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Sustainable Maintenance Management System for Rural Road Networks in Hilly Terrain: Evidence from Kangra District, Himachal Pradesh

Vivek Dhiman[1] ,Dr. Arjun Kumar[2]

[1] Research Scholar , Arni University, Kathgarh ,Indora, Himachal Pradesh, India

Email ID- vivekdhiman121@gmail.com

[2] Faculty of Civil Engineering Department, Arni University, Kathgarh ,Indora, Himachal Pradesh, India

ABSTRACT :

Low volume rural roads play a critical role in providing connectivity, improving socio-economic conditions, and ensuring mobility in hilly regions like Himachal Pradesh. However, these roads often suffer from poor maintenance due to limited financial resources, harsh climatic conditions, and inadequate maintenance strategies. This study focuses on the development of a Maintenance Management System (MMS) for low volume rural roads in Kangra district, Himachal Pradesh. A framework is proposed based on road inventory, pavement condition surveys, performance evaluation, and prioritization models using a Pavement Condition Index (PCI) approach. The study integrates Geographic Information System (GIS) tools for mapping and decision-making. Results highlight that nearly 46% of surveyed roads are in *poor to very poor condition*, demanding urgent maintenance. The proposed MMS provides a structured approach to allocate limited funds, prioritize road segments, and improve service life, thereby enhancing rural connectivity.

Keywords: Maintenance Management System, Low Volume Roads, Pavement Condition Index, Rural Roads, Himachal Pradesh, Kangra District.

1. Introduction

Rural roads form the most extensive part of India's road network, covering more than *70% of the total road length* and providing last-mile connectivity to nearly *65% of the country's population* living in villages. In hilly states like Himachal Pradesh, rural roads are not only critical for mobility but also essential for socio-economic upliftment , tourism promotion, agricultural market access, and emergency services. The district of Kangra, being one of the largest and most densely populated districts of Himachal Pradesh, has a rural road network of over *7,000 km*, connecting small villages, agricultural zones, and pilgrimage/tourist centers to district headquarters and nearby towns.

However, the majority of these rural roads are *low volume roads*, typically carrying less than 1,000 vehicles per day, and are constructed using locally available materials with minimal pavement thickness. Despite initial investments made under the *Pradhan Mantri Gram Sadak Yojana (PMGSY)* and state-sponsored schemes, the long-term sustainability of these roads remains a serious concern. Due to *inadequate drainage systems, heavy rainfall, snow, landslides, and steep gradients*, pavements deteriorate rapidly in this region, leading to potholes, rutting, surface cracking, and frequent washouts.

Traditionally, maintenance of rural roads in India has been *reactive rather than preventive*, with funds allocated only when severe damage is reported. This ad-hoc approach has resulted in increasing maintenance backlogs, reduced pavement service life, and higher life-cycle costs. In Kangra district, field surveys reveal that a significant portion of the network is in *poor to very poor condition*, directly affecting rural accessibility and economic activities. The absence of a *systematic Maintenance Management System (MMS)* makes it difficult for authorities to plan, prioritize, and allocate scarce resources effectively.

A *Maintenance Management System (MMS)* is a structured approach that involves:

1. Creating a reliable *road inventory and condition database*,
2. Conducting *pavement performance monitoring* using standard indices such as the Pavement Condition Index (PCI),
3. Establishing a *prioritization framework* for maintenance needs based on technical, traffic, and socio-economic factors, and
4. Developing a *decision-support tool*, often integrated with Geographic Information Systems (GIS), for efficient resource allocation and monitoring.

Globally, MMS has been successfully implemented in both developed and developing countries to reduce maintenance costs and improve rural accessibility. However, *in India, especially in hilly states like Himachal Pradesh, MMS adoption is limited* due to lack of reliable data, technical expertise, and institutional support. Most rural road agencies rely on manual inspections and subjective judgments, which may not reflect the actual performance needs of the road network.

Given these challenges, the present study aims to develop an *MMS framework specifically tailored for low volume rural roads in Kangra district***.** The research focuses on:

- Conducting road condition surveys and calculating PCI values,
- Prioritizing road stretches based on multi-criteria decision analysis (MCDM),
- Integrating GIS tools for spatial analysis and visualization,
- Proposing practical maintenance strategies (routine, periodic, and rehabilitation) that align with available financial and technical resources.

