRI measurements with profilers require calibration and maintenance of equipment; any lapses can result in erroneous data. With the introduction of smartphone measurements, ensuring each phone is calibrated to yield comparable IRI is an issue. There are also data gaps on local roads: the discussions and systems (HMIS, ARMP) largely cover the Strategic Road Network (SRN), but Nepal's Local Road Network (LRN), rural roads under local governments, is extensive and often in worse shape. Data on LRN conditions is sparse or non-standard. While RBN channels some funds to local bodies, the lack of a comprehensive inventory and condition assessment for rural roads is a major challenge for holistic pavement management. It means that outside the SRN, maintenance is still ad-hoc and reactive.

5.3 Human Resource and Capacity Limitations: Implementing advanced pavement management approaches requires skilled human resources – pavement engineers, data analysts, and software operators. Nepal's Department of Roads and related agencies face capacity limitations. Frequent transfers of government engineers can disrupt continuity; those trained in HDM-4 or GIS might be moved to another post. There is also the issue of retaining skilled staff – government pay scales can make it hard to retain experts in IT or data science who are increasingly needed for RAMS and ML tools. As a result, some sophisticated analyses might currently depend on external consultants or researchers on short-term projects, rather than being institutionalized. Bridging this gap involves ongoing training programs and perhaps creating dedicated units or positions focused on pavement management (so that expertise can be concentrated). Encouragingly, the Maintenance Branch and HMIS Unit exist, but their staffing and empowerment need to be strong enough to lead the change.

***5.4 Technology Sustainability and Integration*:** Adopting a new technology is one challenge; sustaining its use and integrating it into daily operations is another. For example, the web-based RAMS being developed will likely introduce new software and workflows. Ensuring that this system doesn't fall into disuse after the consultant handover requires proactive measures: extensive training, user-friendly design, and demonstrating value to the decision-makers. The challenge of system integration is real, the RAMS must interface with existing databases (HMIS) and perhaps with budgeting systems. Past instances (noted anecdotally) in some countries include PMS software being installed but rarely used because engineers stuck to their old Excel sheets or manual methods due to ease or habit. Nepal must overcome institutional inertia to truly embed RAMS and HDM-4 analyses into its annual and multi-annual planning cycles. This might involve mandating the use of RAMS outputs in project proposals or RBN funding decisions, thereby forcing the adoption.

5.5 Terrain and Climate Challenges: Nepal's geography – from high mountains to flood-prone plains – poses technical challenges in pavement management. The extreme variability in conditions means deterioration models have to account for very different mechanisms (freeze-thaw in alpine areas vs. submergence and heat in tropical areas). It's challenging to collect data in remote mountainous regions; condition surveys might miss certain sections due to inaccessibility (landslides or snow blocking roads during survey season). Maintaining consistency in indices across such varied contexts is difficult. Furthermore, climate change is an emerging challenge – more intense rains, extended monsoons, and extreme weather events (landslides, flooding) can rapidly damage roads and invalidate standard deterioration predictions. For instance, a road could be in good condition one year but be devastated by a single landslide or flood event the next. Such stochastic damage is hard to predict and manage in a PMS framework that assumes gradual deterioration. It calls for integrating disaster risk considerations into pavement management: ensuring good drainage, slope protection, and having emergency maintenance funds.

5.6 Monitoring and Enforcement: Ensuring that maintenance works are carried out with good quality is another challenge. A plan and funds do not automatically translate to outcomes if execution is poor. In Nepal, like elsewhere, issues of contractor capacity and quality control can result in suboptimal maintenance (e.g., thin overlays that don't last, patching that fails quickly). Without proper monitoring, the benefit of a PMS can be lost (Park et.al, 2007). For instance, if HDM-4 says a section needs resurfacing and it is done, but the workmanship is bad, the road might deteriorate faster than predicted. This complicates the model calibration and trust in the system. Strengthening supervision, possibly through independent audits or involving local user committees, a practice in Nepal for rural roads, is necessary to ensure maintenance interventions meet standards.

6. Recommendations

Based on the historical review and the challenges identified, we propose the following recommendations to enhance pavement management in Nepal:

6.1 Increase and Secure Maintenance Funding: To address the funding gap, Nepal must increase the financial resources for road maintenance. This could involve revising the fuel levy rates (under RBN's purview) to be commensurate with maintenance needs and inflation. Evidence from other countries' road funds suggests that small surcharges on fuel can generate substantial revenue dedicated to roads. Additionally, advocating for a higher share of the government's infrastructure budget towards maintenance (as opposed to new construction only) is crucial – the classic "fix-it-first" policy. Since the economic returns on maintenance are very high (preventing road deterioration saves user costs), making this case with data can help. The HDM-4 analysis capability once integrated can be used to show economic losses if maintenance is underfunded, strengthening the argument for more funds. Moreover, maintaining donor support for maintenance (e.g., World Bank and ADB loans that include maintenance components) for the next decade can help bridge the gap while domestic funding mechanisms are strengthened. RBN should also explore innovative funding like tolls on high-traffic corridors, public-private partnerships for maintenance of certain highways, and output/performance-based contracts that may leverage private financing(Arianto et al., 2018; McGhee, 2004; Setiadji et al., 2019; Suryoto et al., 2017).

