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Optimization of Maintenance Planning for Low Volume Rural Roads under Budget Constraints in Himachal Pradesh, India

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ABSTRACT

Maintenance of low-volume rural road networks in developing nations is a complex challenge, constrained by limited budgets, insufficient data, and lack of systematic management. In India, rural roads represent nearly 61% of the total road network, forming the backbone of agricultural and economic activities. Despite heavy investments under schemes such as Pradhan Mantri Gram Sadak Yojana (PMGSY), inadequate and reactive maintenance practices have led to early pavement failures and rising rehabilitation costs. This paper presents an Optimization-Based Maintenance Planning Framework (OBMPF) for low-volume rural roads that integrates technical evaluation, Fuzzy Analytical Hierarchy Process (FAHP)-based prioritization, and linear programming-based resource optimization. The proposed system is designed to maximize the improvement of road network conditions under strict budget constraints. A case study conducted in Kangra District, Himachal Pradesh on PMGSY roads demonstrates that the model enhances resource utilization by 25–30% compared to conventional methods. The research emphasizes the importance of adopting analytical and optimization tools to support rational, transparent, and sustainable maintenance decision-making for rural infrastructure.

Keywords: Maintenance management, Low-volume roads, Optimization, Fuzzy AHP, PMGSY, Pavement condition, Budget allocation, Road prioritization.

Introduction

Road transport is the dominant mode of transportation in India, accounting for over 85% of passenger and 65% of freight movement. Rural roads constitute approximately 3.3 million km of this network and are essential for linking remote communities with social, economic, and administrative centers. Their maintenance is therefore not merely a technical issue but a socioeconomic necessity.

However, the management of rural road networks is characterized by inadequate maintenance funding, poor planning, and reactive interventions. Studies by the World Bank (2019) indicate that more than 40% of rural roads in developing countries are in poor or failed condition due to deferred maintenance. The Ministry of Rural Development (MoRTH) reports that only about 35–40% of the total maintenance needs of PMGSY roads are met annually.

The challenges arise due to:

1. **Budgetary limitations** – funds are insufficient and often unevenly distributed.
2. **Data scarcity** – lack of reliable condition and traffic data hampers objective decision-making.
3. **Institutional gaps** – coordination between central and local agencies remains weak.
4. **Reactive maintenance** – most agencies adopt “worst-first” maintenance strategies, ignoring preventive approaches.

The problem becomes critical because deferred maintenance not only accelerates pavement deterioration but also increases rehabilitation costs exponentially. A well-designed maintenance system must therefore balance technical needs with financial realities through optimization.

This research proposes a novel Optimization-Based Maintenance Planning Framework (OBMPF) specifically tailored for low-volume rural roads in India. The framework integrates engineering evaluation, multi-criteria decision-making, and linear optimization to achieve cost-effective and data-driven maintenance planning.

Literature Review

A thorough review of global and national literature was undertaken to understand the evolution of maintenance management practices and to identify the existing research gaps in rural road maintenance optimization.

Evolution of Maintenance Management Systems

The concept of Maintenance Management Systems (MMS) emerged in the 1970s alongside the development of Pavement Management Systems (PMS) in countries like the United States and Canada. Early systems, such as the Washington State PMS (1974), relied on performance models and Markov chains to predict pavement deterioration. Ohio PMS-III and Oklahoma PMS integrated deterministic and probabilistic models for network-level maintenance planning. In Europe, the UK Pavement Management System (UKPMS) and French VISAGE and GIRR systems pioneered the integration of condition data, cost analysis, and GIS-based mapping. Japan's PMS later adopted automated data collection and artificial intelligence techniques to refine performance prediction.

Despite these advances, such systems demand extensive databases, automated survey equipment, and highly skilled personnel — resources that are often unavailable in developing nations. Consequently, there is a need for simplified, adaptable, and cost-efficient systems suited to local conditions.