The novelty of this study lies in its *district-specific approach* that combines engineering evaluation with socio-economic considerations, making it relevant for both *technical planners* and *local governance bodies* such as Panchayati Raj Institutions. By implementing the proposed MMS, Kangra district can significantly reduce maintenance backlogs, extend the service life of its road network, and improve year-round accessibility for rural communities.

2. Literature Review

The development and maintenance of low-volume rural roads have been widely studied across the world, but their management in hilly regions with limited resources continues to present challenges. A review of past studies highlights the importance of maintenance management systems, condition evaluation techniques, prioritization frameworks, and the use of modern technologies like GIS for decision-making.

2.1 Importance of Rural Road Maintenance

Rural roads are vital for ensuring socio-economic development, especially in developing countries. World Bank (1996) emphasized that inadequate road maintenance can increase vehicle operating costs by up to 30% and reduce pavement life by half. Paterson (1987) developed one of the earliest pavement deterioration models for developing countries, stressing preventive over corrective maintenance. In the Indian context, National Rural Infrastructure Development Agency (NRIDA, 2018) highlighted that poor maintenance leads to frequent connectivity disruptions, particularly in hilly regions like Himachal Pradesh, where roads are prone to slope instability and rainfall-induced damage.

2.2 Pavement Condition Assessment Techniques

Condition assessment is the cornerstone of any maintenance management system. ASTM D6433-11 introduced the Pavement Condition Index (PCI), a standardized method widely used globally for evaluating pavement distresses. Shahin (2005) demonstrated that PCI-based frameworks enable transparent and reproducible decision-making. In India, Agarwal et al. (2013) applied PCI methods to rural roads in Uttar Pradesh and showed that systematic surveys help in prioritizing maintenance within limited budgets. Similarly, Gautam and Jain (2018) assessed rural pavements in Madhya Pradesh using PCI and found that more than 40% of roads required immediate intervention.

2.3 Maintenance Prioritization Models

Due to limited financial resources, prioritization of road maintenance is necessary. Hudson et al. (1997) advocated the use of optimization models that balance serviceability with cost constraints. Odoki and Kerali (2000) developed the HDM-4 framework, which integrates traffic, cost, and performance data for pavement management in developing countries. In India, Jain et al. (2015) applied Multi-Criteria Decision-Making (MCDM) techniques that considered traffic volume, pavement condition, and socio-economic importance in prioritizing rural road works. Their results showed that MCDM is more effective than condition-only approaches.

2.4 Maintenance Management Systems in Rural Roads

Haas, Hudson, and Zaniewski (2009) highlighted that a Maintenance Management System (MMS) should be systematic, data-driven, and regularly updated. Developed countries like the USA and Canada have well-established Pavement Management Systems (PMS), but in India, such systems are still evolving. Parida and Aggarwal (2010) demonstrated a PMS framework for state highways, which can be adapted for rural roads with modifications. Kaur and Kaur (2017) emphasized that community participation in rural road maintenance, especially under PMGSY, plays a crucial role in ensuring sustainability.

2.5 Challenges in Hilly and Rural Terrain

Hilly terrains such as Himachal Pradesh present unique maintenance challenges due to steep gradients, excessive rainfall, snow, and frequent landslides. Singh and Sharma (2020) studied rural roads in Uttarakhand and Himachal Pradesh, finding that drainage deficiencies and slope instability were the primary causes of premature pavement failures. Choudhary et al. (2019) reported that flexible pavements in hilly regions deteriorate much faster compared to plains, requiring higher maintenance frequency. Moreover, construction using locally available marginal materials often accelerates pavement distress.

2.6 GIS and Technology in Road Asset Management

In recent years, Geographic Information System (GIS) has emerged as a powerful tool for road maintenance planning. Zhang et al. (2012) applied GIS-based road asset management in China and achieved significant improvements in resource allocation. In India, Parida and Jain (2014) integrated GIS with pavement condition data for urban roads, concluding that the same methodology can be extended to rural roads. GIS provides visualization, spatial analysis, and mapping of poor-condition stretches, thereby assisting engineers and decision-makers in real-time planning.

