

**LAURA CARINE PEREIRA RIBEIRO**

**ESTABLISHING A METHODOLOGY FOR UNPAVED AND PAVED ROADS  
MANAGEMENT SYSTEM**

Tese apresentada à Universidade Federal de Viçosa, como parte das exigências do Programa de Pós-Graduação em Engenharia Civil, para obtenção do título de Doctor Scientiae.

Orientador: Taciano Oliveira da Silva

Coorientador: José Carlos Lopes Ribeiro

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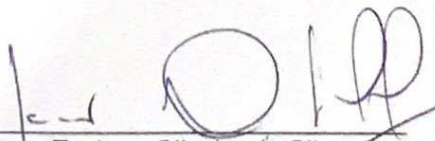
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Assentimento:



Laura Carine Pereira Ribeiro  
Autora



Taciano Oliveira da Silva  
Orientador

Something good going to come your way

Just look out your door...

(RHCP)

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A Deus, por estar sempre me iluminando a cada tomada de decisão.

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## **BIOGRAFIA**

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Em Fevereiro de 2016, iniciou o curso de Engenharia Civil no Centro Universitário Sul de Minas – UNIS, com graduação prevista para ser concluída em Dezembro de 2020.

Em Março de 2016, ingressou no curso de Pós-Graduação em Engenharia Civil, área de concentração em Geotecnia, ao nível de doutorado, na Universidade Federal de Viçosa – UFV, submetendo-se à defesa da dissertação em Outubro de 2020.

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## **BIOGRAFY**

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In February 2016, she started her Civil Engineering undergraduation at Centro Universitario Sul de Minas - UNIS where her graduation will be concluded in December 2020.

In March 2016, she joined the Post-Graduation program in Civil Engineering, - Geotechnics major, at the doctor degree level, at the Federal University of Viçosa - UFV, submitting her dissertation in October 2020.

In September 2018, she joined the University of Wyoming - United States, at the Civil and Architectural Engineering Department – Transportation major, where she spent one (1) year as an academic researcher under Professor Khaled Ksaibati supervision.

## RESUMO

RIBEIRO, Laura Carine Pereira, D.Sc., Universidade Federal de Viçosa, outubro de 2020. **Establishing a methodology for unpaved and paved roads management system.** Orientador: Taciano Oliveira da Silva. Coorientador: Jose Carlos Lopes Ribeiro.

No estado de Minas Gerais, Brasil, as estradas são administradas por agências locais que efetuam mais trabalhos de manutenção e reabilitação (M&R) do que trabalhos de gerenciamento. Além disso, essas agências têm recursos muito limitados e operam sem planos de longo prazo. Assim, neste trabalho teve-se por foco o processo de desenvolvimento de um novo Sistema de Gerenciamento de Estradas Não Pavimentadas (SGENP) e de um Sistema de Gerenciamento de Pavimento (SGP). Esses sistemas de gerenciamento destinam-se a fornecer práticas viáveis para ajudar as agências locais a lidar com os vários desafios associados à manutenção de estradas não pavimentadas e pavimentadas. O objetivo final desses sistemas é ajudar as agências locais a manter suas estradas com o melhor custo-benefício, realizando manutenções dentro dos recursos financeiros disponíveis. A metodologia deste estudo visou estabelecer uma linha de base para os novos SGENP e SGP, para aprimorar as práticas atuais de gerenciamento de estradas não pavimentadas e pavimentadas em Minas Gerais. Antes da implementação em todo o estado, a região da Zona da Mata, no sudeste do estado, foi selecionada uma estrada para realizar estudo piloto sobre o tema. Um conjunto de dados abrangente foi desenvolvido após a coleta de dados. Técnicas estatísticas foram empregadas para estabelecer as novas metodologias. Essas técnicas incluem cadeias de Markov, para desenvolver modelos de deterioração, e análise de algoritmos evolutivos, para desenvolver o processo de tomada de decisão. Como resultado, foi desenvolvido um programa de gerenciamento para estradas não pavimentadas e pavimentadas utilizando uma entrada de dados prática e resultados estatisticamente confiáveis. Com esse programa, pequenas ou grandes cidades e empresas podem melhor gerenciar a sua malha viária, aplicando manutenções pontuais, com o melhor custo-benefício para o órgão competente, visando sempre o seu limite orçamentário.

Palavras-chave: Estradas pavimentadas. Estradas não pavimentadas. Manutenção.

## ABSTRACT

RIBEIRO, Laura Carine Pereira, D.Sc., Universidade Federal de Viçosa, October, 2020. **Establishing a methodology for unpaved and paved roads management system.** Advisor: Taciano Oliveira da Silva. Co-advisor: Jose Carlos Lopes Ribeiro.

In the state of Minas Gerais, Brazil, roads are mostly managed by local agencies that carry out more maintenance and rehabilitation (M&R) work than management work. In addition, these agencies have very limited resources and operate without any long-term plans. Overall, there is no available guidelines or consistent strategies followed over the state to manage these kinds of roads. As a result, this work was created to develop a new Unpaved Roads Management System (URMS) and a Pavement Management System (PMS). These URMS and PMS are intended to provide feasible practices to help local agencies in dealing with the various challenges associated with maintaining unpaved and paved roads. The ultimate goal of these URMS and PMS is to help local agencies in maintaining their asset of all the roads in best serviceable shape within available resources. The methodology of this study was to establish a prototype for the new URMS and PMS to improve current management practices for unpaved and paved roads in Minas Gerais. Before implementation across the state, was selected a specific road to carry out the pilot study on the topic, a region at Zona da Mata County, close to Viçosa city. A comprehensive dataset was developed after data collection. This dataset was used to develop various methodologies related to URMS and PMS in Minas Gerais. Statistical techniques were used to establish the new methodologies. These techniques include Markov chains to develop deterioration models and analysis of evolutionary algorithms to develop the decision-making process. As a result, a management program for unpaved and paved roads was developed using practical data entry and statistically reliable results. With this program, small or large cities and companies can better manage their road network, applying specific maintenance, with the best cost-benefit for the competent agency, always aiming at their budget limit.

Keywords: Optimization systems. Unpaved roads. Paved roads.

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## CHAPTER 1: Introduction

In 2018, the National Transport Confederation (Confederação Nacional do Transporte - Brazilian agency to manage transports) estimated the length of the Brazilian road network at 1,720,700 km, with 213,453 km on paved roads (13,49%), 1,349,938 km on unpaved roads (86, 51%), which only 157,309 km of the total were planned roads (CNT, 2019). According to the CNT (2019), 61% of the trucks and 95% of the passenger vehicles use the highway system constituting the main element of the Brazilian transportation. It is also predictable that due to the difficulty access to some areas, this number should be much larger than the length exposed.

The state of Minas Gerais has the largest road network in Brazil, equivalent to about 16% of all existing road network in the country. In this state, there are 272,063 km of highways. Of this total, 9,205.5 km are paved federal roads, 22,286 km are paved state roads, and 240,571 km are unpaved municipal roads (Rodovias, 2019). About the pavement, the federal network is almost paved with only 576.60 km of unpaved roads. The state network is divided into 22,286 km of paved, 4,925.75 km of unpaved, and 316.4 km with paving work in progress. The municipal network is basically composed by unpaved roads (Rodovias, 2019).

In the bibliography research phase of this work, it was possible to observe that the municipal roads network does not have the required maintenance conditions or technical support to assist the decisions to make. This problem results in surfaces that are inappropriate for the traffic, resulting in bad conditions to the trucks and shipments, to the cars and the travelers, and triggering considerable environmental damage (Maibach et al., 2008; Bickel and Friedrich, 2013). This context shows the need to create an effective maintenance management system for all types of roads (UN, 2015). To create a methodology for this work, it is necessary to keep in mind some aspects to consider in order to create a multi-agent system (MAS): the type of the road and the current condition, the types of trucks available and their weight, and finally the available budget to perform the maintenance.

Currently, developed countries have an efficient management system to prioritize roads segments to be maintained according to available budget: Pavement Management Systems (PMS) for paved roads and Unpaved roads Management Systems (GRMS) for unpaved roads (WTTC, 2014). In this study, it is necessary to

understand how these maintenance systems work to develop a cost-effective maintenance management system for paved and unpaved roads. This system will be created thinking carefully about all the stages of execution, which will predict the future condition of the road and then compute the best maintenance option according to the budget and available time of each situation.

### **1.1. Problem Statement**

Collecting feasible roads condition (unpaved or paved) data is considered by companies and research as one of the main challenges of building any management system. Measuring actual roughness is still not a feasible option for monitoring unpaved roads but works well to paved roads (Aleadelat, 2018). Currently, the state of Minas Gerais utilizes inexpensive, less labor-intensive windshield surveys to evaluate road conditions that one can observe at DNIT guide (DNIT, 2003). However, these surveys are not able to follow the whole dynamic nature of the unpaved roads. Unpaved roads can change quickly due to the various traffic and weather conditions. Hence, local agencies are in need for an automated and low-cost data collection method to monitor all the roads. Also, the acquired data feed from any new data collection method should be frequent to control the dynamicity of these roads.

At this time, there are no available guidelines or consistent strategies followed in Minas Gerais to manage unpaved or paved roads. Normally, local agencies base their decisions on local considerations and run their maintenance according only to their experience (Veryard, 2016). Usually, these agencies know the best maintenance practices that should be followed to maintain any road. Nonetheless, according to some local agents, these agencies do not know which roads should be given the priority for maintenance projects every year (Graham, 2014).

On one hand, it is a cost-effective approach for many local agencies to prefer managing an asset of unpaved roads compared to paved ones. On the other hand, the amount of dust and potholes is considered a major flaw of maintaining an asset of unpaved roads comparing to paved roads.

### **1.2. Research Objectives**

This research study aims to develop several methodologies that can facilitate the management of unpaved and paved roads in Minas Gerais, Brazil. The new methodologies will help local agencies in optimizing their limited budgets and

maintaining unpaved or paved roads under their jurisdictions in the best serviceable shape. The main objectives of this study are summarized as follows:

1. Developing a regression model to use the historical unpaved roads dataset to match the method needs that is feasible for small local agencies in Minas Gerais state, Brazil.
2. Developing a deterioration model for paved roads in Minas Gerais (Brazil) using Markovian process to predict the future condition and future needs.
3. Developing a deterioration model for unpaved roads at Zona da Mata county, Minas Gerais (Brazil) using Markovian process to predict the future condition and future needs.
4. Developing a comprehensive optimization methodology that can help local agencies in selecting the most appropriate maintenance type for any unpaved or paved road under their jurisdiction. This will include estimating potential projects costs and funding allocation.

