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Optimization Models for the Maintenance Management of Tropical Paved and Unpaved Roads

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Abstract: The degradation of paved and unpaved roads stands as a critical concern in contemporary infrastructure management. When faced with limited budgets, it is important to identify the optimal combination of road preservation strategies to minimize the lifecycle cost of the road network. Specific studies are necessary to improve the maintenance management systems and analyze the behavior of road surface deformation. To narrow these knowledge gaps, this study investigates a management system that focuses on the application of optimization techniques for managing both paved and unpaved tropical roads. Probabilistic deterioration models were constructed using the Markovian process, resulting in precise degradation curves in the context of 18 unpaved road segments in the Zona da Mata County of Minas Gerais (Brazil), along with 88 paved roads located in Minas Gerais. An optimization algorithm was proposed for the prediction of maintenance resources for unpaved and paved roads, emphasizing the cost-effectiveness of preventive and minor rehabilitation treatments over reconstruction. Comparisons between the maintenance costs of unpaved and paved roads indicated that the full rehabilitation costs of paved roads were approximately 10 times higher per kilometer compared to those of unpaved roads. The models effectively captured the trend wherein a major treatment leads to minor additional treatments being necessary for the subsequent several years in both scenarios. The findings of this study provide future directions for the optimized allocation of resources in the management of transportation infrastructures.

Keywords: transportation infrastructures; pavement management system; tropical roads; probabilistic deterioration models

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1. Introduction

1.1. Research Context

The degradation of the existing road network is a pressing concern in contemporary infrastructure management. The existing road network has aged, leading to the appearance of different types of distresses such as cracking, raveling and potholing on the road surface. In the Brazilian state of Minas Gerais (MG), which is the focus of the present study, a total of 271,160 km of roadway must be maintained by federal, state, or local entities [1].

The deterioration level of roads is directly related to different factors, such as the volume of traffic and the maintenance activities undertaken over their lifespan. Nowadays, the costs of maintenance and rehabilitation activities are rising dramatically [2]. The lack of maintenance procedures has resulted in irreparable harm to economic growth rates, as poorly maintained roads contribute to delays, road accidents and increased vehicle operating costs. Without proper and timely maintenance interventions, the condition of the pavement rapidly deteriorates from "good" to "poor" over a relatively short period, necessitating higher funding for rehabilitation [3].

Over the past decade, maintenance management systems have significantly improved due to technological advances. Numerous researchers have dedicated efforts to elaborating on maintenance management systems and investigating the road surface deformation behavior. They include interesting strategic and systematic processes aimed at maintaining and enhancing the road network [4–6].

1.2. Literature Review

1.2.1. Maintenance Management of Paved and Unpaved Roads

Pavements are designed to last for a certain period. Throughout their life cycle, they begin in optimal conditions, declining until they reach failure [7]. The evaluation of the pavement deterioration level is important in assisting those responsible for selecting maintenance activities in their decision-making process. Deterioration should be estimated based on functional and structural factors [8]. Maintaining paved roads in appropriate conditions requires special attention. Depending on the structural health of the road, varying degrees of maintenance activities are necessary. Different types of paved road maintenance can be used [9,10]:

- Asphalt overlays: roads undergo restoration through resurfacing procedures. Rather than removing the deteriorating pavement, it serves as a base onto which a new layer is applied.
- Patching: this involves filling potholes or excavated areas in asphalt pavement. The swift repair of such issues helps to prevent further deterioration and the need for costly repairs. Without prompt patching, water infiltration can lead to more extensive and serious infrastructure issues.
- Reshaping: when a road surface is too damaged to be smoothed, the unpaved sub-base can be reworked to eliminate large potholes and restore a flattened crown.
- Slab replacement: pavement sections that are chipped, cracked, or uneven are replaced, avoiding the need to replace the entire stretch.
- Smoothing: reworking the surface of a road without delving too deeply into the sub-base. Smoothing procedures address minor damage resulting from regular use.

In addition, it is important to highlight that reconstruction is carried out when the paved roads have deteriorated beyond cost-effective maintenance. Reconstruction is usually carried out in phases to minimize traffic disruptions.

On the other hand, unpaved roads are constructed when the volume of commercial traffic (gross weight exceeding 3 tons) is low [11]. In this case, it is necessary to identify and characterize aspects related to the ride comfort, users' safety, vehicle performance and transportation costs, based on subjective and objective evaluations [12–14]. Several agencies and local researchers have suggested different types of subjective rating methods for representing unpaved road conditions, such as PASER, Unpaved-PASER, Ride Quality Rating Guide (RQRG) and Gravel Roads Rating System (GRRS) [15]. The GRRS offers standardized evaluations for seven different types of distresses: potholes, rutting, washboards, loose aggregate, dust, crown and roadside drainage [16].

Five primary factors affecting the quality of an unpaved road can be listed: traffic load, subgrade quality, construction practices, water and maintenance programs. According to Kabindra, Pramen and Thomas [17], the following types of maintenance programs are generally recommended for unpaved roads:

- Routine maintenance: this involves mitigating blockages and damage on unpaved roads through regularizing surfaces or patching methods. It also involves maintaining bridges and drainage structures, in addition to implementing erosion control procedures.
- Periodic maintenance: employing maintenance practices to address various issues that arise, where the extent of distress does not warrant full-scale rehabilitation or reconstruction services.

- Rehabilitation: applying a thin unpaved overlay to improve the durability and functionality of the road.

1.2.2. Optimization Methodologies for Road Management Systems

Life cycle costs analysis (LCCA) systems have been widely used to investigate the overall economic effectiveness of various alternatives for the design of pavements and their maintenance and rehabilitation (M&R). The LCCA enables the appropriate assessment of the lifetime impacts of their practices [18–20]. In addition, various statistical models and machine learning algorithms have been elaborated on to improve the performance of transportation systems, based on innovative strategies for traffic modeling, estimation and monitoring [21]. Accurate systems for traffic evaluation are vital tools that support decision-making by commuters and transportation system officials, particularly in managing road conditions effectively [22,23].

According to previous literature [16,24], the management systems can be considered a multi-objective optimization approach due to different factors: (i) engineers or decision-makers want to maximize the network road conditions within a limited budget; (ii) preventive and minor rehabilitation treatments are more cost-effective than reconstruction (iii) the budget must exceed a certain threshold to maximize societal benefits; and (iv) the best combination of road segments for rehabilitation should include those with more traffic volume. In some works, this system can be conceptualized as a two-level optimization process, as it connects decision-makers at two levels [25]. This scenario can be exemplified by two sets of objective functions: one aligned with governmental objectives and the other driven by the priorities of city governors or the company's stakeholders.