2.7 Research Gap

While several studies have demonstrated PCI, PMS, and GIS applications for highways and urban roads, limited research exists for rural road networks in hilly districts like Kangra. Most available studies are either national-level frameworks or case studies from plains, which do not fully capture the unique challenges of mountainous terrain. Furthermore, socio-economic considerations such as connectivity to agricultural markets, schools, and healthcare facilities are often overlooked in prioritization frameworks.

Summary of Literature Review

1. Studies worldwide stress the importance of systematic maintenance and preventive strategies.
2. PCI and MCDM are reliable approaches for condition assessment and prioritization.
3. GIS integration enhances decision-making capacity.
4. District-specific frameworks for hilly rural roads remain scarce, creating a research opportunity to design a tailored MMS for Kangra district.

3. Methodology

The methodology adopted in this study involves the development of a systematic Maintenance Management System (MMS) for low volume rural roads in Kangra district, Himachal Pradesh. The process includes selection of study area, data collection through field surveys, pavement condition evaluation, prioritization of maintenance needs, and formulation of a practical MMS framework with GIS integration.

3.1 Study Area

The study was conducted in Kangra district, which has one of the largest rural road networks in Himachal Pradesh. The district is characterized by undulating topography, high rainfall, and frequent slope instability, all of which adversely affect the performance of low-volume roads. A representative sample of approximately 200 km of rural roads was selected for detailed condition surveys. The roads include both bituminous surfaced pavements and water-bound macadam (WBM) type roads constructed under PMGSY and state schemes.

3.2 Data Collection

Comprehensive data collection was undertaken to establish an accurate road inventory and to assess the current condition of pavements. The following categories of data were collected:

- Road inventory data: Information on road length, width, pavement type, construction year, drainage facilities, shoulder condition, and connectivity details was recorded.
- Pavement condition surveys: Visual inspections were carried out to identify surface distresses such as cracking, potholes, ravelling, rutting, edge failures, and drainage problems. Distress types, severity levels, and extent were noted following ASTM D6433 guidelines.
- Traffic data: Classified traffic counts were conducted for selected stretches to estimate Average Daily Traffic (ADT) and axle loading, with special emphasis on agricultural vehicles and small commercial transport typically operating on rural roads.
- Socio-economic data: Information regarding the population served, agricultural productivity, market connectivity, and proximity to schools and health centers was collected from Panchayati Raj institutions and district development records.

3.3 Pavement Condition Index (PCI) Evaluation

The Pavement Condition Index (PCI) method, based on ASTM D6433-11, was used for quantifying the pavement condition on a scale of 0 to 100. Each distress type observed during the surveys was assigned a deduct value based on severity and density. The deduct values were combined to calculate the overall PCI for each road section. The PCI values were then classified into standard categories: Excellent (85–100), Good (70–84), Fair (55–69), Poor (40–54), and Very Poor (below 40). This quantitative evaluation ensured objective assessment of pavement performance.

3.4 Prioritization of Road Sections

Given the limitations of maintenance funds, it was necessary to prioritize road sections for intervention. A multi-criteria decision-making (MCDM) framework was adopted. The following parameters and weights were considered:

- Pavement condition (PCI value): 50 percent weight
- Traffic volume (ADT and commercial vehicles): 25 percent weight

- Socio-economic importance (population served, access to markets and institutions): 15 percent weight
- Connectivity to essential services such as health centers, schools, and district headquarters: 10 percent weight

A composite priority index was developed by combining these weighted scores. Road sections with higher index values were ranked as critical for immediate maintenance.

3.5 Maintenance Strategies

Based on the PCI values and prioritization, suitable maintenance strategies were suggested. These were divided into three categories:

- Routine maintenance: Activities such as pothole patching, crack sealing, roadside drainage cleaning, shoulder repairs, and vegetation removal.
- Periodic maintenance: Surface dressing, thin overlays, or renewal coats to restore riding quality and prevent structural deterioration.
- Rehabilitation and reconstruction: Major strengthening, overlaying with bituminous layers, or complete reconstruction of severely damaged stretches where PCI values were below 40.

The selection of strategy was linked with both pavement condition and socio-economic criticality of the road.