### **1.3. Research Tasks**

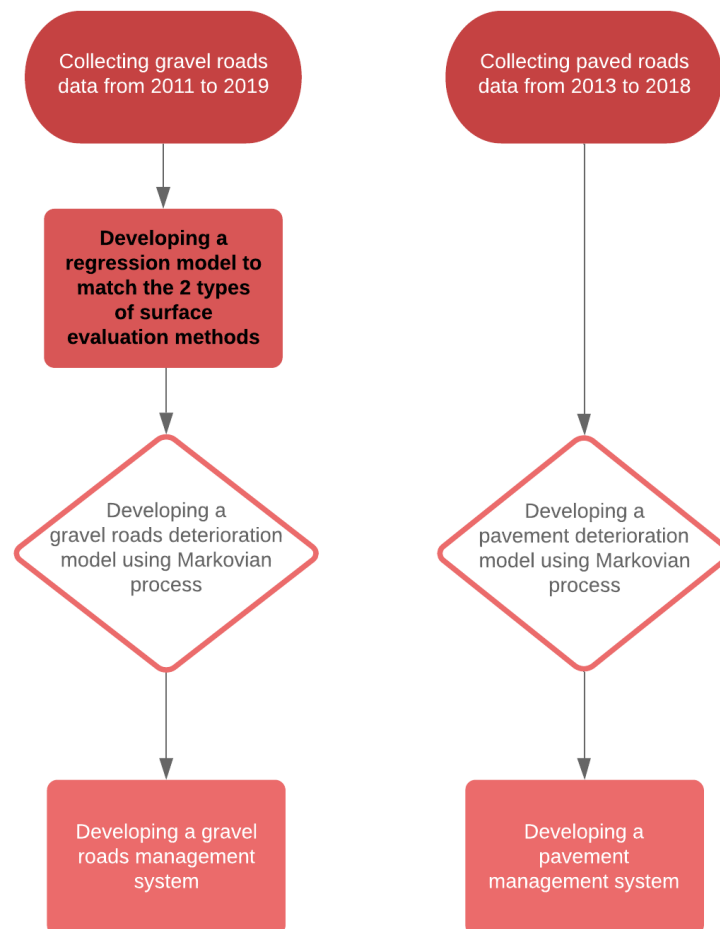
Several tasks were identified and accomplished to achieve the objectives of this research study. Figure 1 shows a schematic diagram for the different research tasks that were accomplished for this study. These tasks include intensive field data collection efforts, in addition to, programming and analytical efforts that yielded important tools for the management of unpaved and paved roads. Every accomplished task yielded a research paper as shown in the following subsections.

#### **1.3.1. Collecting Unpaved roads/Paved Roads Condition Data**

Zona da Mata, located in the southeastern part of the state of Minas Gerais, was selected to perform a pilot study prior to any statewide implementation of the new GRMS. On other hand, to perform a pilot study to develop the PMS, was considered the entire state of Minas Gerais. In this state, there are 272,063 km of highways. Of this total, 9,205.5 km are paved federal roads, 22,286 km are paved state roads, and 240571 km are unpaved municipal roads (Rodovias, 2019). The paved dataset was formed by a collection from CNT group. On the other hand, the unpaved dataset was collected by the authors. A rating team of three collected all the data to evaluate the entire road network. The rating team used the DNIT 008 guide (DNIT, 2003) from the Brazilian transportation and infrastructure agency (Departamento Nacional de

Infraestructura de Transportes-DNIT) to follow the procedures to evaluate the paved roads, and was also followed two visual windshield surveys to evaluate unpaved roads: the Ride Quality Rating Guide (RQRG) and the Unpaved roads Rating Standards (GRRS) from Wyoming Technology Transfer Center (WTTC, 2014). During the rating process, the rating team performed a road segmentation process based on many factors such as: usage levels, changes in surface type, intersections, surface conditions, and type of surroundings (i.e. crops or houses).

The main purpose of the segmentation was to obtain uniform, consistent, homogeneous, and more representative ratings. This intensive data collection effort resulted in a comprehensive database that was used later to establish or to validate the developed methodologies in this research study. This task is going to be described in all four papers during this study.



**Figure 1: Research Methodology**

### **1.3.2. Developing a regression model to match the 2 types of surface evaluation methods**

This task describes the methodology developed to create a regression model to standardize the objective method to evaluate unpaved roads based on the results of subjective method. This result is going to extend the historical data and fill the gaps to create a PMS to maintain the roads, once each state or city have their preference for one of these two surveys methods. The overall Brazilian network of unpaved county roads exceeds 1,359,045.3 km according CNT (2019). This network is usually composed of roads with poor maintenance due to lack of financial resources and proper technical knowledge. There are two types of functional evaluations to classify the surface conditions of tropical unpaved roads. The objective of this research task was to establish a correlation between the results of these two evaluations, objective and subjective evaluations.

Such correlation represents the fact of the subjective assessment better represents the conditions of tropical unpaved roads, as authors have already found, and match the two types of evaluation to create a unique dataset. The analysis was composed of one road of 4,050 km that was split into 18 sample units of 150 meters each. In the subjective evaluation, the study team drove through the road's sections, ranking them according to the road's travel quality. In the objective evaluation, the team evaluated the surface conditions of sampling units representing the road sections, rating them according to their Unsurfaced Road Condition Index (URCI) (DNIT, 2003). Multivariate statistical analysis was used to establish correlations between the subjective evaluation and the road distresses.

Based on the results, regression models were developed to predict objective values based on subjective values in two different situations: when the roads have periodic maintenance, and when the roads do not have periodic maintenance. As these models provide precise results, it is possible to use the both objective or subjective methodology to evaluate roads standardizing the methods and filling the gaps to create a pavement management system to better maintain the roads. This study will compose chapter 2 of this thesis.

### **1.3.3. Developing an unpaved roads/paved roads deterioration model using Markovian process**

In this research task, a probabilistic performance models that predict the deterioration patterns of unpaved roads and paved roads were established using Markov Chains (MC). The implementation of this probabilistic modeling approach has been widely used in the management of paved roads as it is flexible and requires minimal historical data to develop performance models (Aleadelat, 2018).

- **Unpaved road deterioration model**

In this task, the developed prediction equations are based on the GRRS system which is a modification to the Pavement Surface Evaluation and Rating (PASER) system from Transportation Information Center (Walker, 1989). This system is the most popular system to evaluate unpaved roads in the U.S.A.

The dataset from Viçosa city was collected by the authors and was used to develop the initial and the start vectors. Then, the functional conditions were used to develop the Transition Probability Matrices (TPM) (Pinsky and Karlin, 2011). The application of MC requires, at least, two successive time series historical data. Then, the found TPM and the initial vectors were used to develop the Markov Chains and the service life prediction equations for the unpaved and paved roads. It was found that the average service life of an unpaved roads around 8 and 16 months. Nevertheless, the prediction of unpaved roads service life is very hard as these roads are very dynamic with interrelated deterioration modes.

- **Paved road deterioration model**

The developed prediction equations are based on the PCI system from the AASHTO guide (AASHTO, 2001). This system is the most popular system to evaluate paved roads in all over the world.

The dataset from Minas Gerais state was collected by the CNT organization, which was used to develop the initial and the start vectors. Then, the functional conditions were used to develop the Transition Probability Matrices (TPM) (Pinsky and Karlin, 2011). It was found that the average service life of a paved road is around 10 and 20 years, and it is easier to predict than unpaved roads.

The formulation of any distress at the road surface encourages the formulation of many others. Lastly, the new equations will be used in the development of another comprehensive optimization model to select unpaved roads maintenance practices. This research task is going to be divided in two papers consolidated in chapter 3 and chapter 4, working respectively with paved and unpaved roads.

#### **1.3.4. Developing an unpaved roads/paved roads management system**

This research task established a comprehensive optimization model that helps local agencies in selecting maintenance strategies and allocating funds to the various unpaved roads projects and paved roads projects. Every year, local agencies implement many maintenance strategies to preserve their asset of roads. These strategies include, but are not limited to, blading, re-unpaving, and applying chemical treatments for unpaved, and for paved roads include, but not limited to, fog seals, crack seals, slurry seals, traction seal and thin overlays (Asphalt Institute, 1996; Huntington and Ksaibati, 2011).

In Brazil, there is a lack in the management systems that are appropriate for small local agencies which are responsible for the management of unpaved or paved roads. Previous efforts to establish URMS/PMS strategies are mostly limited to the developing agency or state. Normally, each state or public agency will have their own goals or ambitions while managing the roads. Due the poor conditions of the roads and limited budget to spend on infrastructure, it is necessity to develop strategies specific to Minas Gerais which can be implemented by local agencies to manage the vast roads network in the state.

The established optimization model works towards maximizing the overall roads network conditions considering traffic volumes and subject to the assigned budgets. A user can run this tool by simply uploading an Excel sheet with the required parameters. Using this tool, a decision maker will be able to identify the most appropriate treatment type for each unpaved/paved road, service level, estimated project cost, predicted road condition, and whether to fund a project or not. Other local agencies in Brazil can use the same tool with some modifications. This research task was documented in chapter 5 on this thesis.

#### 1.4. Thesis Organization

In this research study, the new established methodologies are presented in four papers. Each paper is presented solely in a separate chapter throughout this thesis. The first chapter is the introduction. It is based on general information to give the lector all the important leads that are necessary to understand the other chapters. The first paper or chapter 2 talks about the evaluating road assessment systems for tropical low-volume unpaved roads. The second paper or chapter 3 talks about developing a deterioration model using Markovian probabilistic process for Brazilian unpaved county roads. The third paper or chapter 4 talks about developing a deterioration model using Markovian probabilistic process for Brazilian paved roads. And the fourth paper or chapter 5 talks about developing an optimization model to manage unpaved and paved roads. The chapter 6 summarizes the conclusions from all the previous chapters, and presents ideas and suggestions to future works on this field. At the end of this thesis, a brief guide to explain how to use the system is presented in an Appendix.

#### REFERENCES

- AASHTO, (2001). AASHTO Pavement Management Guide. Washington, DC: AASHTO.
- Aleadelat, W. (2018) Establishing a Methodology for Unpaved roads Management System, Ph.D. Dissertation. Department of Civil and Architectural Engineering, University of Wyoming.
- Asphalt Institute (1996) Asphalt in Pavement Maintenance, Manual Series No. 16, Third Edition, Asphalt Institute, Lexington, KY, 1996.
- Bickel, P., and R. Friedrich (eds.) (2013), Environmental External Costs of Transport, Springer Science & Business Media, Stuttgart.
- Confederação Nacional do Transporte – CNT (2019) Anuário CNT do transporte – estatísticas consolidadas 2019. Brasília: 2019.
- DNIT- DEPARTAMENTO NACIONAL DE INFRAESTRUTURA DE TRANSPORTES, (2003) - Levantamento visual contínuo para avaliação da superfície de pavimentos flexíveis e semi-rígidos Procedimento. NORMA DNIT 008/2003 – PRO.
- Graham, D. (2014), Causal Influence for Ex-Post Evaluation of Transport Interventions, International Transport Forum, Paris.
- Huntington, G & Ksaibati, K. (2011) Management of Unsealed Gravel Roads. Transportation Research Record: Journal of the Transportation Research Board. 2011. DOI: 10.3141/2232-01.

Maibach, M., Schreyer, C., Sutter, D., Van Essen, H. P., Boon, B. H., Smokers, R. and Bak, M. (2008). Handbook on estimation of external costs in the transport sector. CE Delft

Pinsky, M. A., Karlin, S. (2011) An Introduction to Stochastic Modeling (Fourth Edition), 2011

Rodovias (2019) Rodovias – Estado de Minas Gerais. Viewed 20/09/2019. <<https://www.mg.gov.br/conheca-minas/rodovias>>

United Nations (2015), Transforming our World: The 2030 Agenda for Sustainable Development, New York.

