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Development of a Maintenance Management System for Low Volume Rural Road Networks in Himachal Pradesh, India

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Abstract
Rural roads are the lifelines of India's rural economy, linking agricultural regions with markets and promoting social inclusion. However, their long-term sustainability is challenged by inadequate maintenance and resource constraints. This paper presents the development of a Maintenance Management System (MMS) designed specifically for low-volume rural roads. The proposed MMS integrates engineering evaluation, multi-criteria decision analysis using the Fuzzy Analytical Hierarchy Process (FAHP), and an optimization framework for resource allocation. Three modules were designed: (i) identification of critical road sections, (ii) selection of critical maintenance activities, and (iii) allocation of limited resources. The system was implemented and validated using data from a PMGSY rural road network in Kangra District, Himachal Pradesh, India. The results revealed a 25–30% improvement in maintenance prioritization efficiency and up to 20% savings in resource expenditure compared to traditional methods. The developed framework provides a practical, cost-effective, and scalable solution for maintenance planning in developing regions.

Keywords: Rural road network, Maintenance management system, Low volume roads, Fuzzy AHP, Optimization, PMGSY, Pavement condition, Resource allocation.

Introduction

India's rural roads constitute the most extensive and critical component of the national transportation system, accounting for nearly 61% of the total road length. They connect remote villages to towns and facilitate access to healthcare, education, and markets. Programs such as Pradhan Mantri Gram Sadak Yojana (PMGSY) and Bharat Nirman have expanded connectivity, but their sustainability depends on systematic maintenance planning. Maintenance is essential for preserving the functional and structural integrity of road assets. Yet, the challenge of maintaining such a large rural road network is exacerbated by limited funding, poor data availability, and fragmented institutional responsibilities. Deferred maintenance leads to rapid pavement deterioration, higher vehicle operating costs, and increased reconstruction requirements.

Conventional maintenance management methods used in developed countries rely heavily on advanced instruments, automated data collection, and sophisticated databases. Such systems are often infeasible for developing nations where roads are dispersed and resources are limited. Thus, there is a pressing need for a context-appropriate maintenance management framework that combines engineering reasoning, simplified data collection, and optimization techniques. The present study aims to fill this gap by developing an innovative, efficient, and user-friendly Maintenance Management System for Low Volume Rural Road Networks applicable to India and similar contexts.

Literature Review

A comprehensive review of literature was undertaken to understand the global evolution of maintenance management systems (MMS), their application in rural road networks, and the need for a simplified framework suitable for Indian conditions. The literature reveals that while developed countries have advanced and data-intensive Pavement Management Systems (PMS), developing nations still rely largely on ad hoc and reactive maintenance practices.

Evolution of Maintenance and Pavement Management Systems

The concept of a systematic pavement management system originated in the 1970s with the pioneering efforts of the Washington State Department of Highways and AASHO Road Test studies in the United States. These early systems introduced the idea of linking pavement performance models with maintenance decision-making. Subsequent development of PMS in Canada, United Kingdom, and Japan incorporated performance prediction, cost-benefit analysis, and network-level optimization.

Haas et al. (1994) defined pavement management as the coordinated set of activities designed to maintain pavements at an acceptable level of service at minimum overall cost. The U.S. Federal Highway Administration (FHWA) later emphasized integrating data collection, performance modeling, and financial planning to guide decision-making for highway maintenance.

In Europe, several advanced PMS frameworks have been implemented. The UK Pavement Management System (UKPMS) integrates automated distress surveys, structural evaluations, and decision rules for maintenance prioritization. The French VISAGE and GIRR systems link condition monitoring with rehabilitation programming through graphical and GIS-based interfaces. Japan's PMS, meanwhile, uses a combination of analytical models and artificial intelligence to predict deterioration and recommend treatments dynamically.

While these systems have achieved high levels of precision and automation, they are resource-intensive and require specialized expertise, making them difficult to replicate in developing economies or local-level rural contexts.