6.2 Continue Capacity Building and Institutionalize Training: To tackle human resource limitations, a structured capacity development program is recommended. This could establish a "Pavement Management Cell" within DoR or RBN with a clear mandate and dedicated staff specializing in RAMS, data analysis, and pavement engineering. These staff should undergo regular training. Partnerships with universities (both domestic like Tribhuvan University's Institute of Engineering, and international) can be leveraged to run short courses or certification programs in pavement management. It's also recommended to retain trained personnel by providing incentives or clear career pathways for those with specialized skills so that the investment in training is not lost. Institutional memory can be improved by developing manuals or standard operating procedures for the new RAMS, HDM-4 calibration, survey methods, etc., ensuring that even if specific individuals transfer, the practice can be picked up by successors .

***6.3 Integrate Multi-Index Decision Framework*:** Nepal should formalize a decision framework that utilizes multiple pavement performance indices in a complementary manner. Concretely, we recommend the Department of Roads adopt a policy where both SDI and IRI thresholds are used for maintenance triggers. For example, a section might be scheduled for periodic maintenance if SDI ≥ 3 (major distresses) or IRI ≥ a certain value (say 6 m/km) even if SDI is low (meaning the surface is becoming rough due to minor unevenness). Similarly, if feasible, incorporate PCI surveys on sample stretches or critical roads to gather more detailed information, perhaps RBN can fund a pilot where a few key highways get annual PCI evaluation by a consultant or university team. The correlation models developed can be used to estimate PCI from IRI for planning purposes, as suggested by Shrestha et al., but ground-truthing with some actual PCI data will improve confidence. The outcome would be a more robust prioritization: roads with high roughness and those with significant distresses both get attention. The ARMP guideline can be updated to reflect this multi-criteria approach, moving beyond the single-index (SDI) emphasis of the 2005 guideline.

6.4 Leverage Low-Cost Technologies for Data Collection: We recommend a wide deployment of smartphone-based roughness surveys (e.g., Roadroid) across the network. Given the successful calibration and validation of Roadroid in Nepal, DOR can equip each Division Road Office with the necessary tools (a smartphone with the app and a mount for vehicles) and training. A protocol should be developed for how to conduct the surveys (speed, times of day, calibration checks) to ensure consistency. If every division collects IRI data on all their blacktop roads annually using this method, the central HMIS will receive a much richer dataset. Similarly, explore other technologies: for instance, GIS mapping of potholes or cracks via community reporting or drone imagery in critical areas. While sophisticated AI-based crack detection might be long-term, an intermediate step could be a simple mobile app for engineers to photograph and log distresses with GPS coordinates, feeding into a GIS layer. Since Nepal has mountainous regions, consider equipping maintenance teams with tablets with GIS maps so they can mark locations of observed issues in real time. By embracing these low-cost tech solutions, Nepal can significantly reduce the data scarcity on secondary roads and improve timeliness (data updated more frequently than the current annual cycle, maybe semi-annual for critical roads).

6.5 Enhance Climate Resilience in Pavement Management: Considering findings that rainfall and climate factors markedly affect Nepal’s pavements, incorporate climate resilience measures into pavement management.

This means two things:

(a) Include climate risk in the RAMS decision rules – e.g., sections in high-rainfall or landslide-prone zones might be prioritized for interventions like sealing cracks (to prevent water intrusion) or improved drainage, even if their current SDI/IRI is moderate. The Markov hazard model with rainfall provides a basis to quantify the risk; those probabilities can be translated into maintenance priority scores.

(b) Invest in engineering measures that make pavements last longer under extreme weather: better drainage systems, slope stabilization, use of moisture-resistant materials or additives in asphalt (like polymer modifiers), and properly designed culverts. RBN and DoR could allocate a portion of maintenance funding specifically for preventative maintenance just before and after the monsoon (pre-monsoon check for drain clearance, post-monsoon patching). Additionally, coordinate with the Department of Hydrology and Meteorology to get real-time data feeds into RAMS; perhaps even develop a warning system for road sections (for example, if a weather station reports extremely high rainfall, automatically flag nearby road segments for inspection). These steps will help reduce climate-related road failures and align with broader government goals of infrastructure resilience.

6.6 Expand Pavement Management to Local Roads: While the focus so far has been on national highways, it is recommended to extend pavement management principles to provincial and local road networks. RBN and DoR can play a mentoring role here. For instance, develop a simplified PMS toolkit for local governments, this could be an Excel-based tool or a mobile app that allows a local engineer to rate their roads (maybe using a simplified PCI or just roughness class) and prioritize maintenance. Since not all local bodies have engineers, RBN could fund a provincial-level maintenance support unit that helps clusters of local governments. This is crucial because local roads (earthen or graveled, many being upgraded to low-cost blacktop) often degrade quickly and investments are wasted without maintenance. A start could be to pilot a Local Road Asset Management System in one province, demonstrating how inventory and condition surveys can guide local road maintenance effectively. Given JICA’s involvement in rural road safety and ADB’s involvement in feeder roads, those agencies might support such pilots. The eventual goal is a nationwide asset management culture: every road, whether national or local, is monitored and maintained methodically.