Veryard, D. (2016) “Quantifying the socio-economic benefits of transport”, Discussion Paper n. 2016-06, ITF/OECD Publishing, Paris

Walker, D. Unpaved (1989) PASER Manual: Pavement Surface Evaluation and Rating. Wisconsin Transportation Information Center, Madison, 1989.

Wyoming Technology Transfer Center – WTTC (2014). Unpaved Road Quality Rating Guide. September 2014.

## **CHAPTER 2: Evaluating Road Assessment Systems for Tropical Low-Volume Unpaved Roads**

### **Abstract**

The overall Brazilian network of unpaved county roads exceeds 1,349,938 km. This network is usually composed of roads with poor maintenance due to lack of financial resources and proper technical knowledge. This paper addresses the application of functional evaluations to classify the surface conditions of tropical unpaved roads. The objective of this paper was to establish a correlation between the results of objective and subjective evaluations of the unpaved roads conditions. Such correlation will determine if the subjective assessment better represents the conditions of tropical unpaved roads as many authors have already found. The analysis was composed of one road of 4050 km that was split into 18 sample units of 150 meters each. In the subjective evaluation, the study team drove through the road's sections, ranking them according to the road's travel quality. In the objective evaluation, the team evaluated the surface conditions of sampling units representing the road sections, rating them according to their Unsurfaced Road Condition Index (URCI). Multivariate statistical analysis was used to establish correlations between the subjective evaluation and the road distresses. Based on these results, regression models were developed to predict objective values based on subjective values in two different situations: when the road have periodic maintenance, and when the roads do not have periodic maintenance. As these models provide precise results, it is possible to use the both objective or subjective methodology to evaluate roads "standardizing" the methods and filling the gaps to create a Pavement Management System to better maintain the roads. With this system, cities or states or even big agencies can better optimize their available budget maximizing the cost-benefits during the maintenance process.

Keywords: Unpaved Road, Multivariate Analysis, Pavement Management System, Low-Volume Roads.

## 1. INTRODUCTION

The overall Brazilian road network is 1,720,700 km long. Of this total, 1,349,938 km are unpaved of which 1,114,110 km are under county jurisdictions (CNT, 2019). In most cases, the offices responsible for the maintenance of unpaved roads in Brazil are linked to municipalities that do not have adequate financial resources for their maintenance and rehabilitation. In addition, these agencies lack the technical knowledge necessary to prioritize these activities (Silva, et al., 2011). Allocating adequate investments to these roads would result in increasing the roads service life, the productivity levels and bringing social benefits to communities by providing access to markets, services, jobs and information (Machado, 2013). However, the impact of these investments is not well understood as infrastructure placement is usually driven by endogenous economic, political, or social factors (Aggarwal, 2018)

Some unpaved roads carry extra-heavy volumes of traffic, usually in a single direction, composed of vehicles with load capacity between 30 and 40 tons and vehicles with load up over 40 tons. In other countries, the development of the automated models for optimizing unpaved road vertical alignments is one of the main goals of planners and designers before road construction to increase the service life (Nahvi, et al., 2019), but with the minimal investments in infrastructure, it is almost impossible to develop cost-effective models for developing countries. For this reason, there is a need to identify the most effective way to predict performance and maintain roads in developing countries (Babapour, et al., 2018).

Performance prediction is necessary for road condition evaluations, and for unpaved roads, it can be determined based on functional evaluations. This functional evaluation encompasses the processes of identification and characterization of aspects of its rolling surface connected to the comfort and safety of the user. Subjective and objective models can be utilized for rating the conditions of unpaved roads which provide the nucleus for a maintenance management system (Shahin, 1994).

The subjective method utilized in this study was adapted to tropical roads by Fontenele and Sória (2003), who studied the coherence analysis of the results of subjective assessment carried out by a panel of evaluators in sections and sample units of unpaved roads of the city of São Carlos, State of São Paulo, Brazil. They analyzed their surface conditions and assigned scores (0 – 100/ poor to excellent) that

represented their individual perceptions of the surface condition called Present Serviceability Ratio (PSR).

The objective assessment utilized in this study is based on the U.S. Army Corps of Engineers (USACE) methodology (Eaton and Beaucham, 1992). The primary consideration in this objective assessment of unpaved roads is the identification of roads and their subsequent division into branches, sections, and sample units. The methodology determines the Unsurfaced Road Condition Index (URCI). The referred index URCI is determined through the quantification and analysis of the roads surface distresses. Thus, the URCI can be utilized to determine the priority of maintenance on an unpaved road. An Unpaved Roads Management System (URMS) is widely used and it is a complete decision-making method to prioritize the maintenance.

A URMS is composed by seven steps: define the roadway network and collect inventory data, collect condition data, predict condition, select treatments, report results, select pavement management tool, and keep the process current (Wolters et al., 2011). To achieve these first 3 steps, is necessary to standardize the surveys, once the objective and subjective methods have different triggers.

This research had the objective of creating a regression model to standardize the objective method to evaluate unpaved roads based on the results of subjective method. This result is going to extend the historical data and fill the gaps to create a URMS to maintain the roads, once each state or city have their preference for one of these two surveys methods.

## **2. OBJECTIVES**

The first objective of this paper is to evaluate the applicability of the objective method (Eaton and Beaucham, 1992) in the assessment of unpaved roads of the Viçosa city, in the State of Minas Gerais, Brazil, based on the results of subjective evaluations carried out on these roads using a Fontenele and Sória methodology (2003). The hypothesis in this paper is that a subjective functional assessment, based on personal aspects of technical assessment is more suitable to reflect the tropical road serviceability than the objective functional assessment, based on standardized measures of distresses. To compare and match the functional condition given by objective evaluation and the condition given by Fontenele and Sória (or subjective

evaluation) which represents better the tropical soil condition, multivariate analysis must be used.

The second objective was to establish a correlation between both assessment types using multivariate analysis with the software R 3.5 (Venables and Smith, 2005) in two different situations: when roads receive periodic maintenance and when roads did not receive any maintenance.

This correlation will result in a model that will guide a reliable value to the roads functional evaluation to further develop a condition index. Once the functional assessment used after the correction is based on standardized and worldwide measures, this functional condition developed with the regression can be used to implement a reliable unpaved roads management system.

### 3. BACKGROUND

Normally, roadway functional assessment encompasses the processes of identification and characterization of road surface aspects linked to the user's comfort and safety, vehicle performance and transportation cost. The assessment includes subjective or objective evaluations (Aggarwal, 2018).

Various agencies and researchers have suggested several subjective rating methods to survey unpaved road condition including PASER, Unpaved-PASER, Unsurfaced Road Condition Index method, unmanned aerial vehicle based remote sensing and image processing, and a method developed by the U. S. Army Corps of Engineers (USACE) for cold regions (Saha and Ksaibati, 2017). Another important one is the Ride Quality Rating Guide (RQRG), which measures the quality of unpaved roads and the driver perception, and there is also the Unpaved roads Rating System (GRRS), which provides average assessments of the seven worldwide distresses. They are potholes, rutting, washboards, loose aggregate, dust, crown, and roadside drainage (Eaton and Beaucham, 1992). They are described on Table 1 and 2 respectively.

**Table 1: Severity level of pothole (Eaton and Beaucham, 1992).**

DEPTH (mm)	AREA (m <sup>2</sup> )		
	< 0,1	0,1 – 0,3	> 0,3
< 25	Low	Low	Moderate
25 – 50	Moderate	Moderate	High
> 50	Moderate	High	High

**Table 1: Types of distresses and levels of severity for the classification of unpaved roads (Eaton and Beaucham, 1992).**

Type of distresses	Level of severity		
	Low	Medium	High
Crown	Small amounts or evidence of ponding water on the road or a completely flat road surface, or both	Moderate amounts or evidence of ponding water on the road surface or a bowl-shaped road surface, or both	Large amounts or evidence of ponding water on the road surface or severe depressions in the wheel paths on the road surface, or both
Washboard	Corrugations less than 1 in (2.5 cm) deep or low-severity roughness, or both	Corrugations 1 to 3 in (2.5 to 7.5 cm) deep or medium-severity roughness, or both	Corrugations deeper than 3 in (7.5 cm) or high-severity roughness, or both
Dust	Thin dust that does not obstruct visibility	Moderately thick cloud that partially obstructs visibility and causes traffic to significantly slow down	Very thick cloud that severely obstructs visibility and causes traffic to significantly slow down or stop
Rutting	Ruts less than 1 in (2.5 cm) deep or low-severity roughness, or both	Ruts 1 to 3 in (2.5 to 7.5 cm) deep or medium-severity roughness, or both	Ruts deeper than 3 in (7.5 cm) or high-severity roughness, or both
Loose aggregate	Loose aggregate on the road surface or aggregate berm on the shoulder or less-traveled roadway area of less than 2 in (5 cm), or both	Moderate (2 to 4 in) (5 to 10 cm) aggregate berm on shoulder or less-traveled roadway area; excessive fines are usually found on the roadway surface	Large (greater than 4 in) (> 10 cm) aggregate berm on shoulder or less-traveled roadway area
Drainage	Ponding water or evidence of ponding water in ditch, and overgrowth or debris in ditch	Ponding water or evidence of ponding water in ditch, overgrowth or debris in ditch, and evidence of erosion of ditch into shoulder or roadway	Ponding water or evidence of ponding water in ditch, water running or down road, overgrowth or debris in ditch, and erosion of ditch into shoulder or roadway

In this study, a type of GRRS was used, but in Brazil this methodology is known as Fontenele and Sória (2003). The Present Serviceability Ratio (PSR) symbolizes the average value of the individual opinions issued by a group of trained and calibrated

observers for the measurement of parameters in analysis, when they register their opinions about the distresses affecting the roads (Huntington and Ksaibati, 2015).

In the objective assessment, the pavement distresses are quantified with the technical details of its state of deterioration. A well-established measurement-based unsealed road assessment procedure was developed by the U.S. Army Corps of Engineers - USACE (Eaton and Beaucham, 1992). PAVER is an example of the evaluation index of this modality on paved roads. When the distresses are known, regular maintenance can be applied correctly. The road maintenance is one of the most important engineering services, since it maintains the integrity of the physical characteristics of the cross-section and contributes to the drainage system (Huntington and Ksaibati, 2011).

Unpaved roads are constructed when volume of commercial traffic (gross weight exceeding 3 tons) is less than 400 vehicles per day (Rabello Quadros and Nassi, 2015). In terms of utility, five main factors affecting the quality of an unpaved road can be listed: traffic load, subgrade quality, construction practices, water, and maintenance program (Rohith, Srikanth, and Chowdary, 2016). According to (Kabindra, Pramen, and Thomas, 2014) it is recommended to define the types of maintenance of unpaved roads as follows:

- Routine Maintenance: emergency repairs for blocked and ruined unpaved roads; road patrolling, regularization or patching; drainage structures: external cleaning and repair of ditches and drains, external cleaning of bridges, patches of eroded areas, construction of erosion control and repairs to drainage structures.
- Major Maintenance: maintenance practices used in the case of many distresses in situations which the use of rehabilitation or reconstruction services is not justified.
- Rehabilitation: thin unpaved overlay.
- Reconstruction: complete reconstruction.