The Management System (MS) can be associated with the integrated coordination of various activities involved in the design, construction and maintenance processes related to road infrastructures, allowing them to provide acceptable conditions at minimal costs. The MS encompasses various methods aiding decision-makers in identifying optimized strategies for constructing, evaluating and maintaining roads in an acceptable condition over a specified period within a designated budget [26]. The optimization approaches encompass mathematical programming techniques aimed at minimizing or maximizing various factors to enhance the road management systems [27–29].

1.2.3. Pavement Management System (PMS)

The implementation of a Pavement Management System (PMS) is particularly crucial in situations where road conditions are poor and resources are limited. A robust PMS aims to delineate maintenance strategies that minimize costs while maximizing the return on invested resources, thereby extending the service life of roads and properly allocating limited budgets [30]. Furthermore, an effective PMS must continually update itself by exploring alternative strategies, identifying the optimal workflow, and leveraging feedback mechanisms to enhance overall decision-making processes [31].

The following procedures typically guide the customization of a pavement management process to meet the unique needs of each local agency: defining the roadway network and gathering inventory data, collecting condition data, predicting road conditions, selecting treatments, reporting results, choosing pavement management tools and ensuring ongoing updates [32].

Predicting road conditions requires a comprehensive understanding of pavement performance and the distinctions between analyzing it at the network and project levels. At the network level, the entire network is evaluated to identify the appropriate types of maintenance and the road sections to be repaired. At the project level, only the selected sections are analyzed to determine the most appropriate treatment procedures [33].

The road performance models are derived from various pavement characteristics (e.g., functional conditions, width, length, rut) and enable the prediction of pavement parameters arising from traffic loads and climatic conditions (e.g., deflections, stresses, strains, moisture content, temperature, etc.) [34–36].

1.2.4. Unpaved Roads Management System (URMS)

According to Saha, Ksaibati and Atadero [8], an Unpaved Roads Management System (URMS) is a strategic and systematic process for maintaining and upgrading the road network. When funding is limited, the URMS identifies the best combination of projects for road preservation, providing the most benefit to society in terms of the overall lifecycle cost of the road network. A URMS consists of various stages, with the "prediction of conditions step" being the most intricate. To predict the paved road conditions, it is necessary to develop deterioration models based on the road's conditions over the years. The established models facilitate the prediction of key responses of the paved road, based on empirical, mechanistic or mechanistic–empirical information calibrated with field-observed data.

URMSs lack standardized procedures for determining surface condition ratings or deterministic approaches to modeling surface deterioration. Evaluating roads and establishing the pavement condition index (PCI) are essential for assessing the infrastructure conditions. However, the typical PCI methodology is not applicable to unpaved roads, as it primarily focuses on detailed examinations of distresses of paved roads, such as cracking and potholes [37].

To determine future needs based on road conditions, a URMS applies either probabilistic or deterministic models. In Brazil, deterministic models are commonly utilized, based on expert opinion curves derived from field staff experience. However, these deterministic techniques do not properly account for uncertainties associated with pavement deterioration due to traffic and weather. In contrast, probabilistic models take these uncertainties into consideration, resulting in more precise curves [8].

1.3. Research Gaps and Original Contributions of the Present Study

In situations where funding is limited, the MS provides the optimal combination of projects for road preservation, reaching the greatest benefits in terms of the overall lifecycle cost of road infrastructures [38]. Since the growth of the road network has not kept pace with the considerable increase in transport demand in Brazil, efficient pavement management systems (PMSs) for tropical roads are necessary.

When confronting budget constraints, determining the optimal preservation procedures becomes pivotal for minimizing the overall costs throughout the lifecycle of paved and unpaved roads. The previous studies of Rejani et al. [39] only focused on the pavement maintenance and rehabilitation of urban roads, using the Highway Development and Management System (HDM-4) to minimize the total costs for a target road roughness. Therefore, specific studies are still needed to formulate robust management systems for both paved and unpaved roads. According to previous works [40,41], the inherent limitations of existing approaches highlight the need to develop computational methods that can effectively analyze the residual conditions of different infrastructure elements. Moreover, a research gap exists in standardized procedures for the surface condition exploration of unpaved roads. The conventional PCI methodology is inapplicable to unpaved roads, given its predominant focus on detailed examinations of distresses specific to paved roads.

To narrow these knowledge gaps, the present paper proposes a methodology for identifying the best combination of initiatives for road preservation within a specified budget. In MG, approximately 90% of roads are unpaved, and most roads require an efficient management system. Therefore, the present work presents innovative optimization techniques for managing unpaved and paved roads using similar structures and simple datasets. Maintenance resources were predicted for 18 unpaved road segments in the Zona da Mata County (ZMC) of MG, along with 88 paved roads located in MG.

2. Materials and Methods

This section presents the methods used for data collection, the roadway segmentation process, the procedures for the characterization of road conditions, the deterioration models applied in this study and the algorithm proposed to identify the best combination of projects for road preservation. It is important to mention that the present model does not consider political factors but rather purely the life cycle costs related to unpaved and paved roads.

2.1. Road Segmentation and Classification

Four different types of data were collected to develop this research: roadway segmentation data, traffic counts, road width values and road conditions information. Roadway segmentation was conducted by defining segments that start and end at points of new construction, intersections with other roads or other alterations along the road.

Data from unpaved roads were directly collected in the field, which imposes some challenges regarding accessibility and terrain conditions. For example, the average width of the sections was determined using tape measurements. Rutting was obtained using a standardized ruler and straightedge. The average daily traffic volume was determined using the methodology proposed in the DNIT manual for traffic studies. Data regarding paved roads were obtained from the "Rodovias" website managed by the government of the state of MG.

Based on the segmentation process and using the ArcGIS software, a total of 18 unpaved road segments were delineated in the ZMC of MG, alongside 88 paved roads distributed throughout MG. Figure 1 shows a paved road in MG awaiting maintenance to prolong its service life, while Figure 2 illustrates an unpaved road in poor condition in MG.

Figure 1. Paved road located in MG. Reproduced from Salomão et al. [42], as permitted under the Creative Commons Attribution License Agreement.

The unpaved road conditions were characterized by seven distinct parameters: cross-section/crown, roadside drainage, rutting, potholes, loose aggregate, dust and corrugation. The Pavement Surface Evaluation and Rating (PASER) manual describes that the surface of unpaved roads can be rated on a five-point scale, where five represents an excellent condition and one indicates a failed condition for unpaved roads. For this paper focusing on MG roads, we proposed transforming this five-point scale into a nine-point scale, following the Gravel Roads Rating System (GRRS) guidelines [15]. This approach aimed to reduce errors when human raters need to assess the infrastructure conditions. Then, a Pavement Serviceability Index (PSI) was calculated, following the recommendations of the RQRG created by the Wyoming Technology Transfer Center (WYT2/LTAP) [43]. This nine-points scale was applied for unpaved roads, based on the Overall Road Condition Index (ORCI). This methodology resulted in the ride quality, and the extreme values nine and one represent the best and worst conditions, respectively.

Figure 2. Unpaved road located in the ZMC of MG.