Maintenance Management in Developing Countries

In developing countries, road maintenance is often neglected until the condition deteriorates significantly, leading to higher life-cycle costs. Ibrahim (2004) studied road management in Iraq and concluded that deferred maintenance can increase rehabilitation costs by nearly 400%. White (2005) reported similar issues in sub-Saharan Africa, where weak institutional frameworks and insufficient funds lead to poor-quality roads and frequent reconstruction cycles.Cedergren (1988) emphasized that inadequate drainage is a critical factor leading to early pavement failures, while Christopher et al. (1997) demonstrated that proper sub-surface drainage could double pavement lifespan. Studies in Kenya and Ghana by the World Bank (2010–2018) also highlighted the urgent need for low-cost, condition-based maintenance systems to ensure the sustainability of rural transport infrastructure. The key lessons from these studies are the importance of preventive maintenance, multi-criteria evaluation, and rational fund allocation. However, most developing countries lack reliable data and technical tools, necessitating simpler frameworks adaptable to field conditions.

Multi-Criteria Approaches in Maintenance Prioritization

Maintenance planning requires evaluating multiple parameters — structural integrity, surface condition, safety, traffic importance, and drainage quality. Because of their subjective and often conflicting nature, multi-criteria decision-making (MCDM) methods have gained prominence.

The Analytical Hierarchy Process (AHP) developed by Saaty (1980) has been widely used for structured decision-making by pair wise comparison of criteria. However, AHP assumes precise judgments, which may not reflect real-world uncertainty. To overcome this, the Fuzzy Analytical Hierarchy Process (FAHP) was introduced by Chang (1996), allowing the incorporation of linguistic variables and uncertainty in expert opinions. Chandra and Sekhar (2007) applied FAHP to prioritize low-volume roads based on surface distress, roughness, and traffic, demonstrating that fuzzy approaches better capture subjective uncertainty. Parida et al. (2011) used AHP to rank urban road maintenance priorities based on structural condition, traffic intensity, and functional importance. Similarly, Agarwal et al. (2004) developed a rational approach for highway section prioritization using weighted condition indices and expert input.Although these studies show that AHP and FAHP can effectively handle complex maintenance decisions, they were mostly applied to highways or urban roads with higher data availability, not rural networks.

Indian Context and Maintenance Challenges

India’s rural road sector presents a unique set of challenges: vast network length, limited technical manpower, and funding constraints. According to MoRTH (2023), rural roads form about 61% of India’s road network, but less than half of the required maintenance needs are funded annually.The Pradhan Mantri Gram Sadak Yojana (PMGSY) has been instrumental in expanding connectivity, but its sustainability depends heavily on timely and planned maintenance. NRRDA (2014) emphasized developing systematic maintenance management practices to ensure serviceability. However, field-level practices remain mostly reactive — based on visual inspections and subjective judgment rather than analytical models.Research in India has mainly focused on high-volume and urban roads. Sarkar (2011) proposed a maintenance prioritization approach for urban pavements using fuzzy logic and neural networks, while Jain et al. (1996) developed a cost-based maintenance priority ranking for national highways. For rural networks, Roy et al. (2003) and Parida (2011) suggested that maintenance planning must integrate local factors like drainage, terrain, and socio-economic importance — parameters often ignored in urban models.

Despite these contributions, there remains a lack of a simplified, field-applicable, and data-efficient maintenance management framework specifically designed for low-volume rural roads in hilly terrains and resource-constrained settings.

Summary of Research Gaps

From the reviewed literature, the following key research gaps are identified:

1. **Lack of integrated frameworks:** No single system in India simultaneously addresses road condition assessment, prioritization, and budget optimization for rural roads.
2. **Limited applicability to low-volume roads:** Most models target urban or highway systems and rely on data-intensive methodologies unsuitable for rural conditions.
3. **Absence of optimization in resource allocation:** Prioritization studies exist, but few combine prioritization with optimization models to handle financial constraints.
4. **Need for user-friendly systems:** Rural agencies require simple, Excel-based tools for field implementation rather than complex, software-dependent models.
5. **Inadequate use of fuzzy logic:** Despite its ability to handle uncertainty in decision-making, FAHP has not been widely implemented for rural road maintenance management in India.

This review highlights the need for a comprehensive, flexible, and practical Maintenance Management System for low-volume rural roads, integrating FAHP for prioritization and optimization techniques for rational resource allocation. Such a system would bridge the gap between research and practice and provide an effective decision-support tool for rural infrastructure management.

Identified Research Gaps

From the above review, key issues emerge:

- Absence of a unified maintenance management framework for rural India.
- Inconsistent data collection and lack of standardized condition indices.
- Weak linkage between road condition, maintenance prioritization, and funding allocation.
- Overreliance on high-cost, equipment-based evaluation methods.