6.7 Monitoring, Evaluation, and Adaptation: Finally, we recommend establishing a strong monitoring and feedback mechanism for the pavement management system. This includes periodic audits of the ARMP outcomes, e.g., each year, review a sample of roads that were maintained in terms of improvement of pavement condition as expected and the verification of deterioration rate with results predicted from the model. Use these evaluations to calibrate models like HDM-4 and ANN with local performance data (this calibration loop is often neglected). Monitoring should also track the performance of contractors on maintenance works; introducing performance incentives or penalties could improve quality. Additionally, maintain a research collaboration between practitioners and academics: for example, allow research teams to access HMIS data (with appropriate agreements) so they can analyze and provide suggestions (as was done in the ANN and Markov studies). This creates a culture of continuous improvement where the PMS is not static but adapts based on new data and insights. As new technologies emerge Nepal's system should be open to integrating them. By keeping an eye on innovation and having a formal channel (perhaps an RBN technical committee or a university partnership) to test and incorporate these, Nepal can remain at the cutting edge relative to its resources. Implementing these recommendations would help Nepal consolidate the gains made so far and overcome current challenges. They emphasize sustainability, both financial and institutional, and the smart use of technology and data. In essence, the recommendations aim to ensure that the pavement management approaches in Nepal become more proactive, comprehensive, and resilient, thereby delivering safer, smoother roads for the public and better value for money in infrastructure spending.

7. Conclusion

Nepal's experience with pavement management over the past several decades illustrates a journey from rudimentary practices towards a more systematic, technology-informed, and data-driven approach. This historical review has highlighted three critical dimensions of that journey: technical developments in performance modeling and condition assessment, the evolution of institutional frameworks and policies, and the adoption of modern tools and technologies. Technically, Nepal has moved beyond reliance on simple visual indices (like the 0–5 SDI) to embrace a broader set of performance measures and predictive models. The integration of IRI measurements into routine monitoring and the introduction of advanced modeling techniques like ANN tailored to Nepal's context are significant.

These efforts are bringing Nepal's pavement engineering knowledge closer to global best practices, while addressing local challenges such as monsoon impacts and constrained budgets. Institutionally, the creation of Roads Board Nepal in 2002 stands out as a turning point. It introduced sustainable financing and accountability for road maintenance, enabling planned interventions rather than crisis response. Complementary policies, like the 2005 standard maintenance planning procedure focusing on SDI, established a repeatable process for prioritizing works. International partnerships (World Bank, JICA, ADB) have been instrumental, not only in funding but in transferring knowledge and systems. The collaborative nature of Nepal's progress (with foreign-aided projects and local implementation) underscores that institutional evolution and technical capacity-building must go hand in hand. As a result, Nepal today has a defined mechanism for maintenance planning, something that did not exist a few decades ago. On the technology front, Nepal is poised to leap into a new era with the impending deployment of a GIS-based Road Asset Management System integrating HDM-4. This will effectively digitize and streamline the entire pavement management process, from data collection to multi-year planning. The willingness to adopt innovations like smartphone roughness measurement (Roadroid) demonstrates Nepal's pragmatic approach to technology, finding cost-effective solutions suited to its needs. The incorporation of GIS and environmental data reflects an understanding that pavement management in the 21st century must be holistic, considering spatial and climatic factors, not just the pavement in isolation. Despite these advances, the review also makes clear that challenges remain. Ensuring adequate funding, enhancing human resources, maintaining data quality, and extending systematic management to all road classes are areas needing continued effort. The recommendations put forth, from boosting funding to leveraging technology for data, are actionable steps to address these issues. If followed, they can help Nepal avoid the "build-neglect-rebuild" trap and instead preserve its road assets efficiently.

In conclusion, Nepal's trajectory in pavement management is a story of gradual modernization under resource constraints. It showcases how a developing country can progressively implement key elements of pavement management science: regular condition monitoring, use of objective indices, predictive modeling, and rational planning, all supported by an enabling institutional environment. The involvement of local researchers in advancing these methods is a heartening sign of growing self-reliance in technical expertise. Nepal's case also reinforces a fundamental lesson in infrastructure management: sustainable outcomes emerge when technology, policy, and institutions progress in unison. By continuing the current path – investing in data, tools, and people, and by heeding the lessons of the past and present. Nepal is well-positioned further to improve the longevity and quality of its roads. This will not only save money in the long run but also enhance road user experience and safety, contributing to the nation's socio-economic development. The historical perspective offered in this paper serves to appreciate how far Nepal has come and to illuminate the road ahead for pavement management endeavors.

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