To maintain the roads properly, maintenance practices and the functional condition must be known. But in tropical soils, the objective methodology which is used to establish the functional condition is not accurate (Wolff and Caldas, 2018). Most of the

problems including functional road conditions are multivariate in nature and a statistical multivariate analysis (MVA) must be applied (Wolters et al., 2011). Thus, in this work, the subjective assessment was used as the response of the analysis and the seven distresses were used as predictors (Morero and Ortiz, 2019). In other words, the analysis was made to find a pattern recognition by providing an understanding of the 7 important patterns underlying relationships the subjective evaluation.

#### **4. METHODOLOGY**

The roadway functional condition provides information about what is happening on the roads. With the current condition (and historical data if it is available) it is possible to make a prediction of pavement performance using statistical methods and predict the remaining service life.

The experiment included subjective and objective assessments performed on an unpaved road of 4050 km that was split into 18 sample units with 150 m each selected randomly, located in the city of Viçosa, at the Zona da Mata North County, in the State of Minas Gerais, Brazil, to obtain the functional condition.

The subjective assessment procedure reproduced general aspects of the evaluation adopted by Fontenele and Sória (2003), and the objective assessment followed the USACE methodology (Eaton and Beaucham, 1992). This section was selected because it represented the average surface conditions of the tropical unpaved road network in the neighborhoods of the city of Viçosa.

The evaluation team was composed of five and three undergraduate civil engineering students for the subjective and objective sections respectively. The three students from the objective assessment team were also part of the subjective team. All evaluators received field training about procedures of both types of functional assessment.

In the objective assessment, the training included the types and severity of distresses presented in Table 1, and how to measure them following the procedure established by Eaton from USACE (Eaton and Beaucham, 1992). The rating of a road section was adopted as the average rating of its sample units in agreement with the same methodology. Figure 1 shows one of the evaluators measuring the sample unit.



**Figure 1.**Team member during objective assessment.

**Source:** The author.

In the subjective assessment, the evaluation team drove through the 18 sample units at a speed of about 40 km/h, assigning scores in the range of 0 to 100 (or PSR) according to the individual perception of their quality of travel, meaning 0 is a failed road and 100 is a brand new road (Fontenele and Sória, 2003). The rating of a road section was adopted as the average rating of its sample units, as was done in the objective assessment rating.

Statistical analyzes were performed using R 3.5 software. Statistical modeling, regression analysis and model selection techniques were used. Models are functions that aim to simplify the relationship between outcome and exposure, and it is possible that different models describe the same phenomenon (Emiliano, et al., 2010). Thus, it is necessary to define through scientific methodologies some selection method to identify the most appropriate model.

In this work, two modes of model selection were considered in order to find the one that best expresses the relationship between PRS and other covariates, manual (forward and backward) and automatic (stepwise). In the forward method, it starts with the simplest model and then new covariates are added, while in the backward model it starts with the complete model and then one covariate is removed at a time. The stepwise method incorporates both methods and uses the Akaike criterion to select the best model. The importance of each variable in the model was assessed by the Wald test and the corresponding p-value was verified.

Two statistical models were used: linear regression model (LR) and Beta regression model (BR). LR defines a linear relationship between the dependent variable and an independent variable. BR is an important class of models used to model continuous random variables in the range  $[0,1]$ , such as ratios and proportions. According to Ferrari and Cribari Neto (2004), this model is capable of modeling linear and nonlinear relations, allowing to make very accurate estimates, regardless of the sample size or the tendency of the data to values close to zero or one. The Table 3 presents some characteristics of the linear regression model and the Beta regression model.

**Table 2: Types of regression models (Morero and Ortiz, 2019).**

Regression model	Distribution	Link Function	Estimation	Interval
Linear	Normal	Identity	Least squares	$(-\infty, \infty)$
Beta	Beta	Logit	Maximum likelihood	$[0,1]$

The total of 508 statistical analysis were performed to both cases:

- 127 linear regression were used to perform case 1.
- 127 Beta regression were used to perform case 1.
- 127 linear regression were used to perform case 2.
- 127 Beta regression were used to perform case 2.

The linear regression models considered in the model selection evaluation were those that presented all negative and significant coefficients. Since the coefficient of determination ( $R^2$ ) increases as the number of covariates increases, it was decided to use the adjusted coefficient of determination ( $R^2_{adj}$ ) to evaluate the explanatory power of the models. Thus, the linear regression models were evaluated according to two criteria: higher the  $R^2_{adj}$  or all significant parameters. For the use of the Beta regression model, the original values of the PSR were divided by 100 to be in the range  $[0,1]$ .

## 5. DATA COLLECTION

The city of Viçosa is 300.5 km<sup>2</sup> and it is located at Zona da Mata North in the State of Minas Gerais, Brazil. Viçosa is 229 km away from the capital Belo Horizonte with latitude between 20° 41' 20" S and 20° 49' 35" S, longitude between 42° 49' 36" W and 42° 54' 27" W, and elevation of 650 meters. To the north, the city has boundaries with the cities Teixeira and Guaraciaba, to the south Paula Cândido and Coimbra, to the east Cajuri and São Miguel do Anta and to the west the city abuts Porto Firme. The study was based on the road VCS 296 which is 4.1 km long and it has easy access to the city, as illustrated in Figure 2.

The data collection was made in two different years, September 2017 and September 2018. September in South America is the beginning of the spring season, when the annual routine maintenance happens before the rain starts.

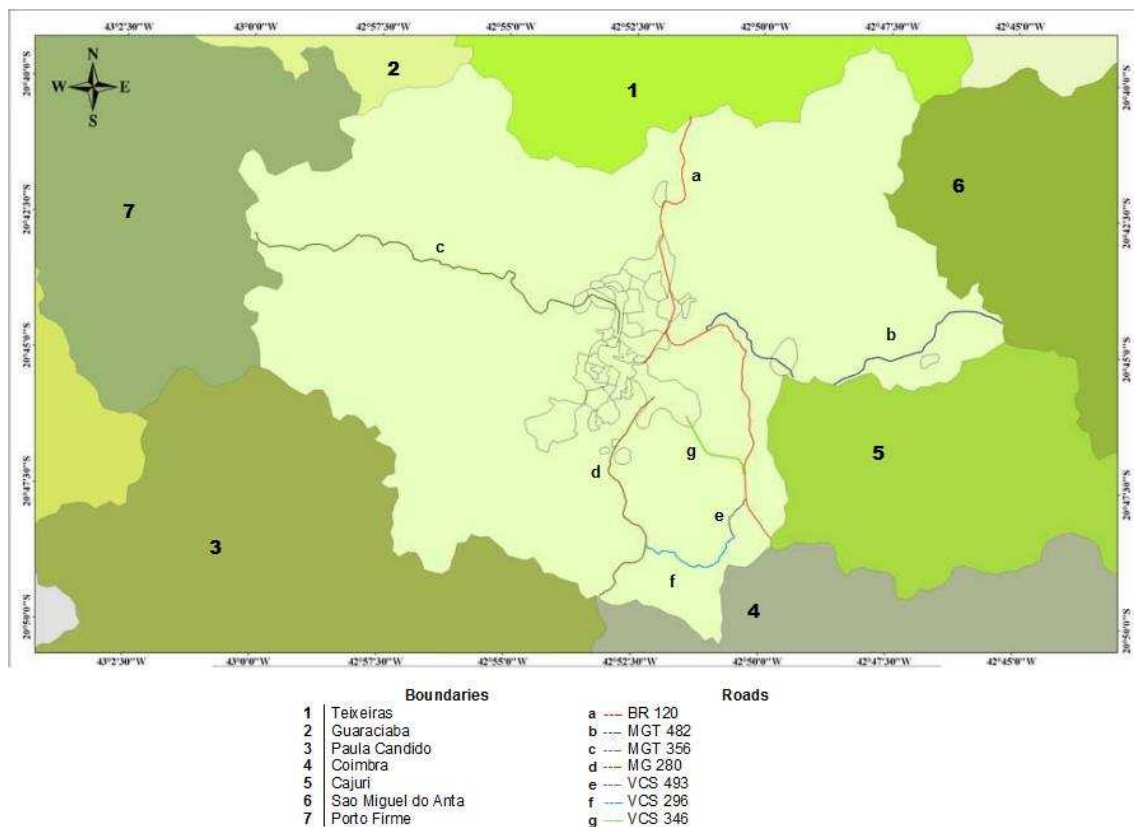


Figure 2: Road location.

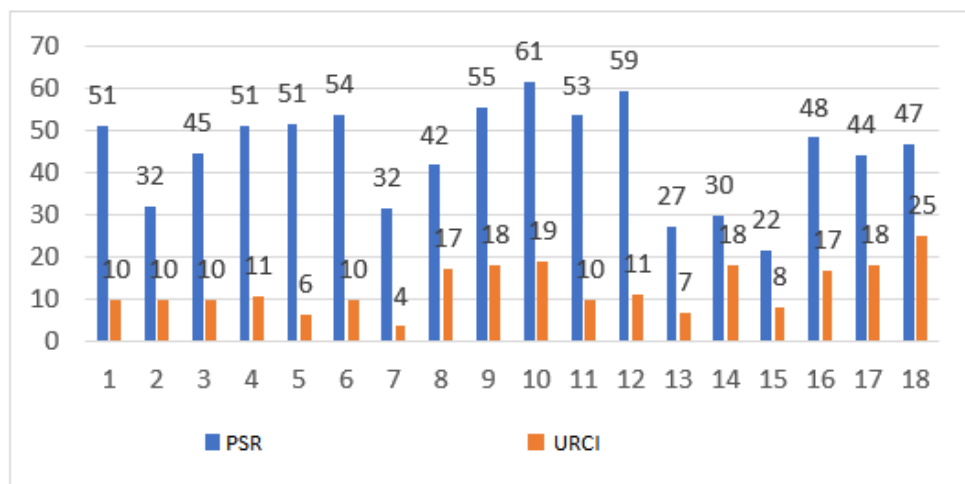
Source: The Author

## 6. DATA ANALYSIS

### 6.1. First Case: roads with no preventive maintenance – September 2017

In September of 2017, the Brazilian road referred above was selected for this study because it was in a bad condition and they had no preventive maintenance for at least 1 year. Functional evaluations were made, and Figure 3 shows the results of the subjective (PSR) and objective assessments (URCI) performed on this road.

It should be emphasized the road selected presented different surface characteristics in comparison to roads in temperate regions, including the presence of sandbanks and erosive furrows which are distresses not mentioned in moderate weather places. That is why the use of the objective methodology in tropical areas may require modifications.



**Figure 3: Functional assessments in September 2017 with no preventive maintenance.**

**Source: The Author**

Without direct correlation between the PSR and URCI ( $R^2_{adj} = 0.0848$ ), the second option was to correlate the distresses values analyzed on the objective assessment (presented in Table 1 and 2) to the overall subjective value to each sample unit. To investigate the correlation between the PSR and the URCI presented in Table 4, advanced analyses were made using the software R 3.5, and the statistical results were showed on Table 5.