On the other hand, paved roads were assessed using the AASHTO methodology, which ranks conditions from 0 to 100, with 100 representing a newly constructed road and 0 indicating a failed road. According to this rating system, the primary variables are the distresses rutting, fatigue cracking, longitudinal cracking, transverse cracking, patches, potholes, raveling, bleeding and roughness. The evaluation results were reported using the AASHTO guide to road classification, categorizing roads as “Excellent”, “Good”, “Fair”, “Poor”, or “Failed” [44]. Therefore, a five-point scale was used for the paved roads investigated in this research.

2.2. Deterioration Models

Huntington and Ksaibati [15] developed a deterioration model for roads in Wyoming (USA), which served as a foundation in the current study for elaborating the deterioration model for the Brazilian roads.

An average deterioration was estimated in the present research, based on overall road conditions. At first, the obtained pavement condition database was appropriately organized according to the defined condition states. Then, the first aspect of the data quantification process involved categorizing the pavements. The subsequent step encompassed generating data matrices for each pavement classification.

The deterioration evolution of unpaved and paved roads was predicted through the Markovian chains. After defining the number of conditions (k) to be considered in the statistical evaluation, the transition matrix with dimensions $k \times k$ was used to evaluate the transition probability of states [45], as indicated in Equation (1).

$$P\Delta t = \begin{bmatrix} p_{11} & p_{12} & p_{13} & \cdots & p_{1k} \\ 0 & p_{22} & p_{23} & \cdots & p_{2k} \\ 0 & 0 & p_{33} & \cdots & p_{3k} \\ \vdots & \vdots & \vdots & & \vdots \\ 0 & 0 & 0 & \cdots & 1 \end{bmatrix} \quad (1)$$

The unit value presented in this matrix ($P\Delta t$) corresponds to the maximum input value for each event. The probability value of p_{kk} was defined considering that there was no further condition state after the k state, so it is a limited value [46]. The transition probability from a state i to a state j, for a generic time interval (Δt), is represented by p_{ij}, with $i = j = 1, \ldots, k$, as indicated in Equation (2) [47].

$$p_{(\Delta t)ij} = \text{Prob}\ (X_{t+\Delta t} = j | X_t = i) \quad (2)$$

Then, Markovian chain techniques and regression analyses were conducted using the R statistical software (version 3.5). Using the probabilistic Markovian process and beginning with the data matrix, the transition matrix was calculated to derive the probability distribution matrix. Subsequently, this matrix was used to determine the expected age of the roads based on their conditions, resulting in the development of a statistical model for road deterioration.

2.3. Algorithm Proposed to Identify the Best Combination of Projects for Road Preservation

Five treatment options were proposed for the unpaved roads: general maintenance, chemical and mechanical stabilization, preventive rehabilitation, medium rehabilitation and paving procedures (GM, 1-R, 2-R, 3-R and 4-R, respectively). In addition, six treatment options were proposed for paved roads: general maintenance, preventive rehabilitation, minor rehabilitation, medium rehabilitation, major rehabilitation and reconstruction (GM, 1-R, 2-R, 3-R, 4-R and 5-R, respectively). The characteristics of these treatment options were discussed in Section 3. The decision trees for the unpaved and paved roads are illustrated in Figures 3 and 4, respectively.

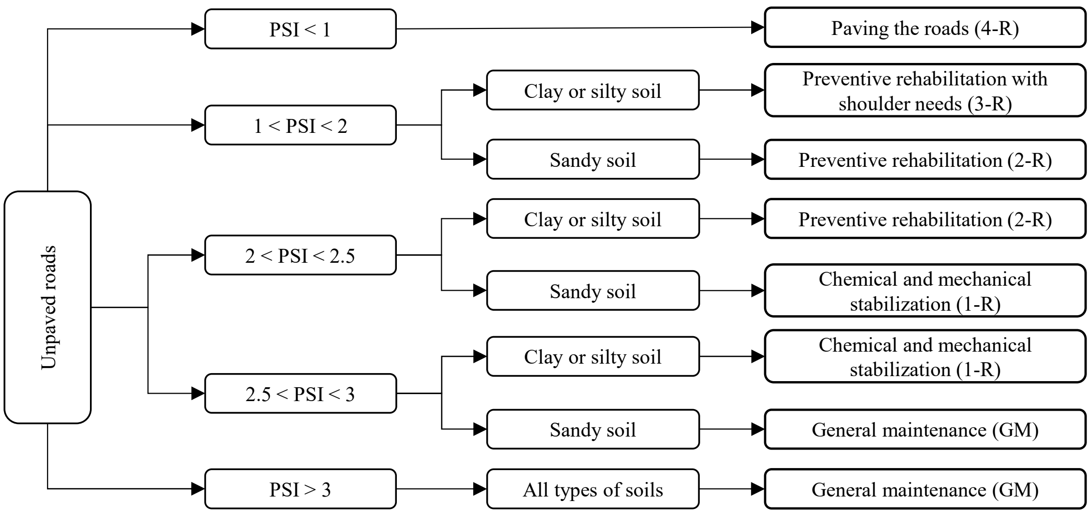

Figure 3. Decision tree for the unpaved roads.

Hence, it is evident that the proposed URMS and PMS take into account not only the cost factor but also local conditions, including the ORCI and the average daily traffic (ADT) data. The objective of the developed model was to maximize a function that considers three independent parameters: the road condition, ADT, and cost-factor, as indicated in Equations (3) and (4).

$$\text{Maximize} \sum_{i=1}^{n} \frac{ORCI \times ADT_i}{Cost - factor_{\ i}\ (treatment\ type)} \times (x_i) \quad (3)$$

$$\text{Subjected to} \sum_{i=1}^{n} TreatmentCost_{\ i} \times (x_i) \leq Budget\ , x_i \in \{0,1\} \quad (4)$$

where ADT_i expresses the average daily traffic for road i, Cost-Factor$_i$ is the function of the treatment type, x_i is an integer equal to one if the project is selected and zero if it is not selected and ORCI represents the minimum index among the distress indices. This is a combinatorial optimization problem where one selects a collection of projects of maximum value while satisfying some weight constraints.