This study addresses these limitations by developing low-cost, simple, and integrated MMS using minimal data and decision-support techniques accessible to field engineers.

Objectives and Scope

Objectives

The primary objective of this study is to design and implement a Maintenance Management System for Low Volume Rural Roads (MMS-LVRR) that enables effective maintenance prioritization, activity selection, and optimal resource allocation.

Specific objectives include:

1. To identify critical parameters influencing deterioration of rural roads, including structural, functional, environmental, and traffic-related factors.
2. To develop a Fuzzy AHP-based prioritization model for identifying critical road sections.
3. To establish a framework for selecting appropriate maintenance activities corresponding to severity and urgency levels.
4. To optimize maintenance expenditure through resource allocation modeling, ensuring the highest return on investment.
5. To validate and implement the developed system using a real-world case study in Himachal Pradesh under PMGSY.

Scope

1. **Geographical Coverage:** Kangra District, Himachal Pradesh, with a representative sample of low-volume PMGSY roads (<2 MSA).
2. **Technical Scope:** Application limited to flexible pavements with bituminous surfacing.
3. **Analytical Scope:** Inclusion of FAHP, condition index modeling, and optimization algorithms for resource allocation.
4. **Operational Scope:** Design of a user-friendly Excel-based tool for engineers without advanced computational skills.
5. **Evaluation Scope:** Sensitivity analysis for model robustness, examining how variations in weights or budgets affect outcomes.
6. **Policy Implications:** The developed methodology supports government agencies like NRRDA and PWD in scientific maintenance planning.

This comprehensive scope ensures the MMS is both technically sound and practically implementable.

Methodology

The methodology developed for this research aims to establish a scientific, transparent, and practically implementable Maintenance Management System (MMS) specifically designed for low-volume rural road networks**.**
The proposed MMS consists of three interlinked modules:

1. Identification of critical road sections,
2. Selection of appropriate maintenance activities, and
3. Optimization of resource allocation under budgetary constraints.

The step-by-step methodology adopted in this study and its details are elaborated below.

Module I – Data Collection and Identification of Critical Road Sections

The first module focuses on collecting condition data from the field and analyzing it to identify road sections that require immediate maintenance attention.

1) Selection of Study Network

The methodology was applied to a 215-km PMGSY rural road network in Kangra District, Himachal Pradesh. This network represents typical low-volume flexible pavements (traffic <2 MSA) serving agricultural and local connectivity functions.

Comprehensive field surveys were carried out to assess three key condition domains:

Condition Type	**Parameters Considered**	**Measurement Method**
Functional Condition	Surface roughness, riding comfort, potholes	Bump Integrator (IRI), visual inspection
Structural Condition	Deflection, cracking, rutting	Benkelman Beam Deflection (BBD), distress mapping

Drainage Condition	Shoulder erosion, cross-slope, side drain efficiency	Field observation and rating scale

Each parameter was evaluated using standardized procedures from **IRC:SP-72-2015** and **Rural Road Maintenance Manual (NRRDA, 2014)**.

Normalization of Condition Scores
Since each parameter was measured in different units, data were normalized using the min–max method:

Ni=Xi−XminXmax−XminN_i = \frac{X_i - X_{min}}{X_{max} - X_{min}}Ni=Xmax−XminXi−Xmin

where NiN_iNi = normalized value for parameter i, XiX_iXi = observed value, and Xmax,XminX_{max}, X_{min}Xmax,Xmin are the maximum and minimum observed values respectively.
Normalized scores range from 0 (poor condition) to 1 (good condition).

Condition Index Development
Individual parameters were aggregated to form three indices:

- **Functional Condition Index (FCI)**
- **Structural Condition Index (SCI)**
- **Drainage Condition Index (DCI)**

Each index represents the average health of the road section under that specific domain.

Module II – Prioritization Using Fuzzy Analytical Hierarchy Process (FAHP)
Once condition indices were obtained, prioritization of sections was performed using the Fuzzy Analytical Hierarchy Process (FAHP) to handle uncertainty and subjectivity in expert opinions.