**Table 3: PSR and URCI from subjective and objective assessment from September 2017.**

PSR	URCI						
	1 - Cross section	2 - Drainage	3 - Corrugation	4 - Dust	5 - Pothole	6 - Rutting	7 - Loose Aggregate
51	41.1	57	0	4	45.6	1.7	20.3
31.9	40	55.8	0	0	53.9	16.6	19
44.6	41.1	57	0	2	48.6	0	20.3
51	40	55.8	0	0	53.2	0	4.9
51.4	34.8	58.2	0	2	71.6	0	0
53.7	41.1	57	16.2	0	58.2	0	11.2
31.7	41.1	57	0	2	72.1	0	0
41.7	44.5	50	19.5	2	34.7	1.6	0
55.2	41.1	57	0	15	31.1	7.9	20.3
61.4	39	54.6	0	15	41.4	5.2	19.8
53.4	41.1	32.2	0	15	58.1	5.6	51.8
59.4	38	30.4	0	15	49.5	3.6	46.69
27.4	40	41.5	0	4	55.1	12.9	50.6
29.8	38	53.6	5.7	15	58.3	6.5	46.9
21.6	40	55.8	0	4	55.1	12.5	29.9
48.2	42.5	58.4	0	2	30.6	4.6	13.6
44.2	39	31	0	2	57.6	14.6	19.8
46.8	31.8	58.6	0	2	25.7	4.7	18.5

Source: The Author

**Table 4: Statistical results using Linear Regression.**

Model	Coef.	St. Error	t	p-value
<b>LR (1)</b>				
Interception	97.2775	17.7555	5.479	<0.0001***
Corrugation	-0.4037	0.4013	-1.006	0.3327
Drainage	-0.4846	0.2417	-2.006	0.0662
Pothole	-0.3750	0.1741	-2.154	0.0505
Rutting	-1.4885	0.4563	-3.262	0.0062**
<b>LR (2)</b>				
Interception	50.3674	3.5427	14.217	<0.0001***
Rutting	-1.0430	0.4669	-2.234	0.0401**

LR (1): Higher R<sup>2</sup>.adj.

LR (2): All the coefficients are negative and significant.

\*\*\* p-value &lt; 0.001

\*\* 0.001 ≤ p-value &lt; 0.01

\* 0.01 ≤ p-value &lt; 0.05

The LR (1) model among the adjusted models presented the highest R<sup>2</sup>.adj. (0.3754). The interpretation of this model is as follows: as increases of one unit in covariate-controlled Rutting (corrugation, drainage and pothole) decreases on average 1.4885 the value of PSR. The LR (1) is given by the expression below:

$$LR 1 = 97.2775 - 0.4037 * \text{Corrugation} - 0.4846 * \text{Drainage} - 0.3750 \\ * \text{Pothole} - 1.4885 * \text{Rutting}$$

The LR (2) model among the adjusted models was the only one that presented all negative and significant coefficients. The interpretation of this model is as follows: the increase of one unit in rutting decreases on average 1.04 the value of PSR. The LR (2) is given by the expression below:

$$LR 2 = 50.3674 - 1.0430 * \text{Rutting}$$

Second, it was used the Beta regression to also adjust the assessments and compare with the linear regression. The results were presents on Table 6.

**Table 5: Statistical results using Beta regression.**

Model	Coef.	St. Error	t	p-value
<b>Beta (1)</b>				
Interception	1.9312	0.6866	2.813	0.0049**
Drainage	-0.0231	0.0092	-2.497	0.0125*
Dust	0.0348	0.0161	2.159	0.0308*
Loose Aggregate	-0.0139	0.0069	-1.995	0.0461*
Pothole	-0.0126	0.0057	-2.233	0.0255*
Rutting	-0.0431	0.0160	-2.697	0.0070**
<b>Beta (2)</b>				
Interception	1.8503	0.6440	2.873	0.0040**
Drainage	-0.0199	0.0089	-2.246	0.0247*
Pothole	-0.0148	0.0063	-2.364	0.0181*
Rutting	-0.0573	0.0165	-3.467	<0.0001***

Beta (1): Higher R<sup>2</sup>adj.

Beta (2): All the coefficients are negative and significant.

\*\*\* p-value < 0.001

\*\* 0.001 ≤ p-value < 0.01

\* 0.01 ≤ p-value < 0.05

The resulted model using Beta regression (1) among the adjusted models presented the highest R<sup>2</sup>adj (0.6137). The interpretations of these parameters are:

- Increasing 1% in the drainage ratio, PSR decreases by 2.31 percentage points keeping the other variables constant.
- Increasing 1% in dust ratio, PSR increases by 3.48 percentage points keeping the other variables constant.

- Increasing 1% in loose aggregate ratio, PSR increases by 1.39 percentage points keeping the other variables constant.
- Increasing 1% in pothole ratio, PSR increases by 1.26 percentage points)) keeping the other variables constant.
- Increasing 1% in rutting ratio, PSR increases by 4.31 percentage points keeping the other variables constant.

The Beta (1) is given by the expression below:

**3**

$$\mathbf{Beta (1) = 1.9312 - 0.0231 * Drainage + 0.0348 * Dust - 0.0139} \\ \mathbf{* Loose Aggregate - 0.0126 * Pothole - 0.0431 * Rutting}$$

The Beta (2) model among the adjusted models was the only one that presented all negative and significant coefficients (pseudo  $R^2_{adj} = 0.4936$ ). The interpretations of these parameters are:

- Increasing 1% in the drainage ratio, PSR decreases by 1.99 percentage points keeping the other variables constant.
- Increasing 1% in the pothole ratio, PSR decreases by 1.48 percentage points keeping the other variables constant.
- Increasing 1% in the rutting ratio, PSR decreases by 5.73 percentage points keeping the other variables constant.

The Beta (2) is given by the expression below:

**4**

$$\mathbf{Beta (2) = 1.8503 - 0.0199 * Drainage - 0.0148 * Pothole - 0.0573 * Rutting}$$

Using one of these models, it is possible to reuse old data sets composed by objective analysis which are not sensitive enough to represent tropical weather and create a reliable historical data to improve the maintenance.

## 6.2. Second Case: the same road after preventive maintenance – September 2018

After September 2017, two preventive maintenances (before and after the rains) were applied to the test sections. In September 2018, the functional condition was collected again, and the results can be seen in Figure 4.

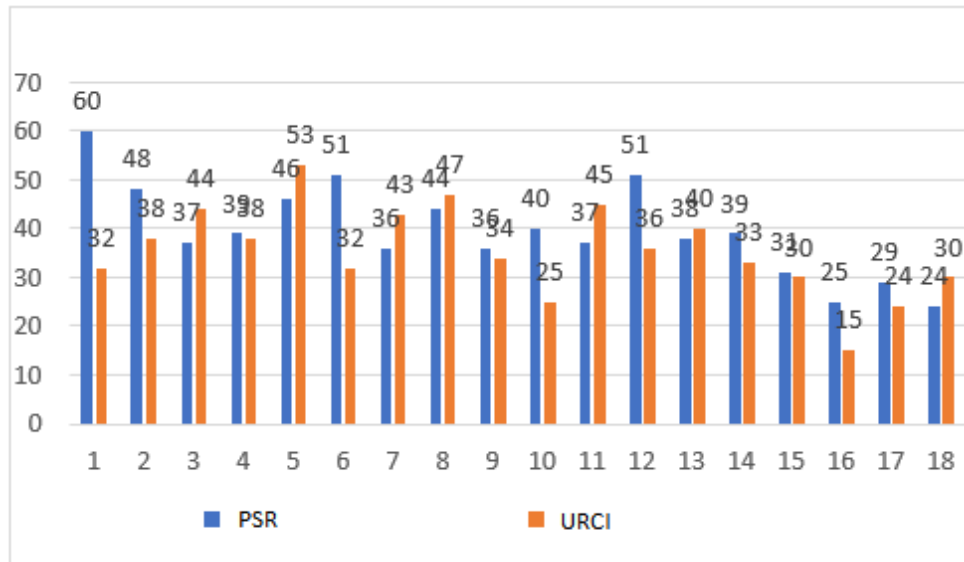


Figure 4: Subjective and objective assessments in September 2018 with preventive maintenance.

Source: The Author

As expected, regular maintenance reduced severe distresses. Table 7 summarizes the URCI values from the objective assessment. A similar analysis was made to compare the objective and subjective evaluations, and the statistical results were presented on Table 8.

Table 6: PSR and URCI from subjective and objective assessment from September 2018.

PSR	URCI						
	1 - Cross section	2 - Drainage	3 - Corrugation	4 - Dust	5 - Pothole	6 - Rutting	7 - Loose Aggregate
60	32.2	38	10	2	41.5	0	39.2
48	32	38	9.6	2	0	0	33.4
37	41	38	9	4	0	0	0
39	33	28	3.1	2	0	6.8	43.7
46	25	28	3.7	2	0	5.6	20
51	33	38	0	4	40.3	14	0
36	57.7	4.3	2	2	4	0	20
44	45.2	66	0	2	0	0	0
36	24.9	38	0	2	0	2	0
40	48	66	0	2	0	0	20
37	24.9	48	0	2	0	2	20

Continued							
PSR	URCI						
	1 - Cross section	2 - Drainage	3 - Corrugation	4 - Dust	5 - Pothole	6 - Rutting	7 - Loose Aggregate
51	24.9	48	0	2	0	0	43
38	33	38	0	15	0	0	28
39	25	38	0	15	0	0	44
31	52	26	4	4	0	0	44.8
25	43	38	0	15	7	0	0
29	43	38	0.8	15	38.6	0	0
24	33	38	0	15	0	5.2	0

Source: The Author

Table 7: Statistical results using Linear Regression.

Model	Coef.	St. Error	t	p-value
<b>LR (3)</b>				
Interception	57.3061	6.6700	8.592	<0.0001***
Cross Section	-0.3339	0.1709	-1.954	0.0696
Dust	-0.9640	0.2982	-3.233	0.0055**
<b>LR (4)</b>				
Interception	45.1823	2.6546	17.020	<0.0001***
Dust	-0.9559	0.3234	-2.956	0.0093**

LR (3): Higher R<sup>2</sup>.adj.

LR (4): All the coefficients are negative and significant.

\*\*\* p-value &lt; 0.001

\*\* 0.001 ≤ p-value &lt; 0.01

\* 0.01 ≤ p-value &lt; 0.05

The LR (3) model among the adjusted models presented the highest R<sup>2</sup>.adj. (0.4157), that is, this model presents the highest percentage of the explanation of the PSR. The interpretation of this model is as follows: the increase of one unit in dust controlled by covariates cross section, decreases on average 0.9640 the PSR. The LR(3) is given by the expression below:

5

$$LR (3) = 57.3061 - 0.3339 * \text{Cross Section} - 0.9640 * \text{Dust}$$

The LR (4) model among the adjusted models was the only one that presented all negative and significant coefficients. The interpretation of this model is as follows: the increase of one unit in dust decreases on average 0.9559 PSR. The LR (4) is given by the expression below:

$$LR (4) = 45.1823 - 0.9559 * Dust$$

Second, was used the beta regression to also adjust the assessments and compare with the linear regression. This section presented linear and Beta regression as the best regression models suitable to this case. The Beta regression results were showed on Table 9.