3.6 GIS Integration

To enhance visualization and decision support, Geographic Information System (GIS) tools were used. The surveyed roads were mapped with condition categories, and thematic layers were prepared to highlight poor and very poor stretches. GIS analysis enabled overlay of socio-economic data such as population density and market locations, helping planners identify critical links that required urgent attention.

3.7 Development of MMS Framework

The final stage involved structuring the Maintenance Management System for Kangra district. The proposed MMS follows a six-step cycle:

1. Road inventory and database creation
2. Pavement condition survey and PCI evaluation
3. Estimation of maintenance needs
4. Priority ranking and selection of appropriate strategies
5. GIS-based decision support and resource allocation
6. Monitoring of performance and feedback for future planning

This cycle is iterative, meaning that regular updates of road condition data are required to ensure the system remains relevant and effective.

4. Results and Analysis

The results obtained from the field surveys, condition evaluation, prioritization model, and GIS mapping are presented and analyzed in this section. The analysis not only focuses on pavement performance but also highlights the socio-economic and planning implications for Kangra district.

4.1 Pavement Condition Survey Outcomes

A total of 200 km of representative rural road network was surveyed in Kangra district, covering a mix of bituminous-surfaced roads and water-bound macadam roads. The Pavement Condition Index (PCI) values were calculated for each section based on the observed distresses. The distribution of PCI values is summarized as follows:

- Excellent (85–100): 12 percent
- Good (70–84): 18 percent
- Fair (55–69): 24 percent
- Poor (40–54): 30 percent
- Very Poor (0–39): 16 percent

These results indicate that nearly 46 percent of the surveyed network falls under poor and very poor categories, requiring urgent maintenance or rehabilitation. Only about 30 percent of the roads can be considered in good to excellent condition. The fair category roads, constituting 24 percent, require timely periodic maintenance to prevent further deterioration.

The analysis also showed that water-bound macadam roads generally performed worse than bituminous pavements, largely due to inadequate surfacing, lack of proper drainage, and heavy rainfall in the region. Roads in higher rainfall zones of Palampur and Shahpur blocks were observed to be in poorer condition compared to relatively drier areas of Kangra town and Dehra blocks.

4.2 Distress Types and Patterns

The predominant pavement distresses observed included potholes, edge failures, longitudinal and alligator cracking, and rutting. Potholes were widespread, particularly in sections where drainage was absent or blocked. Edge failures were more common on narrow rural roads with weak or non-existent shoulders. Ravelling was observed on older bituminous roads with inadequate surface treatment. Rutting and deformation were noticeable in sections carrying agricultural tractor traffic and small commercial vehicles transporting apples, vegetables, and dairy products.

The occurrence of distresses highlights that both traffic loading and environmental conditions play a critical role in accelerating pavement deterioration in hilly rural terrain. Lack of timely maintenance, especially drainage cleaning and shoulder repair, contributed significantly to the rapid deterioration.

4.3 GIS-Based Mapping of Road Condition

All surveyed road sections were mapped using GIS to visualize spatial patterns of pavement performance. The thematic maps revealed that poor and very poor condition roads are concentrated in Palampur, Nurpur, and Shahpur regions, which experience heavy rainfall and frequent landslides. By contrast, relatively better condition roads were found in Kangra town, Dehra, and parts of Nagrota Surian where the terrain is more moderate.

The GIS mapping enabled the identification of connectivity gaps by overlaying population centers, agricultural markets, and institutional facilities such as schools and health centers. Several villages were found to depend on road stretches categorized as poor or very poor, highlighting the urgent socio-economic implications of inadequate maintenance.

4.4 Prioritization Results

The multi-criteria decision-making framework was applied to the surveyed road sections by combining PCI, traffic volume, socio-economic importance, and connectivity. The analysis produced a composite priority index for each section. The top ten critical road sections identified were those connecting villages with populations greater than 5,000, linking agricultural produce markets, and providing access to health facilities.

For example, a 12 km stretch in the Palampur block connecting three villages to the regional market was ranked as the highest priority, with a PCI value of 38 (very poor), moderate traffic volume, and high socio-economic significance. Similarly, a road in Nurpur block linking schools and a health center was also ranked in the top five due to its essential service connectivity despite having moderate traffic volume.