Optimization Approaches in Maintenance Planning

Optimization has long been recognized as a powerful tool for allocating limited maintenance budgets. Flintsch et al. (2002) used linear programming (LP) to optimize maintenance under financial constraints, demonstrating 20–30% higher efficiency compared to heuristic methods. Madanat (1997) introduced Markov decision processes for stochastic deterioration modeling, while Golabi and Kulkarni (1982) formulated the well-known HDM-III model for highway maintenance optimization.

Stuart et al. (2014) applied genetic algorithms for pavement scheduling, showing their flexibility but also their complexity for small agencies. For rural roads, where data and expertise are limited, linear optimization remains the most practical and implementable approach.

Multi-Criteria Decision-Making for Maintenance Prioritization

Maintenance prioritization involves evaluating multiple parameters — such as surface distress, traffic, deflection, and safety — that often conflict. To handle this complexity, Analytical Hierarchy Process (AHP) and Fuzzy AHP (FAHP) are widely used. Saaty (1980) introduced AHP for decision-making under multiple criteria, later extended by Chang (1996) to include fuzzy logic for uncertainty management.

In India, Chandra et al. (2007) and Agarwal et al. (2004) applied FAHP to prioritize road sections based on condition indices, proving its effectiveness in low-data environments. However, these studies did not link prioritization to actual budget allocation through optimization.

Maintenance Practices in Developing Countries

Developing nations face unique challenges such as weak institutional frameworks, inconsistent data, and climatic stresses. Ibrahim (2004) highlighted that reactive maintenance in Iraq led to a fivefold increase in lifecycle costs. White (2005) reported that poor maintenance in sub-Saharan Africa resulted in over 30% higher transport costs. Cedergren (1988) and Christopher et al. (1997) emphasized the significance of drainage in extending pavement life.

These findings underline the universal need for preventive, data-supported, and financially optimized maintenance systems.

Indian Context and Research Gap

India's rural roads are managed by multiple agencies with fragmented databases and variable maintenance standards. Despite the introduction of PMGSY maintenance policy (NRRDA, 2014), field-level decision-making remains largely subjective. Studies by Parida et al. (2011) and Sarkar (2013) propose various prioritization frameworks but often exclude optimization due to computational limitations.

The identified gaps are:

- Lack of integrated frameworks combining condition assessment, prioritization, and optimization.
- Limited focus on low-volume, hilly, and climatic-sensitive rural networks.
- Inadequate use of fuzzy logic for handling subjective uncertainty.

This research aims to fill these gaps through a combined FAHP-Optimization approach, providing a holistic, data-driven, and practical maintenance planning model.

Objectives and Scope

Objectives

The primary goal of this study is to develop a budget-constrained maintenance planning model that ensures maximum road network improvement within limited funds. Specific objectives include:

1. To identify technical, functional, and environmental parameters influencing rural road performance.
2. To develop a Fuzzy Analytical Hierarchy Process (FAHP)-based framework for determining maintenance priority.
3. To establish a linear optimization model for allocating funds to competing road sections under budget limits.
4. To validate the framework using a real-world PMGSY network in Himachal Pradesh.
5. To compare the proposed approach with existing conventional methods.

Scope of the Study

1. **Geographical Coverage:** Rural road network in Kangra District, Himachal Pradesh.
2. **Technical Coverage:** Low-volume flexible pavements (<2 MSA) with bituminous surfacing.
3. **Analytical Scope:** Integration of FAHP prioritization with linear optimization.
4. **Implementation Scope:** Excel-based prototype enabling field-level usability.
5. **Evaluation:** Comparative performance, cost efficiency, and sensitivity analyses.

The developed system is designed for scalability and can be adapted for other Indian states or similar developing contexts.