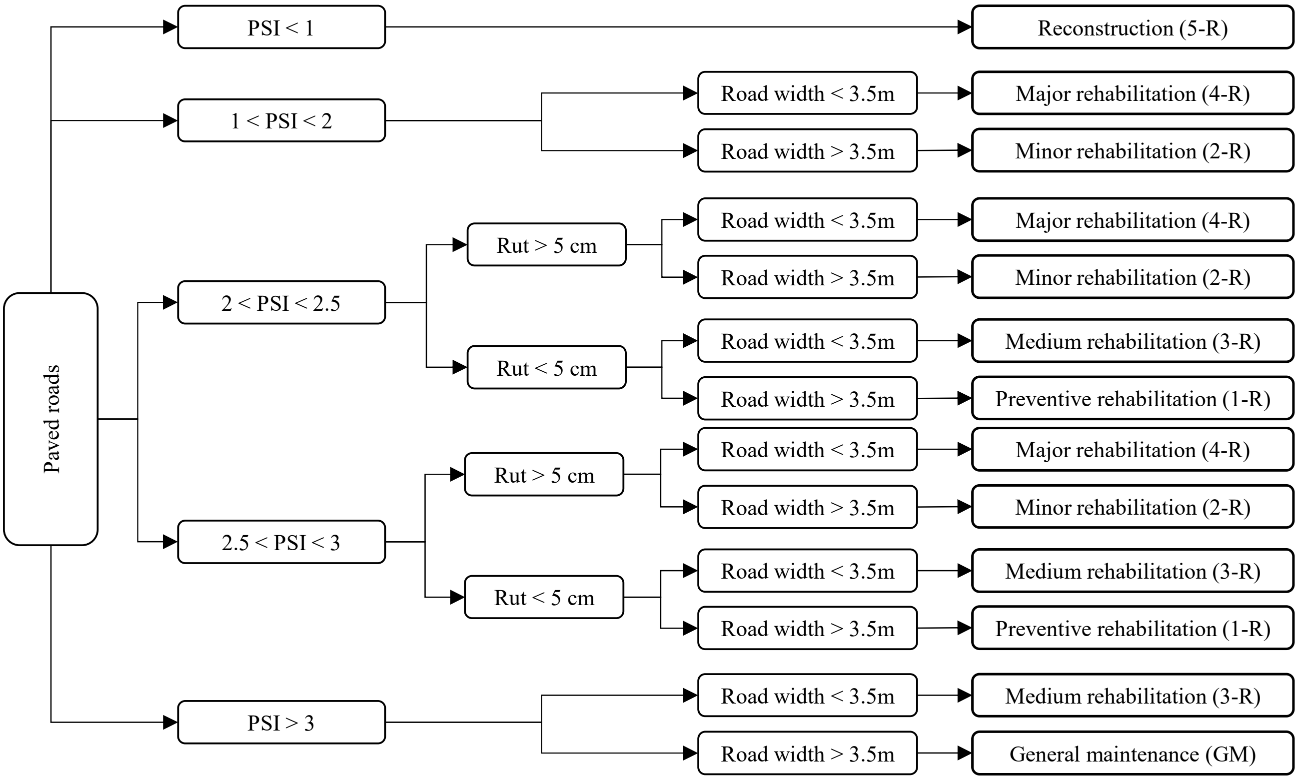

Figure 4. Decision tree for the paved roads.

3. Results and Discussion

The collected information for unpaved and paved roads is presented in the comprehensive database summarized in Tables 1 and 2, respectively. The information provided in these tables is also graphically represented in Figures 5 and 6, respectively. A detailed analysis of the traffic counts reveals significant patterns in vehicle usage. The unpaved road segments experienced traffic volumes of less than 400 vehicles per day, indicating lighter usage. In contrast, a notable portion of the paved road segments, approximately 20%, handle a heavier traffic load, with daily vehicle counts exceeding 400. The road widths of the segments varied significantly, ranging from 3 to 7 m. The collective length of the road segments was substantial, with the 18 unpaved segments and 88 paved segments together spanning a total distance of 15,236 km. This extensive network underscores the importance of understanding traffic patterns and road characteristics for the effective management of Brazilian roads.

Table 1. Dataset obtained for unpaved roads of MG.

Segment	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
PSI	1	1.8	2.81	2.51	1.5	0.88	1.63	0.89	1.8	1.03	1.19	3.06	1.22	1.63	0.9	0.93	1.22	3.24
Length (km)	1.94	0.91	0.62	0.65	1.02	0.13	0.27	1.52	0.57	1.18	1.00	2.65	0.26	0.56	0.13	0.90	0.60	1.30
Soil	Sand	Silt	Clay	Sand	Silt	Clay	Silt	Silt	Sand	Silt	Clay	Silt	Silt	Clay	Clay	Sand	Sand	Silt

The Markovian process enabled the determination of the following matrices: the transition probability data, transition probability matrix and probability distribution matrix. The results presented in Tables 3 and 4 represent the transition probability data obtained from the unpaved and paved roads datasets, respectively.

Table 2. Dataset obtained for paved roads of MG.

Segment	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
PSI	1	2	3	3	2	3	2	1	2	3	2	2	2	2	2	2	1	2
Length (km)	35	9	6.5	45	10	32	17	23	7	103	291	3	60	26	75	33	11	97
Width (m)	7.0	7.0	7.0	7.0	7.0	3.8	6.5	3.0	7.2	7.2	7.2	7.2	7.2	7.2	7.2	3.7	6.6	4.0
Rut (cm)	0.4	0.4	0.4	0.4	0.5	0.51	0.53	0.45	0.77	0.43	0.51	0.51	0.51	0.51	0.5	0.48	0.5	0.54
Segment	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**
PSI	3	3	2	2	3	1	2	3	2	2	2	2	1	2	2	2	1	2
Length (km)	50	6.5	91	6.5	5	43	105	19	21	28	15	14	11	29	10	177	247	268
Width (m)	6.5	8.0	3.7	3.7	4.2	4.2	3.6	3.6	3.6	8.0	4.5	4.1	6.6	6.6	6.6	4.2	4.1	4.1
Rut (cm)	0.51	0.48	0.77	0.77	0.77	0.48	0.5	0.45	0.51	0.51	0.43	0.5	0.54	0.54	0.54	0.45	0.45	0.77
Segment	**37**	**38**	**39**	**40**	**41**	**42**	**43**	**44**	**45**	**46**	**47**	**48**	**49**	**50**	**51**	**52**	**53**	**54**
PSI	2	3	2	1	2	2	1	3	3	2	2	3	4	4	4	3	2	4
Length (km)	91	109	17	49	160	49	6	124	59	69	17	239	831	209	823	341	41	670
Width (m)	3.8	3.8	80	8.0.	8.0	8.0	8.0	3.8	4.4	3.4	3.3	3.8	3.8	5.5	5.5	5.0	5.0	3.7
Rut (cm)	0.45	0.5	0.76	0.77	0.25	0.43	0.4	0.48	0.25	0.76	0.77	0.56	0.57	0.53	0.54	0.53	0.5	0.4
Segment	**55**	**56**	**57**	**58**	**59**	**60**	**61**	**62**	**63**	**64**	**65**	**66**	**67**	**68**	**69**	**70**	**71**	**72**
PSI	4	4	4	3	3	3	2	3	2	3	3	2	4	4	3	2	4	3
Length (km)	338	246	11	547	311	890	417	457	77	268	73	202	154	875	324	137	946	140
Width (m)	5.2	5.2	5.2	5.2	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Rut (cm)	0.55	0.51	0.4	0.4	0.57	0.58	0.57	0.81	0.54	0.58	0.86	0.86	0.79	0.58	0.84	0.99	0.76	0.84
Segment	**73**	**74**	**75**	**76**	**77**	**78**	**79**	**80**	**81**	**82**	**83**	**84**	**85**	**86**	**87**	**88**		
PSI	4	2	3	4	3	3	3	2	4	2	1	3	4	1	3	3		
Length (km)	48	179	30	27	78	212	79	4	25	151	142	256	198	135	86	15		
Width (m)	3.7	3.4	4.7	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0		
Rut (cm)	0.55	0.49	0.45	0.25	0.77	0.77	0.25	0.25	0.25	0.5	0.76	0.48	0.48	0.58	0.55	0.58		