These results demonstrate that socio-economic parameters, when integrated with condition data, alter prioritization significantly compared to using PCI values alone. Roads with slightly better condition but higher socio-economic importance were ranked above severely deteriorated but less critical stretches.

4.5 Maintenance Needs and Strategies

Based on PCI classification and prioritization, the estimated maintenance requirements for the 200 km sample network were as follows:

- Routine maintenance required: 25 percent of the network
- Periodic maintenance required: 29 percent of the network
- Rehabilitation or reconstruction required: 21 percent of the network
- No immediate action required: 25 percent of the network

This indicates that nearly half of the surveyed roads require either periodic maintenance or full rehabilitation in the short term. Routine maintenance activities such as pothole patching, crack sealing, and drainage clearing were recommended for about one-quarter of the roads. For roads with PCI below 40, rehabilitation strategies such as overlaying with dense bituminous macadam or reconstruction were proposed.

4.6 Implications for Resource Allocation

The results underline that the current practice of reactive maintenance is insufficient to meet the demands of Kangra's rural road network. A systematic MMS approach can help in rational allocation of scarce resources by identifying roads that yield maximum socio-economic benefits when maintained. Preventive maintenance of fair and good roads can also extend their service life, thereby reducing the long-term financial burden.

Furthermore, the findings highlight the importance of integrating the MMS framework with PMGSY monitoring systems. By updating PCI values and socio-economic data annually, district-level agencies can improve transparency and accountability in road maintenance planning.

4.7 Policy-Level Observations

The results suggest that Kangra district requires a shift from construction-centric planning to maintenance-focused planning. Community participation, particularly through Panchayati Raj institutions, can be encouraged for routine maintenance activities such as drainage clearance and shoulder upkeep. At the state level, introducing performance-based maintenance contracts under PMGSY may ensure better quality and accountability.

5. Discussion

The findings of this study provide valuable insights into the present condition and maintenance requirements of low-volume rural roads in Kangra district, Himachal Pradesh. The results confirm that nearly half of the surveyed network falls under poor to very poor condition, which directly affects rural accessibility and socio-economic development. This observation is consistent with previous studies in hilly states such as Uttarakhand and Jammu & Kashmir, where steep terrain, high rainfall, and lack of systematic maintenance have accelerated pavement deterioration.

One of the major observations is that the deterioration of rural pavements in Kangra is not solely due to traffic loads but is strongly influenced by environmental and construction-related factors. Roads in higher rainfall zones showed extensive potholes, edge failures, and drainage-related damage, underscoring the importance of adequate drainage design. This confirms the earlier findings of Singh and Sharma (2020), who reported that poor drainage is a primary cause of rural road failures in hilly terrain. The implication is that maintenance strategies in such regions should not only focus on surface rehabilitation but also on strengthening roadside drainage and slope protection.

The prioritization model applied in this study demonstrated the usefulness of integrating socio-economic importance with pavement condition indices. In practice, maintenance decisions in rural districts are often guided by immediate complaints or political interventions, rather than objective evaluation. The multi-criteria decision-making (MCDM) approach used here provided a transparent and rational method to rank roads. Roads serving larger populations, agricultural markets, and essential services such as schools and health centers received higher priority even if their PCI values were slightly better than other roads. This aligns with Jain et al. (2015), who emphasized that socio-economic parameters must be included in prioritization frameworks for rural infrastructure planning.

The GIS-based mapping of condition data further added value to the analysis. Visualizing the road network according to condition categories and overlaying them with population centers and service nodes helped identify critical gaps in connectivity. For instance, GIS revealed clusters of villages that depended on very poor road stretches for market access. This spatial analysis supports more informed decision-making and can assist local agencies in communicating road needs to higher authorities. Earlier studies by Parida and Jain (2014) demonstrated similar benefits of GIS integration, but their work focused primarily on urban roads. This study confirms that GIS is equally valuable for rural hilly road networks.

From a policy perspective, the results underline the urgent need for a shift in maintenance planning practices in Kangra district. At present, maintenance tends to be reactive, carried out only when severe damage occurs. Such an approach is inefficient because it leads to high rehabilitation costs and service disruptions. Preventive maintenance of fair-condition roads, as recommended in this study, would extend their service life and reduce future financial burdens. This echoes the conclusions of Paterson (1987), who argued that preventive strategies are far more cost-effective than corrective maintenance.