Methodology

The proposed Optimization-Based Maintenance Planning Framework (OBMPF) was designed to develop a systematic, data-driven, and cost-effective process for maintenance planning of low-volume rural roads. The methodology is structured into four major stages, each containing multiple sub-modules. These stages are:

1. Data Collection and Condition Assessment,
2. FAHP-Based Prioritization,
3. Maintenance Activity Selection, and
4. Budget-Constrained Optimization and Implementation.

Stage 1 – Data Collection and Condition Assessment

Accurate and comprehensive data collection is the foundation of any maintenance management system. For this study, 25 road sections covering approximately 215 km of PMGSY rural road network in Kangra District, Himachal Pradesh, were selected. The selected roads represent typical low-volume flexible pavements in hilly terrain, subjected to climatic variations and limited traffic (<2 MSA).

Data Categories and Parameters

Data were collected under three broad categories — **structural**, **functional**, and **drainage** conditions — representing the overall health of the pavement system.

Category	Parameters	Measurement Method
Structural	Pavement deflection, surface cracking	Benkelman Beam Deflection (BBD), Visual Survey
Functional	Roughness, potholes, rutting	Bump Integrator, Distress Survey
Drainage	Side drain effectiveness, shoulder erosion, cross-fall adequacy	Field Inspection and Rating

Additional parameters, such as traffic volume (Average Daily Traffic) and pavement age, were also recorded for contextual analysis.

Data Standardization and Normalization

To ensure uniform comparison among parameters with different units and scales, all raw data were normalized using min–max normalization:

$$X' = \frac{X - X_{\min}}{X_{\max} - X_{\min}} \quad X' = \frac{X - X_{\min}}{X_{\max} - X_{\min}}$$

This normalization converted all values to a scale of 0 to 1, where 1 represents the best condition and 0 represents the worst.

The normalized parameters were later aggregated to form composite indices for each condition domain (structural, functional, drainage).

Field Challenges

Data collection in rural and hilly regions poses several challenges: lack of traffic counters, variable terrain, and inconsistent drainage patterns. Therefore, simplified yet robust field procedures were adopted, ensuring reliability while maintaining cost-efficiency.

Stage 2 – FAHP-Based Prioritization

The Fuzzy Analytical Hierarchy Process (FAHP) was used to prioritize road sections based on multiple criteria that reflect their maintenance urgency. The process integrates both quantitative measurements and expert judgments to handle the uncertainty inherent in human evaluations.

Selection of Evaluation Criteria

Based on literature review and expert consultations with engineers from PWD Himachal Pradesh, five major criteria were finalized:

- Surface condition
- Structural condition
- Drainage condition
- Traffic importance
- Socioeconomic relevance

Each criterion was further subdivided into sub-criteria (e.g., cracks, rutting, potholes under surface condition).

Fuzzy Pairwise Comparison Matrix

Experts were asked to compare the relative importance of each criterion using linguistic scales such as “equally important,” “moderately more important,” and “extremely more important.” These qualitative judgments were then converted into Triangular Fuzzy Numbers (TFNs).

For example, a typical fuzzy scale mapping was as follows:

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

The fuzzy comparison matrices were aggregated across all experts using the geometric mean method.

Computation of Fuzzy Weights

The fuzzy synthetic extent method (Chang’s approach) was applied to compute normalized fuzzy weights for each criterion. Defuzzification was performed using the centroid method to derive crisp weights that reflect the relative importance of each parameter.

The final weights (W_i) for the five main criteria were found to be approximately:

- Functional condition – 0.34
- Structural condition – 0.30
- Drainage – 0.18
- Traffic – 0.10
- Socioeconomic importance – 0.08

These weights were used to compute the Section Priority Index (SPI) for each road section using:

$$SPI = \sum (W_i \times S_i) \quad SPI = \sum (W_i \times S_i)$$

where S_i = normalized score for criterion i .

The resulting SPI values ranged from 0.34 (least urgent) to 0.85 (most urgent).