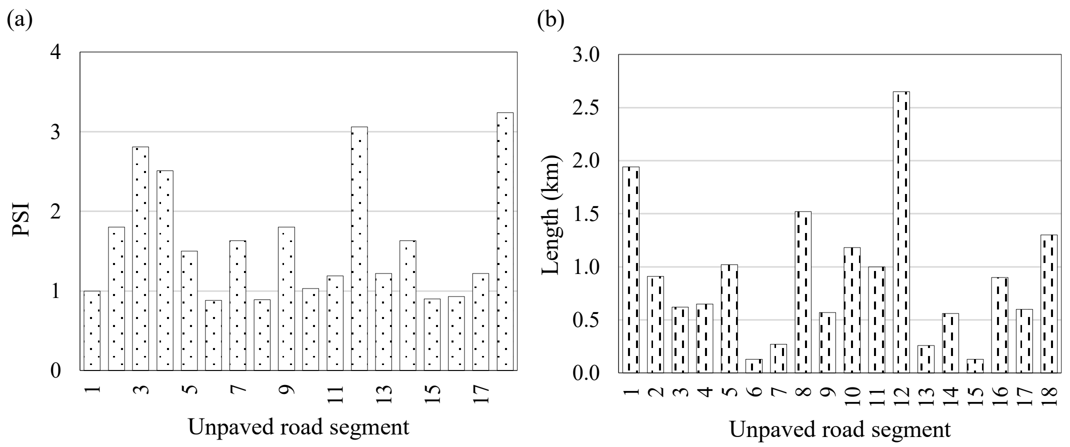

Figure 5. PSI (**a**) and length (**b**) values obtained for unpaved roads of MG.

Table 5 shows the transition probability matrix for the unpaved roads. A transition matrix of a Markovian process contains information on how the deterioration process moves from one state to another in terms of probabilities. According to the obtained data presented in Table 5, it was possible to observe that after 1 year, the percentage of roads that stay at level 9 was represented by the element 0.333. Similarly, the 0.481 element represents the percentage of roads that deteriorate from level 9 to level 8, and 0.185 represents the percentage of roads that deteriorate from level 9 to level 7.

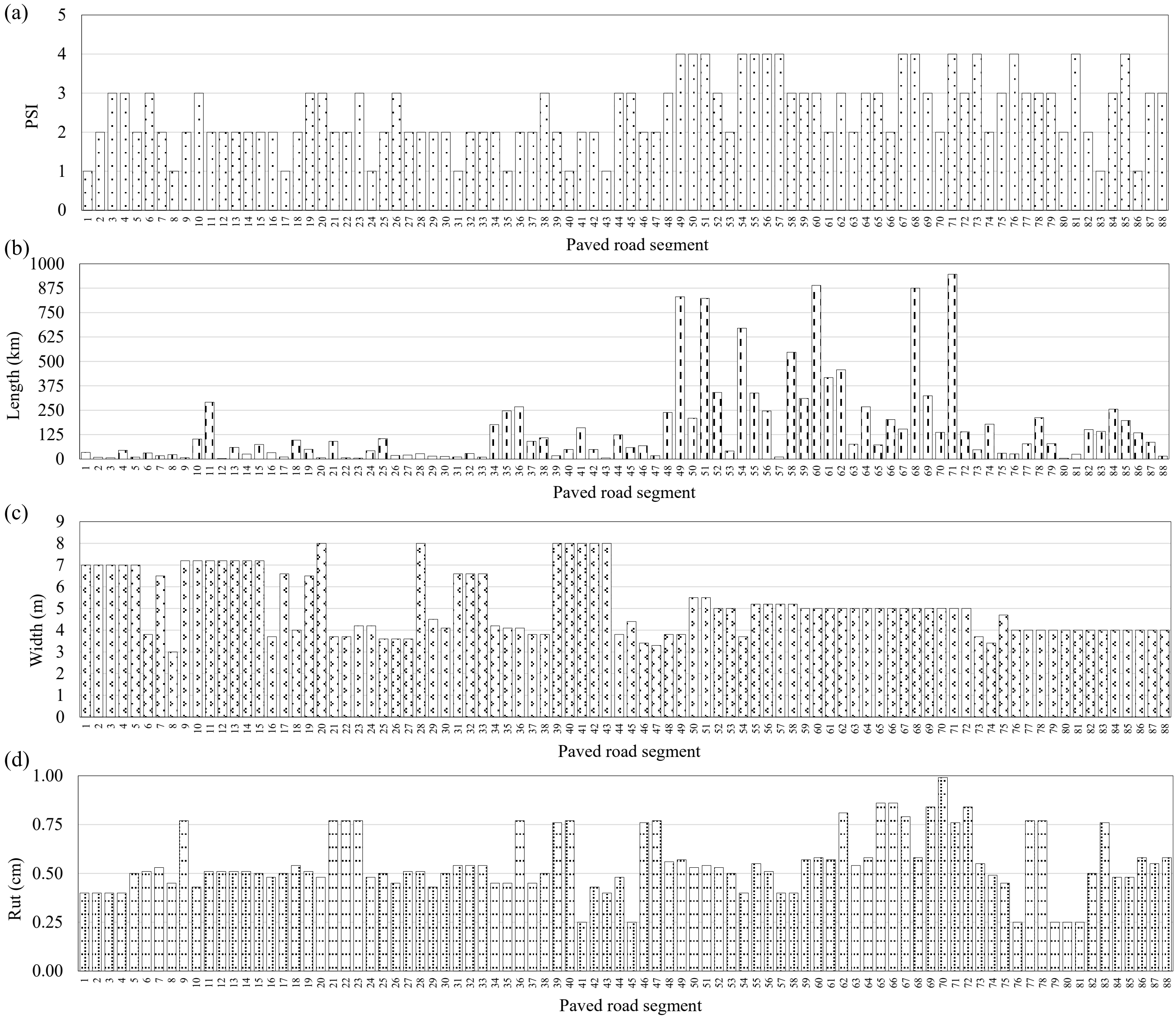

Figure 6. PSI (**a**), length (**b**), width (**c**) and rut (**d**) values obtained for paved roads of MG.