Criteria Selection
Based on literature review and expert consultation, five main criteria were chosen:

1. Functional condition (roughness and surface defects)
2. Structural condition (deflection, cracking)
3. Drainage and shoulder condition
4. Traffic intensity
5. Socio-economic importance of the route

Expert Judgment and Pairwise Comparisons
Experts from PWD Himachal Pradesh and academic institutions were asked to compare the relative importance of these criteria using linguistic terms such as equally important, moderately important, and extremely important. These judgments were translated into Triangular Fuzzy Numbers (TFNs)**.**

Example of fuzzy scale mapping:

Linguistic Term	TFN (l, m, u)
Equally Important	(1, 1, 1)
Moderately Important	(2, 3, 4)
Strongly Important	(4, 5, 6)
Very Strongly Important	(6, 7, 8)
Extremely Important	(8, 9, 9)

Fuzzy Weight Calculation

Using **Chang's synthetic extent analysis**, fuzzy weights were computed and defuzzified using the centroid method. The final relative weights obtained were:

- Functional Condition – 0.34
- Structural Condition – 0.31
- Drainage Condition – 0.18
- Traffic Volume – 0.10
- Socio-economic Importance – 0.07

These weights reflect the higher significance of surface and structural parameters in determining maintenance urgency.

Computation of Section Priority Index (SPI)

The **Section Priority Index (SPI)** for each road section was calculated as:

SPI=∑i=1nWi×CiSPI = \sum_{i=1}^{n} W_i \times C_iSPI=i=1∑nWi×Ci

where WiW_iWi = weight of criterion i, and CiC_iCi = normalized score of that criterion.

SPI values range from 0 (lowest priority) to 1 (highest priority). Sections with SPI > 0.70 were classified as critical and targeted for immediate maintenance.

Validation of Prioritization Model

Consistency ratios were checked to ensure logical coherence of expert judgments (CR < 0.1). Sensitivity analysis with ±10% variation in weights showed negligible rank changes, confirming the robustness of the FAHP-based prioritization.

Module III – Selection of Maintenance Activities

After identifying high-priority sections, appropriate maintenance activities were selected using a condition-activity decision matrix developed from IRC and MoRTH guidelines.

Pavement Condition	Recommended Treatment	Expected Improvement (%)	Typical Cost (₹ lakh/km)
Minor cracks / good structure	Patch repair + fog seal	20–25	2–4
Moderate cracks / rutting	Surface dressing / thin overlay	40–50	6–9
Severe cracking / deflection >2 mm	Overlay / strengthening	70–80	10–15
Structural failure	Partial reconstruction	>90	15–20

Subject to:

For each road section, the Activity Urgency Index (AUI) was computed as:

AUI=IiCiAUI = \frac{I_i}{C_i}AUI=CiIi

where IiI_iIi = improvement potential, CiC_iCi = cost per km.

Sections with higher AUI were considered most cost-effective for maintenance intervention.

Module IV – Resource Allocation and Optimization
Maintenance budgets are often limited, requiring optimal allocation to achieve the maximum network improvement. An optimization model was developed for this purpose.

Optimization Model Formulation
Maximize Z=∑i=1n(Ii×Xi)\text{Maximize } Z = \sum_{i=1}^{n} (I_i \times X_i)Maximize Z=i=1∑n(Ii ×Xi)

∑i=1n(Ci×Xi)≤B\sum_{i=1}^{n} (C_i \times X_i) \leq Bi=1∑n(Ci×Xi)≤B
Xi=1 if section i is funded; 0 otherwiseX_i = 1 \text{ if section } i \text{ is funded; } 0 \text{ otherwise}Xi=1 if section i is funded; 0 otherwise

where ZZZ = total improvement, IiI_iIi = improvement index, CiC_iCi = cost, and BBB = available budget (₹2.5 crore).

This **linear programming (LP)** problem was solved using the **Simplex method** in MS Excel Solver.

Implementation and Output
The optimized allocation provided a prioritized list of road sections with corresponding activities and costs. The model ensured maximum overall condition improvement within available funds. Outputs included:

- Total network improvement percentage
- Number of sections maintained
- Budget utilization ratio

Module V – System Development and Implementation

To ensure field applicability, the MMS was developed as a **user-friendly MS Excel tool**. This tool allows engineers to:

- Enter field data (roughness, deflection, drainage ratings).
- Automatically calculate SPI and AUI indices.
- Generate ranked maintenance lists.
- View optimized fund allocation and expected improvement.

The interface includes macros and color-coded dashboards for quick visualization of critical sections.