Validation of FAHP Model

To ensure reliability, consistency ratios were checked and found below 0.1, satisfying the AHP consistency requirement. Sensitivity analysis revealed stable results with minor variations in expert judgments, validating the robustness of the FAHP model.

Stage 3 – Maintenance Activity Selection

After prioritizing the road sections, the next step was to assign suitable maintenance treatments based on condition severity and deterioration patterns. A decision matrix was formulated linking condition parameters to appropriate activities.

Pavement Condition	Recommended Maintenance Activity
Minor cracks, low roughness	Routine maintenance (patching, sealing)
Moderate cracks, moderate roughness	Surface dressing or fog seal
Severe cracking/rutting	Bituminous overlay (40–50 mm)
Structural failure	Partial reconstruction
Poor drainage, localized damage	Drainage improvement works

Each activity was associated with an **improvement index (Ii)** and **cost (Ci)**, both expressed per km.

The **Activity Urgency Index (AUI)** was developed to rank treatments for each section:

$$AUI = \frac{I_i}{C_i} \quad AUI = C_i I_i$$

Sections with higher AUI values offer greater improvement per unit cost and are thus prioritized for implementation.

Stage 4 – Budget-Constrained Optimization

The final stage involved allocating limited maintenance funds among competing road sections to achieve the maximum overall network improvement.

Formulation of Optimization Model

The optimization problem was formulated as a **linear programming (LP) model**, expressed as:

$$\text{Maximize } Z = \sum_{i=1}^n (I_i \times x_i) \quad \text{Maximize } Z = \sum_{i=1}^n (I_i \times x_i)$$

subject to:

$$\sum_{i=1}^n (C_i \times x_i) \leq B \quad \sum_{i=1}^n (C_i \times x_i) \leq B \quad x_i = \begin{cases} 1 & \text{if section } i \text{ is selected} \\ 0 & \text{otherwise} \end{cases}$$

where:

I_i = improvement index for section i ,

C_i = cost of activity for section i ,

x_i = decision variable,

B = total available budget (₹2.5 crore).

The model was solved using the Simplex LP algorithm available in Microsoft Excel's Solver Add-in.

Model Implementation

The optimization tool was implemented through an Excel-based interface that allows users to:

- Input SPI, AUI, cost, and budget.
- Automatically generate prioritized maintenance lists.
- Obtain optimal activity allocation for each section.
- Display total improvement and budget utilization results.

Validation and Sensitivity Testing

The optimization model was validated by comparing results with actual PWD maintenance plans. Sensitivity testing was conducted by varying:

- Budget levels ($\pm 25\%$).
- Improvement index weights ($\pm 10\%$).

The results showed minimal ranking changes (<5%), confirming the stability and flexibility of the model under different funding scenarios.

Stage 5 – Output and Decision Support

The final output of the OBMPPF is a **ranked maintenance plan** that specifies:

- Priority order of road sections,
- Recommended maintenance activity,
- Estimated cost and expected improvement,
- Optimized allocation of available funds.

The system generates a summary report containing key performance indicators such as:

- Percentage of network improved,
- Total expenditure,
- Remaining deferred maintenance backlog.

This output provides a transparent and rational decision-support tool that local engineers and policymakers can easily understand and implement without requiring specialized software or programming skills.

Advantages of the Proposed Methodology

The developed methodology offers several distinct advantages over conventional maintenance planning approaches:

1. **Integrative Framework:** Combines condition evaluation, FAHP prioritization, and optimization within one coherent process.
2. **Data Simplicity:** Relies on easily measurable field data suitable for low-resource contexts.
3. **Transparency:** Decision criteria and weights are explicitly defined and traceable.
4. **Cost Efficiency:** Ensures maximum network improvement under limited funding.
5. **Scalability:** Can be extended to other districts or states with minor calibration.

In summary, the methodology represents a balanced fusion of engineering assessment and mathematical optimization. It is designed to be technically sound yet simple enough for rural road engineers to apply at the district level, offering a scalable model for sustainable maintenance planning under budget constraints.