Table 3. Transition probability data obtained from the unpaved roads dataset.

RQRG	9	8	7	6	5	4	3	2	1
9	9	13	5	---	---	---	---	---	---
8	---	1	10	3	---	---	---	---	---
7	---	---	---	11	1	---	---	---	---
6	---	---	---	4	10	1	---	---	---
5	---	---	---	---	7	12	3	---	---
4	---	---	---	---	---	2	6	---	---
3	---	---	---	---	---	---	1	9	---
2	---	---	---	---	---	---	---	3	3
1	---	---	---	---	---	---	---	---	2

The deterioration models were derived from regression analyses applied to the mean data obtained from the Markovian distribution. Using these models, it was possible to determine the time taken to transition from an excellent condition to a failed condition. Equations (5) and (6) show the deterioration models obtained for the unpaved and paved roads, respectively. In these equations, URCI indicates the unpaved roads condition index, PCI indicates the pavement condition index and AGE is the age (in years).

Table 4. Transition probability data obtained from the paved roads dataset.

PCI	5	4	3	2	1
5	25	17	---	---	---
4	---	57	31	---	---
3	---	---	147	51	---
2	---	---	---	52	11
1	---	---	---	---	2

Table 5. Transition Probability Matrix from the unpaved roads dataset after 1 year.

RQRG	9	8	7	6	5	4	3	2	1
9	0.333	0.481	0.185	---	---	---	---	---	---
8	---	0.071	0.714	0.214	---	---	---	---	---
7	---	---	---	0.917	0.083	---	---	---	---
6	---	---	---	0.267	0.667	0.067	---	---	---
5	---	---	---	---	0.318	0.545	0.136	---	---
4	---	---	---	---	---	0.250	0.750	---	---
3	---	---	---	---	---	---	0.100	0.900	---
2	---	---	---	---	---	---	---	0.500	0.500
1	---	---	---	---	---	---	---	---	1.000

Table 6 represents the transition probability matrix for paved roads of MG. These probabilities are assumed to be constant, i.e., the transition matrix is stationary. According to the data reported in Table 6, it can be observed that the number 0.595 represents the percentage of roads that stay at level five after 1 year. Similarly, the element 0.405 represents the percentage of roads that deteriorate from level five to level four.

Table 6. Transition Probability Matrix from the paved roads dataset after 1 year.

PCI	5	4	3	2	1
5	0.595	0.405	---	---	---
4	---	0.648	0.352	---	---
3	---	---	0.742	0.258	---
2	---	---	---	0.825	0.175
1	---	---	---	---	1.000

The probability distribution derived from the application of the Markovian probability process for unpaved roads is presented in Table 7. In this table, states of maximum probability were highlighted in red. For example, comparing the obtained data from year 1 to year 5, there was a probability of 0.004 for the unpaved road segments to stay at level nine and a probability of 0.037 for these segments to be at level two after 5 years. In year 5, the highest probability value (0.327) indicated the unpaved road segments of MG at level five.

Table 8 represents the probability distribution derived from the application of the Markovian probability process to the paved road dataset. Again, states of maximum probability are shown in red. Comparing the distribution from year 1 to year 5, there was a probability of 0.075 for the paved road segments to stay at level five and a probability of 0.024 for the segments to be at level one. However, the highest probability value in year 5 was 0.415, which indicated paved roads at level three.

Table 7. Probability distribution obtained from the unpaved roads dataset using the Markov process.

RQRG		9	8	7	6	5	4	3	2	1	Total
Year	**1**	0.333	**0.481**	0.185	0	0	0	0	0	0	1
	2	0.111	0.194	**0.451**	0.230	0.011	0	0	0	0	1
	3	0.037	0.067	0.272	**0.413**	0.185	0.021	0.001	0	0	1
	4	0.012	0.023	0.123	0.312	**0.351**	0.134	0.041	0.001	0	1
	5	0.004	0.007	0.049	0.173	**0.327**	0.246	0.152	0.037	0	1

Table 8. Probability distribution obtained from the paved roads dataset using the Markov process.

PCI		5	4	3	2	1	Total
Year	**1**	**0.595**	0.405	0	0	0	1
	2	0.354	**0.503**	0.143	0	0	1
	3	0.211	**0.469**	0.283	0.037	0	1
	4	0.126	**0.389**	0.375	0.104	0.006	1
	5	0.075	0.303	**0.415**	0.183	0.024	1

$$URCI = 0.035 \times (AGE)^2 - 1.082 \times (AGE) + 9.107 \tag{5}$$

$$PCI = 0.005 \times (AGE)^2 - 0.268 \times (AGE) + 4.463 \tag{6}$$

These results suggest that unpaved roads tended to deteriorate more rapidly over time. The good alignment between the experimental findings derived from the methodology outlined in this paper and the results of previous studies underscores the robustness of the proposed methodology. According to previous literature, the faster deterioration of unpaved roads is affected by permeability, materials, construction, traffic, environment and drainage factors. Among them, the most important factor is the permeability and weather [33]. As a result of these factors, tropical roads experience faster deterioration, and unpaved road surfaces are more permeable compared to paved surfaces.

Details related to the five treatment options proposed in this methodology for the unpaved roads (GM, 1-R, 2-R, 3-R and 4-R) are summarized in Table 9, while Table 10 shows the six possible treatment options (GM, 1-R, 2-R, 3-R, 4-R and 5-R) proposed for the paved roads. The estimated costs were provided in BRL because it is the currency used in MG, thus reflecting the local economic context.

Table 9. Treatment types and costs for unpaved roads.

Treatment Type	Details and Applications	Estimated Cost per km	
		BRL	**USD**
GM (General maintenance)	Biannual maintenance procedures	600.00	110.62
1-R (Chemical and mechanical stabilization)	Conventional stabilizing agents	20,000.00	3687.32
2-R (Preventive rehabilitation)	DNIT recommendations	3180.00	586.28
3-R (Preventive rehabilitation with shoulder needs)	DNIT recommendations	71,387.00	13,161.32
4-R (paving the roads)	Addition of pavement	400,000.00	73,746.31

Note: All amounts in BRL have been converted to USD based on the exchange rate from 19 June 2024, where USD 1 = BRL 5.4240.

In Table 11 and Figure 7, the results provided by the optimization algorithm for unpaved roads are organized into four distinct scenarios, as follows: (i) conditions under current circumstances (referred to as the “current condition”), (ii) conditions following four cycles of 3 months without any maintenance (termed “do nothing”), (iii) conditions after applying treatments without budgetary constraints (designated as “no budget constraints”) and (iv) conditions after applying treatments necessary for maintaining the road’s condition within a limited budget (referred to as "limited budget"). The rationale behind the selection of a 3-month period stems from the observed tendency for unpaved roads to require the next level of maintenance every 3 months [24].

Table 10. Details of treatment types proposed in this methodology and costs for paved roads.