**Table 8: Statistical results using Beta regression.**

Model	Coef.	St. Error	t	p-value
<b>Beta (3)</b>				
Interception	0.0466	0.212	0.22	0.8261
Cross Section	-0.0126	0.0049	-2.57	0.0102*
Dust	-0.0405	0.0089	-4.571	<0.0001***
Loose Aggregate	0.0064	0.0028	2.257	0.0240*
Pothole	0.0116	0.0033	3.578	0.0003**
<b>Beta (4)</b>				
Interception	0.3026	0.2535	1.194	0.2325
Cross Section	-0.0135	0.0066	-2.064	0.0389*
Dust	-0.0413	0.0118	-3.51	<0.0001***

Beta (3): Higher R<sup>2</sup>adj.

Beta (4): All the coefficients are negative and significant.

\*\*\* p-value < 0.001

\*\* 0.001 ≤ p-value < 0.01

\* 0.01 ≤ p-value < 0.05

The Beta (3) model among the adjusted models presented the R<sup>2</sup>adj (0.7282), which means this model has the highest percentage of explanation of PSR. The interpretations of the parameters are:

- Increasing 1% in the cross-section ratio, the PSR decreases by 1.26 percentage points keeping the other variables constant.
- Increasing 1% in the dust ratio, PSR decreases by 4.05 percentage points keeping the other variables constant.
- Increasing 1% in the loose aggregate ratio, PSR decreases by 0.64 percentage points keeping the other variables constant.

- Increasing 1% in the pothole ratio, PSR decreases by 1.16 percentage points keeping the other variables constant.

The Beta (3) is given by the expression below:

7

$$\mathbf{Beta (3) = 0.0466 - 0.0126 * Cross Section - 0.0405 * Dust + 0.0064 * Loose Aggregate + 0.0116 * Pothole}$$

The Beta (4) among the adjusted models was the only one that presented all negative and significant coefficients ( $R^2_{adj} = 0.4994$ ). The interpretations of the parameters are:

- Increasing 1% in the cross-section ratio, PSR decreases by 1.35 percentage points keeping the other variables constant.
- Increasing 1% in the dust ratio, PSR decreases by 4.13 percentage points keeping the other variables constant.

The Beta (4) is given by the expression below:

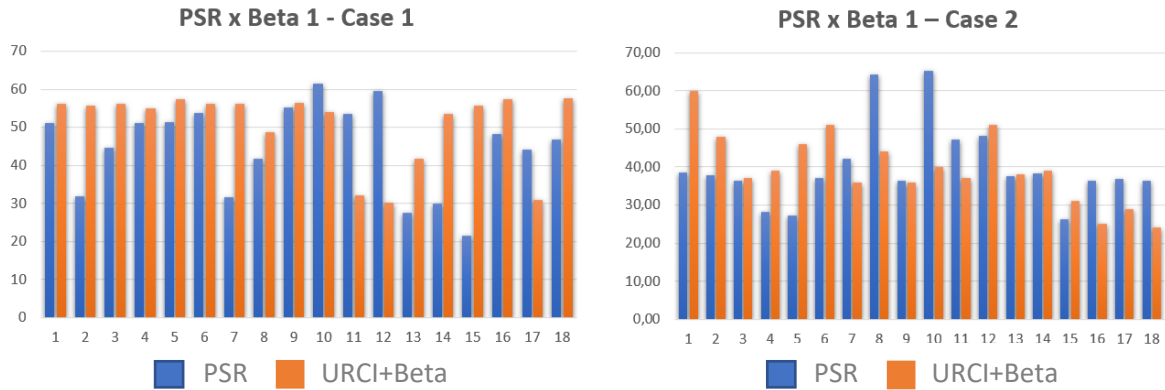
8

$$\mathbf{Beta (4) = 0.3026 - 0.0135 * Cross Section - 0.0413 * Dust}$$

With these options, the resulting index with the model was analyzed and compared with the original index. Both situations were considered satisfactory, which means, both situations are close to the real situation. But using one of these models the result is more accurate.

Considering all the possible models and trying to match both evaluation using them, was possible to conclude that the model Beta 1 was the one with the better result as showed on Figure 5.

$$\text{Beta 1} = 1.9312 - 0.0231 * \text{Drainage} + 0.0348 * \text{Dust} - 0.0139 * \text{Loose Aggregate} - 0.0126 * \text{Pothole} - 0.0431 * \text{Rutting} \quad (R^2_{\text{adj}} = 0.6137)$$



**Figure 5: Results using the Beta 1 model matching the objective evaluation in both cases.**

It was observed a good correlation between the evaluations using the model Beta 1. However, thinking about the road behavior, it is impossible to have a positive variable as the dust is shown in this model. The positive variable in this model means that increasing this specific distress, the overall road condition will increase either, which it is not possible to occur.

Considering that using the objective evaluation from EATON, the dust variable is not very significant over the overall condition. That is why was decided to cut the dust variable from the final model to be used as the chosen model.

## 7. CONCLUSIONS

In the state of Minas Gerais, Brazil, two different road assessments methods to identify unpaved roads distresses were used. The main objective of this paper was to compare the road evaluation between the objective and subjective methods. The hypothesis adopted in tropical countries is that the subjective method which is based on individual perceptions is more suitable in reflecting road serviceability than the objective functional assessment which is based on standardized measures of distresses. The second objective was to establish a correlation between both assessment types and develop a regression model using multivariate analysis with the software R 3.5 to standardize these two surveys. A correlation was created between the two evaluation methods representing two different conditions: when roads have periodic maintenance and when the roads do not have any maintenance.

The developed models can be highlighted as follows:

- They are tailored specifically to low-volume roads in the city of Viçosa, state of Minas Gerais, Brazil. However, these models can be easily modified for each city or state by following the same methodology described in this chapter.
- They can be used to determine the pavement conditions for roads receiving or not receiving periodic maintenance.
- They make it possible to use the objective methodology from U.S. Army Corps of Engineers to evaluate roads by collecting information on the distresses relevant to tropical roads. The models included only five of the seven distresses which are included in both methodologies, subjective and objective.
- Using these regression models to improve the roads evaluation, the ranking method to repair selected roads can be improved. With current pavement condition index assessed using the models, agencies are equipped with the information needed to predict the future condition of a segment, and to create performance prediction models. Then, a PMS (Pavement Management System) can be developed to better maintain tropical unpaved roads at minimal costs.
- For both conditions considered in this chapter, when roads had no preventative maintenance and when they had one-year preventative maintenance, the generated models were satisfactory, which means the created models represent perfectly both situations. However, using the model Beta 1 without the positive variable dust, it is possible to better match the evaluation values in any situation.

## **8. RECOMMENDATIONS**

The cities are always changing practices to better use limited resources. It was demonstrated in this paper a way to undertake a reliable surface condition assessment that can help the cities, state, and companies on how to better evaluate the current condition and manage their roads. It is recommended to conduct a comprehensive

study to determine new, practical and technological data collection methods and deterioration models to predict the roads decline and its maintenance. It is also recommended that the managers consider the use of pavement management systems to allocate resources or predict maintenance and rehabilitation strategies in their jurisdiction.

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## **REFERENCES**

- Aggarwal, S. Do rural roads create pathways out of poverty? Evidence from India. *Journal of Development Economics*. 133 375–395. 2018.
- Babapour, R, Naghdi, R, Ghajar, I, Mortazavi, Z. Forest road profile optimization using meta-heuristic techniques. *Applied Soft Computing* 64. 126–137. 2018.
- Confederação Nacional do Transporte - CNT. Anuário CNT do transporte – estatísticas consolidadas 2017. Brasília: 2017. <http://anuariodotransporte.cnt.org.br/2017/>. Accessed Sep. 25 2018.
- Eaton, RA, Beaucham, RE. Unsurfaced road maintenance management. U. S Army Corps of Engineers – USACE, Cold Regions Research & Engineering Laboratory - CRREL, Special Report 92–26, USA: 1992.
- Emiliano, P. C., Veiga, E. P., Vivanco, M. J., & Menezes, F. S. Critérios de informação de Akaike versus bayesiano: análise comparativa. 19º Simpósio Nacional de Probabilidade e Estatística. 2010
- Ferrari, S., Cribari-neto, F. Beta regression for modelling rates and proportions. *Journal of applied statistics*, 31(7), 799-815. 2004.
- Fontenele, HB, Sória, MA. Uma análise de avaliações subjetivas de estradas não pavimentadas. ENTECA - Maringá-PR p. 407-419. 2003.
- Huntington, G & Ksaibati, K. Management of Unsealed Unpaved roads. *Transportation Research Record: Journal of the Transportation Research Board*. 2011. DOI: 10.3141/2232-01.
- Huntington, G & Ksaibati, K. Visual Assessment System for Rating Unsealed Roads. *Journal of the Transportation Research Board*, No. 2474, Transportation Research

Board of the National Academies, Washington, D.C., 2015, pp. 116–122. DOI: 10.3141/2474-14.

Kabindra, S, Pramen, S & Thomas, K. A Road Maintenance Management Tool for Rural Roads in Kenya. 2014 289-298. DOI: 10.1061/9780784413517.030.

Machado, CC. Construção e conservação de estradas rurais e florestais. O Editor, Vicosá: 2013.

Morero, HA & Ortiz, P. Multivariate analysis to research innovation complementarities, African Journal of Science, Technology, Innovation and Development, 11:4, 469-484. 2019 DOI: 10.1080/20421338.2017.1355586

Nahvi, A, Zhang, Y, Arabzadeh, A, Gushgari, SY, Ceylan, H, Jahren, CT, Gransberg, DD, & Kim, S: Economics of upgrading unpaved roads to Otta seal surface, Applied Economics. 2019 DOI: 10.1080/00036846.2019.1602712.

Rabello Quadros, SG and Nassi, CD “An evaluation on the criteria to prioritize transportation infrastructure investments in Brazil,” Transport Policy, vol. 40, pp. 8–16, 2015.

Rohith, D, Srikanth, K, Chowdary, V. Performance Evaluation of Unpaved Road Sections Sealed Using Open Graded Premix Surfacing with Bitumen and Bitumen Emulsion as the Binders. Transportation in Developing Economies 2: 13. 2016. DOI: 10.1007/s40890-016-0019-4

Saha, P, Ksaibati, K. Developing an Optimization Model to Manage Unpaved Roads. Journal of Advanced Transportation. Article ID 9474838. 2017. DOI: 10.1155/2017/9474838.

Shahin, M. Y. (1994) Pavement Management for Airports, Roads and Parking Lots, Chapman & Hall, London, 1994.

Silva, TO, Carvalho, CAB, Lima, DC, Calijuri, ML, Machado, CC, Oliveira, TM. Avaliação do subleito de rodovias vicinais de baixo volume de tráfego por meio de ensaios geotécnicos. Revista Árvore. 825-833. 2011

Venables, W. N., Smith, D. M. and the R DEVELOPMENT CORE TEAM. An Introduction to R. Notes on R: Programming Environment for Data Analysis and Graphics. Version 2.2.0. Áustria: 2005.

Wolff, MGC, Caldas, MAF “A Model for the Evaluation of Brazilian Road Transport: A Sustainable Perspective,” Journal of Advanced Transportation, vol. 2018, Article ID 5274789, 12 pages, 2018. DOI: 10.1155/2018/5274789.

Wolters, A, Zimmerman, K, Schattler, K & Rietgraf, A. Implementing Pavement Management Systems for Local Agencies: Implementation Guide. 2011. DOI: 10.13140/RG.2.2.12588.36481.