Case Study: PMGSY Rural Road Network

The model was applied to the Kangra District network comprising 25 sections, with traffic volumes below 2 MSA and pavement ages ranging from 4 to 10 years. The total available maintenance budget was ₹2.5 crore.

Key data findings:

- Average Roughness: 4.2–8.5 IRI.
- Average Deflection: 1.1–2.4 mm.
- Drainage Index: 0.5–0.8 (moderate to poor).

The FAHP-derived SPI ranged from 0.34 to 0.85, identifying 10 high-priority sections.

Results and Discussion

Prioritization Results

The SPI values clearly differentiated maintenance priorities:

- **High Priority (SPI > 0.70):** 10 sections.
- **Medium Priority (0.50–0.70):** 9 sections.
- **Low Priority (<0.50):** 6 sections.

PRIORITIZATION RESULTS

- High Priority (SPI > 0.70): 10 sections
- Medium Priority (0.50–0.70): 9 sections
- Low Priority (<0.50): 6 sections

The correlation analysis revealed roughness ($r = 0.88$) and deflection ($r = 0.83$) as dominant factors influencing maintenance urgency.



Fig.1 : Prioritization results showing the distribution of road sections across high, medium, and low priority categories based on Surface Priority Index (SPI) values. Roughness ($r = 0.88$) and deflection ($r = 0.83$) were identified as dominant factors influencing maintenance urgency.

The correlation analysis revealed **roughness ($r = 0.88$)** and **deflection ($r = 0.83$)** as dominant factors influencing maintenance urgency.

Optimization Outcomes

Using the optimization model:

- 20 of 25 sections were funded within ₹2.5 crore.
- Network-level improvement increased by 31% compared to uniform allocation.
- Cost efficiency improved by 26%, and deferred rehabilitation costs were reduced by 29%.

USING THE OPTIMIZATION MODEL:



20 of 25 sections were funded within ₹2.5 crore



Network-level improvement increased by 31% compared to uniform allocation



Cost efficiency improved by 26%, and deferred rehabilitation costs were reduced by 29%

Fig. 2: Optimization model outcomes showing effective allocation of ₹2.5 crore across 20 road sections, resulting in a 31% network-level improvement, 26% gain in cost efficiency, and 29% reduction in deferred rehabilitation costs.

Sensitivity Analysis

When weights in the FAHP were varied by $\pm 10\%$, SPI rankings changed by less than 5%, demonstrating stability. Increasing budget by 25% led to a proportional 19% rise in overall condition index, indicating budget elasticity of the model.

Comparative Assessment

Criteria	Traditional Method	Proposed OBMPF
Decision Basis	Subjective	FAHP + Optimization
Transparency	Low	High
Cost Efficiency	Low	High
Technical Complexity	Low	Moderate
Usability	High	High

Policy Implications

The model supports:

- Evidence-based decision-making for public works departments.
- Transparent fund distribution for PMGSY programs.
- Preventive maintenance planning to extend pavement lifespan.

Adopting this system could lead to national-level savings and improved serviceability of rural road assets.

Conclusion and Future Work

This research developed a comprehensive, optimization-based maintenance planning model for low-volume rural roads under financial constraints. By integrating FAHP prioritization with optimization, it bridges the gap between subjective field judgment and data-driven management.

Key Outcomes:

1. The FAHP model quantified maintenance urgency effectively.
2. The optimization framework enhanced maintenance efficiency by 25–30%.
3. The Excel-based implementation ensures field applicability without expensive tools.
4. The model demonstrated scalability across diverse road conditions.

Future Directions:

- Integration with GIS-based visualization for spatial analysis.
- Development of mobile data entry systems for real-time monitoring.
- Expansion to multi-year maintenance planning models considering inflation and deterioration.
- Testing under different climatic and terrain conditions across India.

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