Treatment Types	Details and Application	Estimated Cost per km	
		BRL	USD
GM (general maintenance)	Asphalt patching Pothole repair Crack sealing Road striping	1875.00	345.69
1-R (preventive rehabilitation)	Chip seal Micro-surface Thin overlay (lower than 5 cm)	51,800.00	9550.15
2-R (minor rehabilitation)	Preparation of the surface Seal coat and thick overlay (higher than 5 cm) 1-R plus shoulder or widening requirements	100,000.00	18,436.58
3-R (medium rehabilitation)	Applied to good-condition roads with shoulder needs 2-R plus shoulder or widening requirements	150,000.00	27,654.87
4-R (major rehabilitation)	Applied to narrow roads with shoulder or widening needs	200,000.00	36,873.16
5- R (reconstruction)	Reconstruction of the road	300,000.00	55,309.73

Note: All amounts in BRL have been converted to USD based on the exchange rate from 19 June 2024, where USD 1 = BRL 5.421299.

Table 11. Unpaved roads treatment decisions obtained with the optimization algorithm.

Segment	Current Condition				Do Nothing		No Budget Constraints		Limited Budget	
	PSI	Length L (km)	Soil Type	PSI × L (km)	PSI	PSI × L (km)	PSI	PSI × L (km)	PSI	PSI × L (km)
1	1.00	1.94	Sand	1.940	0.92	1.783	4.10	7.954	0.92	1.783
2	1.80	0.91	Silt	1.638	1.72	1.564	4.00	3.640	1.72	1.564
3	2.81	0.62	Clay	1.742	2.73	1.692	3.90	2.418	3.90	2.418
4	2.51	0.65	Sand	1.632	2.43	1.578	2.51	1.632	2.51	1.632
5	1.50	1.02	Silt	1.530	1.42	1.446	4.00	4.080	1.42	1.446
6	0.88	0.13	Clay	0.114	0.80	0.104	4.10	0.533	0.80	0.104
7	1.63	0.27	Silt	0.440	1.55	0.418	4.00	1.080	1.55	0.418
8	0.89	1.52	Silt	1.353	0.81	1.228	4.10	6.232	0.81	1.228
9	1.80	0.57	Sand	1.026	1.72	0.979	4.00	2.280	1.72	0.979
10	1.03	1.18	Silt	1.215	0.95	1.119	4.00	4.720	0.95	1.119
11	1.19	1.00	Clay	1.190	1.11	1.108	4.00	4.000	1.11	1.108
12	3.06	2.65	Silt	8.109	2.98	7.892	3.06	8.109	3.06	8.109
13	1.22	0.26	Silt	0.317	1.14	0.296	4.00	1.040	4.00	1.040
14	1.63	0.56	Clay	0.913	1.55	0.867	4.00	2.240	1.55	0.867
15	0.90	0.13	Clay	0.117	0.82	0.106	4.10	0.533	0.82	0.106
16	0.93	0.90	Sand	0.837	0.85	0.763	4.10	3.690	0.85	0.763
17	1.22	0.60	Sand	0.732	1.14	0.683	4.00	2.400	1.14	0.683
18	2.34	1.30	Silt	3.042	0.92	1.190	4.00	5.200	4.00	5.200

Table 12 and Figure 8 present similar results for four different scenarios considered in the optimization algorithm for the paved roads. In this case, the "do nothing" scenario reflects conditions after 12 months without any maintenance. The reason for this 12-month period is that the typical lifespan of paved roads without maintenance is longer than that of unpaved roads [24].

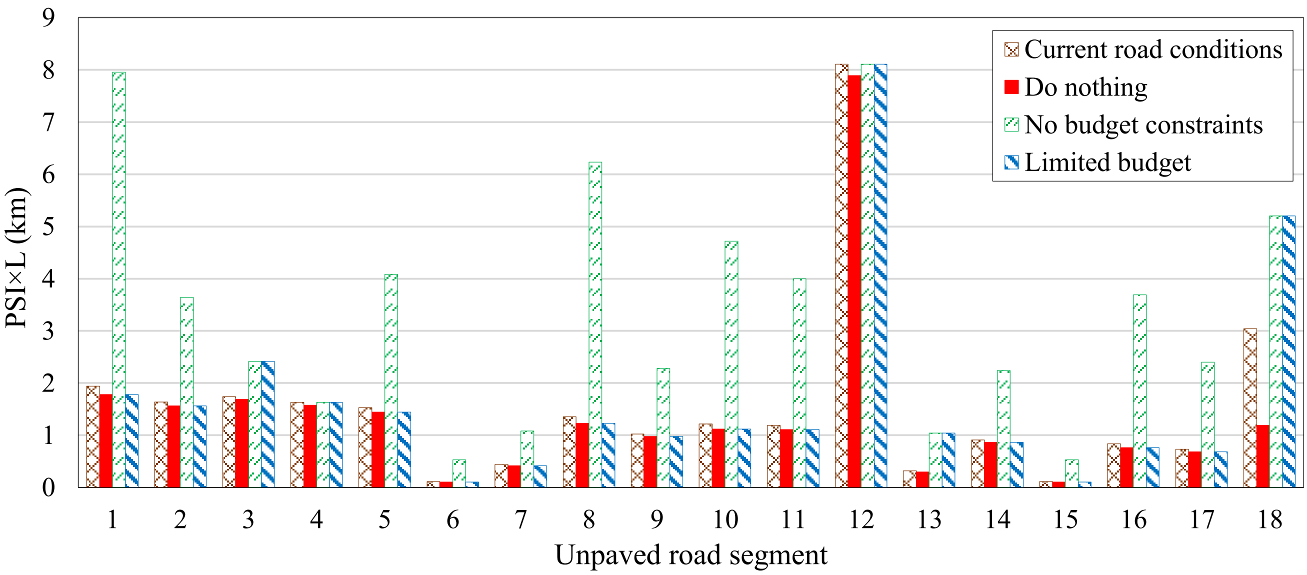

Figure 7. Unpaved roads treatment decisions obtained with the optimization algorithm.

Table 12. Paved roads treatment decisions obtained with the optimization algorithm.