The findings also highlight the importance of community participation in routine maintenance. Activities such as drain cleaning, vegetation removal, and minor pothole filling can be carried out at the local level with support from Panchayati Raj institutions. This approach has already been suggested under PMGSY guidelines, but its implementation remains weak. Strengthening this aspect would not only improve road sustainability but also create local ownership of infrastructure.

A key observation from this study is the need to integrate Maintenance Management Systems (MMS) with existing monitoring frameworks such as those under PMGSY. By adopting a systematic process of data collection, PCI evaluation, prioritization, and GIS-based decision support, agencies in Kangra district can ensure that maintenance planning is more objective and transparent. This would also help in aligning district-level decisions with state and national policy goals.

Another important aspect relates to the availability of resources. The study found that approximately 21 percent of the surveyed network requires rehabilitation or reconstruction, which involves high costs. Given budget limitations, it may not be feasible to rehabilitate all critical stretches simultaneously. In such cases, phased rehabilitation programs combined with routine and periodic maintenance of other sections can optimize resource use. Introducing performance-based contracts, where contractors are paid based on maintaining road serviceability over time, may also be a viable solution for the district.

In summary, the discussion highlights that the proposed MMS framework is not only technically sound but also socio-economically relevant for Kangra district. It addresses the unique challenges of hilly terrain, provides a rational basis for prioritization, integrates modern tools such as GIS, and offers practical strategies for resource allocation. If adopted, this framework has the potential to significantly improve rural accessibility, reduce long-term costs, and support sustainable rural development.

6. Conclusion

The present study on the development of a maintenance management system for low-volume rural roads in Kangra district, Himachal Pradesh, highlights the critical role of systematic planning in ensuring the sustainability of rural road infrastructure. The analysis revealed that a significant portion of the road network is in poor to very poor condition, which directly impacts the accessibility, mobility, and socio-economic well-being of rural communities. The findings reaffirm that environmental factors such as high rainfall, steep gradients, and inadequate drainage are as important as traffic loads in influencing pavement deterioration in hilly terrain.

The study demonstrated that adopting a structured maintenance management system can provide a transparent, rational, and efficient basis for decision-making. By combining road condition evaluation using the Pavement Condition Index with socio-economic considerations and integrating these into a prioritization framework supported by GIS tools, it becomes possible to allocate limited financial resources more effectively. This approach ensures that not only technical needs but also social and economic priorities are addressed, thereby improving the overall efficiency of rural road programs.

The conclusions drawn also point toward the need for a paradigm shift in current maintenance practices. Instead of relying on reactive measures where interventions are carried out only after serious damage has occurred, preventive and routine maintenance should be emphasized. Such a shift will extend the service life of rural pavements, reduce long-term rehabilitation costs, and minimize service disruptions for the local population. The introduction of community-based routine maintenance practices can further enhance road sustainability, while also fostering local ownership and accountability.

The results suggest that a phased maintenance program combining preventive measures for fair-condition roads with targeted rehabilitation of severely deteriorated stretches is the most practical way forward for Kangra district. The inclusion of modern approaches such as performance-based maintenance contracts can also ensure better accountability and long-term quality of work. These strategies are in line with national policies under PMGSY but require stronger institutional mechanisms and consistent monitoring to be effective.

The implications of this research go beyond Kangra district, as many hilly regions in India face similar challenges. The proposed framework can be adapted for other districts and states with appropriate modifications in terms of local conditions, traffic patterns, and institutional capacities. Future research can focus on the development of predictive pavement performance models for hilly rural roads, integration of real-time monitoring technologies such as mobile-based condition assessment, and evaluation of cost-benefit ratios for different maintenance strategies.

In conclusion, the study establishes that an effective maintenance management system, tailored to the specific needs of low-volume rural roads in hilly terrain, is essential for improving accessibility, reducing life-cycle costs, and supporting long-term rural development. By adopting systematic approaches to data collection, condition evaluation, prioritization, and decision support, road agencies in Himachal Pradesh and similar regions can achieve significant improvements in the sustainability and functionality of their rural road networks.

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