## **CHAPTER 3: Developing a Pavement Deterioration Model Using Markovian Probabilistic Process for Minas Gerais State Paved Roads**

### **ABSTRACT**

In the state of Minas Gerais, Brazil, pavement engineers utilize a ranking approach to manage 22,286 kilometers of interstate paved roads. However, the ranking method used to select roads to be maintained is inefficient and inadequate for Pavement Management Systems (PMS). To build a PMS, it is necessary to develop deterioration models, which can be created as site-specific, family and expert opinion curves, or statistical curves. These statistical performance curves, which will be used on this paper, can be established using probabilistic or deterministic techniques. The deterministic technique does not include the uncertainties of pavement deterioration which is related to the weather and to the traffic. On the other hand, the probabilistic models that include these uncertainties result in more precise deterioration models. On this chapter, probabilistic models using the Markovian process were developed for paved roads located in Minas Gerais, Brazil. Regression techniques were used to create the deterioration trails using the predicted distribution assessed from the Markovian process. Results indicated that the deterioration decreases 1 level over a year and the deterioration model developed had the coefficient of determination ( $R^2$ ) above 0.99. As probabilistic models provide more accurate results, it is recommended that these types of models be used by consultants and government officials when managing paved roads.

Keywords: deterioration model, paved roads, pavement management system, tropical roads, Brazilian roads

### **1. INTRODUCTION**

In Brazil, pavements deteriorate due to traffic in addition to the tropical weather and high humidity (Willway et al., 2008). Pavement maintenance is currently a major challenge to transportation engineers due to the complex interaction among factors that result in failure. These failures come from the damaging effects of traffic, the seasonal traffic loading, age, weather, type of maintenance, soil, and etc. (Gupta, Kumar and Rastogi, 2014). In order to maintain roads efficiently, the governments are

trying to develop and implement a Pavement Management System (PMS) to reestablish the roads with a restricted budget (ADB, 2003). A PMS is a tool that provides a systematic method of road condition data collection, storage, analysis and modelling for decision-making associated with improving resources across a pavement network. However, when funding is limited, the PMS identifies the best mix of roads preservation projects that provide the most benefit to society in terms of the overall lifecycle cost of the road network (Leandro et al., 2015).

Prior to starting the implementation process, it is recommended that the government consider forming a steering committee to work as a group in establishing a process to meet the needs. The development of a systematic and repeatable pavement management process is a key component in the effective planning and management of a PMS. Seven steps serve as a guide for customizing a pavement management process that fits the needs of each local agency. The steps are defining the roadway network and collect inventory data, collect condition data, predict condition, select treatments, report results, select pavement management tool, and keep the process current (Pulugurta, Shao, and Chou, 2009).

To predict the condition, which is the purpose of this paper, it is necessary to understand the pavement performance and the differences when it is analyzed at the network or project level. At the network level, the entire network is analyzed to identify the appropriate type of maintenance and the road sections to be repaired. At the project level, only the selected sections are analyzed to determine the right treatment types (material and thickness) to be applied. These performance models derived from all the pavement characteristics (functional condition, width, length, rut) allow the prediction of the main pavement distresses caused by the traffic loads and the climatic conditions, such as deflections, tensions, deformations, thermal tensions, moisture content, and temperature (Maaty, 2017).

Performance prediction models can be of two types: deterministic and probabilistic. Deterministic models predict a single number for the pavement service life or the deterioration level. Probabilistic models include a probability distribution analysis. They are preferably used at the network level, due to the greater uncertainties associated with this level (Moreira et al., 2018). The techniques to create these models are straight line extrapolation, regression (empirical or deterministic), mechanistic-empirical,

polynomial constrained least square, S-Shaped curve, Markovian and Bayesian. At the present time, the most popular technique to develop a deterioration model is the stationary Markovian chains (Del Sole, 2006).

Markovian chains are a technique which assumes that the road network will always deteriorate following the transition obtained from the transition matrix (Saha, Ksaibati, and Atadero, 2017). A transition matrix of a Markovian process contains information on how the process moves from one state to another in terms of probabilities. These probabilities are assumed to be constant (do not change with time), i.e., the transition matrix is stationary. Given the pavement initial condition at year 0 and the transition probability matrix of the pavement Markovian process, an equation can be created for predicting pavement condition (Shahin, 1994).

The use of Markovian models is also evident in research on the management of other infrastructure objects than roads, such as bridges (Tsuda, 2006) and pipelines (Sinha and McKim, 2007). There are two advantages of the use of Markovian models to determine optimal intervention strategies. The first is it allows generalization of the deterioration process into the transition pattern matrix, which is suitable for representing pavement performance. The second advantage allows using the deterioration process even with the lack of historical data, as the probability of observing future state depends only on the probability of observed condition states at present. So, with a minimum of two visual inspections, deterioration progress of the pavement can be predicted (Kobayashi, Do and Han, 2010).

In this paper, the Markovian process was used to develop deterioration models to predict the future conditions of roads. These deterioration models can be used to implement a reliable and cost-effective PMS that provides a reasonable and practical number of maintenance and rehabilitation plans consistent with the number of deployed condition states. The purpose of the study was also to make the modeling process with Markovian chains clear and available for use by other academic researchers or pavement management agencies who are struggling to use the existing data and obtain prediction models to develop and test their optimization methodologies for decision-making.

## **2. OBJECTIVES**

The objective of this research was determining the deterioration model of pavements for all the Minas Gerais (Brazil) state paved roads network, using Markovian chains. In 2018, evaluators traveled 22,286 km through the state to determine the general condition of the road network, considering pavement, signs, and geometric features (CNT, 2018). The roads are classified according to the American Association of State Highway and Transportation Officials (AASHTO) considering their surface condition (AASHTO, 2001). The condition categories are excellent, good, fair, poor, and failed. Of this total, 61.3% were evaluated as fair, poor, or failed. Due to the poor conditions of the pavements, the cost of freight has increased by 28.9%, as roads with distresses are less secure and require more maintenance of vehicles and higher fuel consumption.

Approximately, R\$5,19 billion should be applied for emergency reconstruction and restoration of the roads classified as fair, poor or failed, along with the implementation of adequate signs. For the regular roads, the maintenance of the sections should cost approximately R\$2,55 billion (CNT, 2018). However, the available budget is not enough to cover all these interventions, which necessitates using an optimization system to allocate the money effectively. To develop an optimization system, pavement deterioration models need to be developed. These models are important to predict the future condition of pavements to allow correct rehabilitation treatments to be selected and timed in the best possible way (CNT, 2018).

The aim of this study is to develop a Markovian prediction model using the pavement condition database from Minas Gerais state, Brazil collected by CNT (CNT, 2019). Markovian models start with estimation of the transition probabilities, defined as the probability with which the pavements transits from one state to another (Kobayashi, Do and Han, 2010). This matrix makes it possible to implement a system to allocate existing budgets efficiently.

## **3. BACKGROUND**

### **3.1. Pavement Deterioration**

Pavements are only designed to last for a certain period. During each of these periods or "life cycles", the pavement begins from an optimal condition, declining until it

reaches a failed condition. This decreased level in a pavement condition or service-life is known as pavement deterioration (Shahin, 1994).

Estimating the pavement deterioration is important to help those responsible for maintenance with their decision-making process, and aid them in understanding the pavement performance offered to drivers. Once the deterioration condition is known, professionals are able to find techniques that effectively work to control the mechanisms competing to decrease the pavement service-life. The deterioration should be estimated by evaluating the two main causes: the functional deterioration, and structural deterioration (Saha, Ksaibati, and Atadero, 2017). There are specific assessment methods to determine each of these components. Figure 1, a paved road from Minas Gerais awaits maintenance that will extend its service life.



**Figure 1: Paved road from Minas Gerais in poor condition (CNT, 2018).**

The functional evaluation estimates the condition of the pavement according to the user's perception of detecting surfaces irregularities. It includes surveying aspects which will directly affect the road users in the form of distresses measurement. It depends on the longitudinal roughness, which is generated by the accumulation of permanent deformations under repeated loads in all layers of the pavement. Also, distresses from layers deterioration are measured due to their impact on service level (Ragnoli, Blasiis and Benedetto, 2018). In other words, an increase in the amount of distresses reduces the service level.

Surface evaluation is related to the maintenance techniques necessary to avoid accelerated deterioration in the future, or to determine the restoration measures required to improve the pavement. Although this survey is not intended to represent the user's response, it is related to the response (Pardal, 2014).

For the structural evaluation, the pavement structural condition denotes its adequacy or its ability to resist the deterioration caused by the passages of traffic loads. Thus, a complete picture of the structural pavement condition should be composed of parameters that describe the elastic or viscoelastic deformability of the materials of the layers. These parameters are used to calculate the tensions and deformations due to traffic loads in the pavement structure. Additionally, parameters that describe the resistance of the materials accumulating plastic deformations under repeated loads, depend on the nature of the material, the condition (density, humidity), the history of loading, and also, the integrity of asphaltic and cemented layers, expressed by the level of cracking (Chabot et al, 2008).

These structural conditions indicate the speed at which the pavement deterioration is occurring, i.e. the speed in which the distresses are appearing or increasing in severity. The most cost-effective time to restore a pavement is immediately before the structural condition reaches a level that the pavement deterioration starts to occur at a faster rate. To know this period, the historical data must be studied (Baladi, 2017).

Knowing this information, it is possible to establish a maintenance project schedule of a given road, which consists of identifying the most cost-effective conservation or restoration measure that is enough to place the pavement under adequate or acceptable functional conditions (Montoya-Alcaraz, Mungaray-Moctezuma and García 2020). To achieve this result, Pavement Management Systems (PMS) are now used worldwide.

### **3.2. Pavement Management System**

The term Pavement Management System (PMS) can be understood as the efficient and integrated coordination of the various activities involved in the design, construction and maintenance of pavements that are part of a road infrastructure (road, airport or urban), in order to allow them to provide acceptable conditions to the user at minimal cost. Essentially, the PMS is a set of tools or methods to assist decision makers to find

optimal strategies to construct, evaluate and maintain pavements in an acceptable functional condition over a period of time with a selected budget (Mishra et al., 2015).

When considering infrastructure, where a network with a significant extension and subject to freight traffic is common, the PMS tends to operate at both network and project level in an associated manner. At the network level there is adequate planning of the budget, the resource allocation, and the project selection. On the other hand, at the project level it is possible to find the most cost-effective repair maintenance for each road section (Rodrigue, 2020).

The establishment of a PMS becomes even more important when the road conditions are bad and with a limited availability of resources. The main objective is to use reliable historical data to make a careful decision to run a pavement maintenance program with an organized methodology. Thus, a good PMS seeks to define maintenance strategies looking to minimize the cost and to obtain an ample return on the applied resources increasing the service life (Nishiyama and Domingues, 1995).

A quality PMS should seek to increase the efficiency of decision-making while informing of the consequences of decisions made at various levels. Additionally, PMS must ensure consistency between the decisions made, define the maintenance strategy that minimizes the cost of road transportation, obtain the best return for the resources applied by means of a safe, comfortable and economical transportation, and optimize the use of the attributes destined to the maintenance of the road infrastructure. To achieve all of these objectives, a PMS must have the ability to constantly update itself considering alternative strategies, being able to determine the optimal option, and to use feedback to improve overall decision-making (FHWA, 2007).