Paved Road	Current Condition					Do Nothing		No Budget Constraints		Limited Budget	
	PSI	Length L (km)	Width (m)	Rut (cm)	PSI × L (km)	PSI	PSI × L (km)	PSI	PSI × L (km)	PSI	PSI × L (km)
LMG-633	1	35	7.0	0.40	35	0.96	33.4	4.30	150.5	0.96	33.4
LMG-820	2	9	7.0	0.40	18	1.86	16.7	4.00	36.0	4.00	36.0
MG-050	3	6.5	7.0	0.40	19.5	2.80	18.2	3.90	25.4	2.80	18.2
MG-123	3	45	7.0	0.40	135	2.80	126.0	3.90	175.5	2.80	126.0
MG-123/BR-262	2	10	7.0	0.50	20	1.86	18.6	4.00	40.0	4.00	40.0
MG-129	3	32	3.8	0.51	96	2.80	89.6	4.00	128.0	2.80	89.6
MG-129/BR-120	2	17	6.5	0.53	34	1.86	31.6	4.00	68.0	1.86	31.6
MG-164	1	23	3.0	0.45	23	0.95	21.9	4.30	98.9	0.95	21.9
BR-460	3	79	4.0	0.25	237	2.80	221.2	3.90	308.1	2.80	221.2
BR-462	2	4	4.0	0.25	8	1.86	7.4	4.00	16.0	1.86	7.4
BR-464	4	25	4.0	0.25	100	3.75	93.8	4.00	100.0	4.00	100.0
BR-474	2	151	4.0	0.50	302	1.86	280.9	4.00	604.0	1.86	280.2
BR-482	1	142	4.0	0.76	142	0.95	134.9	4.30	610.6	0.96	135.6
BR-491	3	256	4.0	0.48	768	2.80	716.8	3.90	998.4	2.80	716.8
BR-494	4	198	4.0	0.48	792	3.75	742.5	4.00	792.0	4.00	792.0
BR-496	1	135	4.0	0.58	135	0.95	128.3	4.30	580.5	0.95	128.3
BR-497	3	86	4.0	0.55	258	2.80	240.8	4.00	344.0	2.80	240.8
BR-499	3	15	4.0	0.58	45	2.80	42.0	4.00	60.0	2.80	42.0

Comparisons between the maintenance costs of unpaved and paved roads indicated that the full rehabilitation costs of county paved roads were approximately 10 times higher per kilometer compared to those for unpaved roads, considering the difference in maintenance treatment frequency, which is approximately four times higher for unpaved roads (every 3 months) compared to that for paved roads (every 12 months). The models accurately depicted the pattern where major treatments result in a minimal need for further treatments over the following several years in both situations.

It is important to highlight that other countries may have different optimization priorities. For instance, engineers might aim to maximize the overall network road conditions given an unrestricted budget. In the present study, the options for maximizing network road conditions and minimizing costs were thoroughly examined to showcase the potential of the proposed methodology.

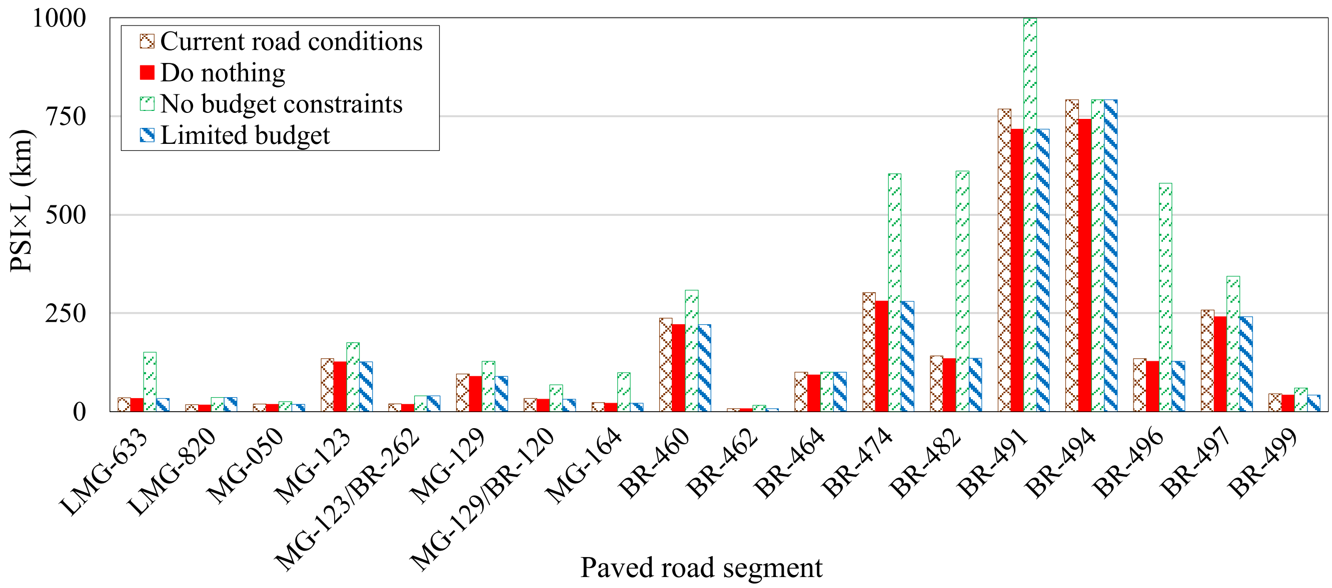

Figure 8. Paved roads treatment decisions obtained with the optimization algorithm.

4. Conclusions

In the present research, optimization techniques for the management of unpaved and paved roads of MG were applied, enabling the evaluation of the best combination of projects for road preservation, considering different constraints. The following conclusions were derived from the present paper:

- Based on the transition probability data, transition probability matrices and probability distribution matrices, it was possible to quantify the probability of unpaved and paved roads being in different condition levels after various periods.
- The Markovian probability distribution matrix revealed that an MG unpaved road that is initially at the highest condition level (nine) would have a higher probability of being at level eight after 1 year (48.1%) and a higher probability of being at level five after 5 years (32.7%). Similarly, a paved road that is initially at the highest condition level (5) would be more likely to remain at level 5 (59.5%) after 1 year and more likely to remain at level 3 (41.5%) after 5 years.
- The regression analysis models developed in this research enabled the determination of the time required for unpaved and paved roads of MG to go from being in excellent condition to being in a failed condition, based on the age of the roads.
- The results of the optimization algorithm for unpaved and paved roads were organized into four distinct scenarios: (i) conditions under the current circumstances (referred to as "current condition"), (ii) conditions without any maintenance ("do nothing"), (iii) conditions after applying treatments without budget constraints ("no budget constraints") and (iv) conditions after applying treatments required to maintain the road condition within a limited budget ("limited budget"). These results showed that the best results were achieved without budget constraints.
- Different preservation projects were evaluated in order to reach the maximization of the overall condition of paved and unpaved roads at minimal costs. Comparisons between the maintenance costs of unpaved and paved roads suggested that the full rehabilitation costs of paved roads were around 10 times higher per kilometer compared

to those of unpaved roads, considering the difference in the maintenance treatment frequency, which is approximately four times higher for unpaved roads (every 3 months) compared to that for paved roads (every 12 months).

- The models effectively captured the trend wherein a major treatment leads to minor additional treatments being needed for the subsequent several years in both scenarios.

The findings of the present study provide future directions for the optimized allocation of resources for the management of roads in MG. Further research is recommended to investigate the implementation of the proposed methodology in other regions and identify minor changes in some procedures that may be needed to reflect distinct local conditions.

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