Module VI – Model Validation and Sensitivity Testing

The developed MMS was validated through:

1. **Comparative Evaluation:** Results were compared with actual PWD maintenance decisions; over 85% alignment was achieved.
2. **Sensitivity Analysis:** Tested for variation in weights (±10%) and budgets (±25%). Changes in ranking were within ±5%, confirming model stability.
3. **Field Verification:** Selected high-priority sections were inspected post-maintenance to assess improvement, confirming model reliability.

Advantages of the Developed Methodology

The proposed methodology provides several benefits over conventional maintenance planning approaches:

- **Scientific Decision-Making:** Uses objective data and analytical modeling instead of intuition.
- **Transparency:** Explicit criteria and weights ensure accountability.
- **Cost Efficiency:** Optimized resource allocation maximizes total network improvement.
- **Practical Usability:** Implementable through MS Excel without specialized software.
- **Scalability:** Applicable to other districts or states with simple calibration.

Summary

The developed methodology integrates **engineering evaluation, fuzzy logic, and optimization techniques** into a single coherent Maintenance Management System for low-volume rural roads. It provides a **quantitative, transparent, and replicable** framework suitable for adoption by local government agencies under resource-limited conditions.

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Case Study: PMGSY Rural Road Network, Himachal Pradesh

A case study was conducted on 215 km of rural roads under PMGSY in Kangra District, Himachal Pradesh. These roads, with traffic volumes below 2 MSA, represent typical low-volume networks in hilly regions.

Data collection included:

- Pavement condition (cracks, potholes, rutting).
- Deflection (Benkelman Beam).

- Roughness (Bump Integrator).
- Drainage and shoulder condition surveys.

Each section was evaluated through FAHP to compute the Section Priority Index (SPI) and subsequently ranked for maintenance urgency.

Results and Discussion

Identification of Critical Sections

The computed SPI values ranged from 0.30 to 0.85, classifying the roads into three categories:
- High priority (SPI > 0.70) → 10 sections
- Medium priority (0.50 ≤ SPI ≤ 0.70) → 9 sections
- Low priority (SPI < 0.50) → 6 sections

Correlation analysis indicated that the functional condition (roughness) had the highest influence (r = 0.89), followed by structural deflection (r = 0.83) and drainage condition (r = 0.72).

Maintenance Activity Selection

Using the Activity Urgency Index (AUI), the system suggested:
- Overlay for 9 sections
- Surface dressing for 7 sections
- Patch repair for 6 sections
- Drainage improvement for 3 sections

When compared with actual PWD maintenance decisions, the model's recommendations matched in 87% of cases, confirming its practical accuracy.

Resource Allocation Optimization

Under a fixed budget of ₹2.5 crore, the optimization model selected activities to maximize network improvement. Compared to the existing equal-budget allocation:

- Overall condition index improved by 28%.
- Budget utilization efficiency increased by 24%.
- Deferred rehabilitation needs reduced by 30%.

Sensitivity and Performance Analysis

The sensitivity test showed minimal variation (<5%) in rankings when parameter weights changed by ±10%. Increasing maintenance budgets proportionally improved network condition, confirming the linearity of the optimization response.

Field engineers appreciated the Excel-based model for its simplicity and transparency, enabling scenario testing and immediate visualization of priority results.

Comparative Assessment

The developed MMS was compared against traditional prioritization methods based on subjective judgment and cost-benefit ratios;

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Criterion	Traditional Method	Proposed MMS
Data Requirement	High	Moderate
Cost Efficiency	Low	High
Accuracy	Subjective	Objective (FAHP)
Resource Optimization	No	Yes
Implementation	Complex	Simple (Excel-based)

The results reaffirm the MMS's suitability for low-resource, field-level applications.

Conclusion and Future Work

The developed Maintenance Management System for Low Volume Rural Roads (MMS-LVRR) effectively integrates field evaluation, FAHP-based prioritization, and resource optimization to enhance decision-making in rural road maintenance. Its simplicity and adaptability make it a valuable tool for public agencies.

Major Findings:

- FAHP-based SPI and AUI indices provide objective prioritization metrics.
- Resource allocation model improves network performance within existing budgets.
- Application on PMGSY roads demonstrated 25–30% higher efficiency.

Future Research Directions:

1. Integration with GIS platforms for spatial visualization.
2. Inclusion of real-time pavement condition monitoring using mobile-based tools.
3. Extension of the system to climate-adaptive maintenance planning considering rainfall and terrain conditions.

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