The project, database and analysis are the three parts considered for the implementation of a PMS. When considering the project, the methods of the existing procedures are reviewed, and the implementation plan is developed. At this stage, the media is activated, in order to obtain the necessary political support. During the second stage, the database is implemented, establishing the collection procedures, developing the database and reporting the results. In the third step, the analysis is implemented using deterioration models and decision trees, in order to generate priority rehabilitation programs, verifying the effects of varying budget levels, and matching the specified standard requirements for each case. When implementing a PMS, the issues

preventing a good software are the limitation of skilled professionals and availability of material resources (Domingues, 1995).

### **3.3. Deterioration Model and Markovian Chains**

In order to make a reliable diagnosis, first it is necessary to apply a series of deterministic/probabilistic models to predict the future conditions of each homogeneous road section after which the prediction is compared with the actual observed performance (Hassan, Lin and Thananjeyan, 2015). Reliable information regarding the age of the pavement and the history of the traffic involved are crucial for the success of this comparison. The result of this analysis will be (Wilde, Thompson and Wood 2014):

- Clarification of the predominant degradation mechanism(s).
- Selection of the performance model(s) most appropriate to the reality of the highway to predict the future need.
- The selection of the proper pavement maintenance to increase the service life at minimal cost.

The design methods commonly used in Brazil are the deterministic ones, elaborated from theoretical and rational extrapolations of observational models obtained by the accumulation of data and experiences. The application of such methods is accompanied by limitations and should only be used when no other technique is available (Balbo, 2007).

On the other hand, there are probabilistic design methods that use theories to predict tensions and deformations from traffic loads and weather changes, which can be matched with the resistant tensions of materials (Neto, 2004). The use of these probabilistic methods results in considerable advantages including better design, reliability, prediction of specific defects, possibility of extrapolation of field results, and compatibility between cost and benefit (AASHTO, 2001).

Currently, the Markovian process is the most popular probabilistic technique used to develop a deterioration model. Markovian chains are based on the premise that future evolution depends exclusively on the current state of the road. Historical data can help to improve the future condition prediction, but it is not mandatory (Sharabah, Setunge and Zeephongsekul, 2007). In other words, the present condition state will always

influence the next condition state. To start the Markovian process, a correlation was created between the road PCI and the Markovian index as Table 1 shows (Stewart, 2009).

**Table 1: Developed Markovian Index (PCI<sub>M</sub>) from PCI index.**

CONDITION CATEGORY	PAVEMENT CONDITION INDEX (PCI)		MARKOVIAN INDEX (PCI <sub>M</sub> )
	Upper limit	Lower Limit	
Excellent	100	86	5
Good	85	75	4
Fair	74	58	3
Poor	57	40	2
Failed	39	0	1

It should be noted that the state transition of a stochastic process may or may not depend on the elapsed time period. When this transition depends on the variable time (t), it is said that the process is non-homogeneous, otherwise it is called a homogeneous (Stewart, 2009). The Markovian process used in this works was the non-homogeneous. In order to predict the deterioration evolution of a paved road through the Markovian chains, it is first necessary to define the number of condition (k) to be considered for the evaluation. The transition matrix with dimension k × k with the following form is used to evaluate the transition probability of states (Ortiz-García, Castello and Smith, 2006):

1

$$P_{\Delta t} = \begin{bmatrix} p_{11} & p_{12} & \dots & p_{1k} \\ 0 & p_{22} & \dots & p_{2k} \\ 0 & 0 & \ddots & \vdots \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The unit value presented in this matrix ( $P_{\Delta t}$ ) corresponds to the maximum input value, for each event. The reason for the probability value  $p_{kk}$  is due to the fact that there is no further condition state after the k state, since it is a limited value (Stewart, 2009). The transition probability from a state i to a state j, for a generic time interval ( $\Delta t$ ), is represented by  $p_{ij}$ , with  $i = j = 1, \dots, k$ , and determined as follows (Yang, 2004):

2

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

Through this equation, it is possible to demonstrate that the state of the pavement at the moment of evaluation ( $t + \Delta t$ ) depends exclusively on the previous state at the initial moment ( $t$ ).

#### **4. METHODOLOGY**

The CNT Highways Survey (CNT, 2018) decided to evaluate the three main characteristics of the Brazilian road network: pavement, signs, and geometric features. The paved roads that were evaluated include federal highways, relevant county roads, and important local roads. These characteristics were analyzed according to condition, distresses, and safety levels. The evaluation result was published in a report, using the AASHTO guide to road classification as Excellent, Good, Fair, Poor, and Failed (AASHTO, 2001).

The data collection method of the CNT Highways Survey is based on standards from the Brazilian National Department of Transport Infrastructure (DNIT) and AASHTO, which is widely recognized for technical references. AASHTO presents nomenclatures, definitions, concepts, and survey methods regarding the main distresses of asphalt pavement (AASHTO, 2001). The main standards used are:

- Standard DNIT 005 (DNIT, 2003a) which defines the terms used for distresses that occur in flexible and rigid pavements.
- Standard DNIT 006 (DNIT, 2003b) which describes the conditions required for the objective evaluation of the surface (flexible and rigid pavements).
- Standard DNIT 008 (DNIT, 2003c) which designates procedures for continuous visual survey required for the evaluation of the surface (flexible and rigid pavements).

Other reference adopted is the Highway Capacity Manual (HCM) (TRB, 2010) which also provides important definitions of aspects related to the road characteristics, as well as methods for analyzing the capacity and operational quality of transportation systems.

In 2018, the data from the entire country was collected by 26 research teams, each consisting of 1 evaluator and 1 driver. Each team received specific instructions about its assigned route. In addition to the research teams, there was a checking team responsible for validating the information that was collected. The information collected

by the checking team was not included in the final results of the survey, since they were just verifying the existing sections. However, if there were inconsistencies, a team was sent to the field to inspect the road again. All the distresses found on each road were combined to develop a Pavement Condition Index (PCI).

The pavement condition data from the available pavement database was appropriately organized according to the defined condition states. One part of this data quantification process was the classification of the pavements, and the second part involved the generation of data matrices for each classification of pavement.

In this paper, statistical analysis were applied to CNT dataset (CNT, 2019) performed on the R statistical software (version 3.5) using Markovian chain techniques and regression analysis. Starting from the data matrix, the transition matrix was calculated to obtain the probability distribution matrix, which was used to estimate the expected road age according to the PCI. These values were used to construct the statistical model for road deterioration.

## **5. DATA COLLECTION**

The CNT (2019) measured the entire federal paved road network and the main local roads, totaling 107,161 km of roads evaluated through the country in 2018. Of the total number of roads evaluated, 57.0% have some type of high severity distresses on the pavement, signs or geometric features. On the same project, the CNT (2019) traveled in Minas Gerais state 15,236 km through the state as illustrated in Figures 2 through 4 to evaluate the general condition of the road network considering pavement, signs, and geometric features. Figure 2 summarizes the annual condition of every segment in the network between 2013 and 2018.

Figure 3 summarizes the average road network condition per year between 2013 and 2018. In 2018, there is a significant drop in the functional condition which is probably due to the reduction in the infrastructure budget that comes from the government. According to CNT (2019), the annual expenditures on infrastructure were R\$8.7 billion in 2016, R\$7.2 billion in 2017 and only R\$5.9 billion in 2018.

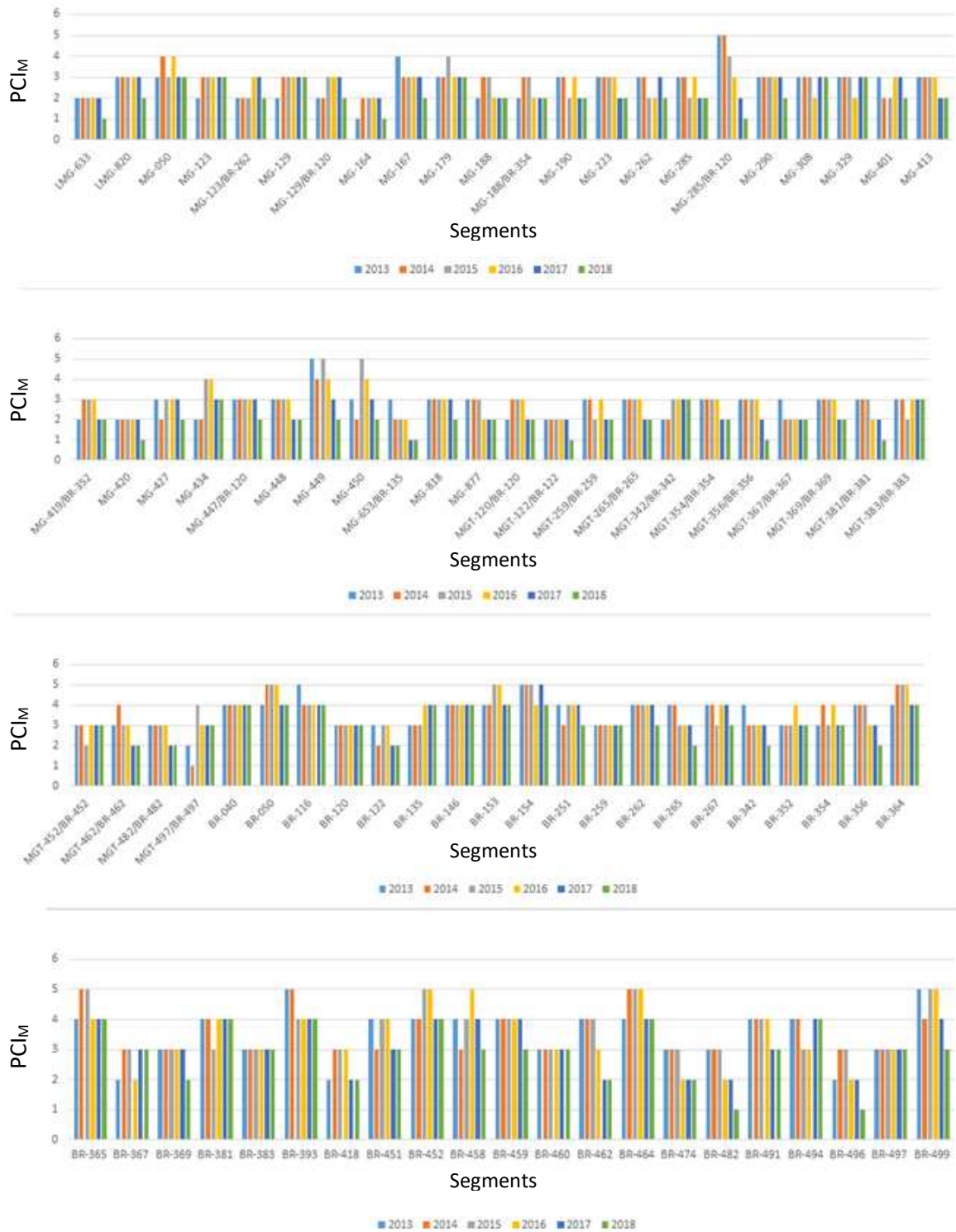


Figure 2: The PCI<sub>M</sub> of all 88 road segments between 2013 and 2018.

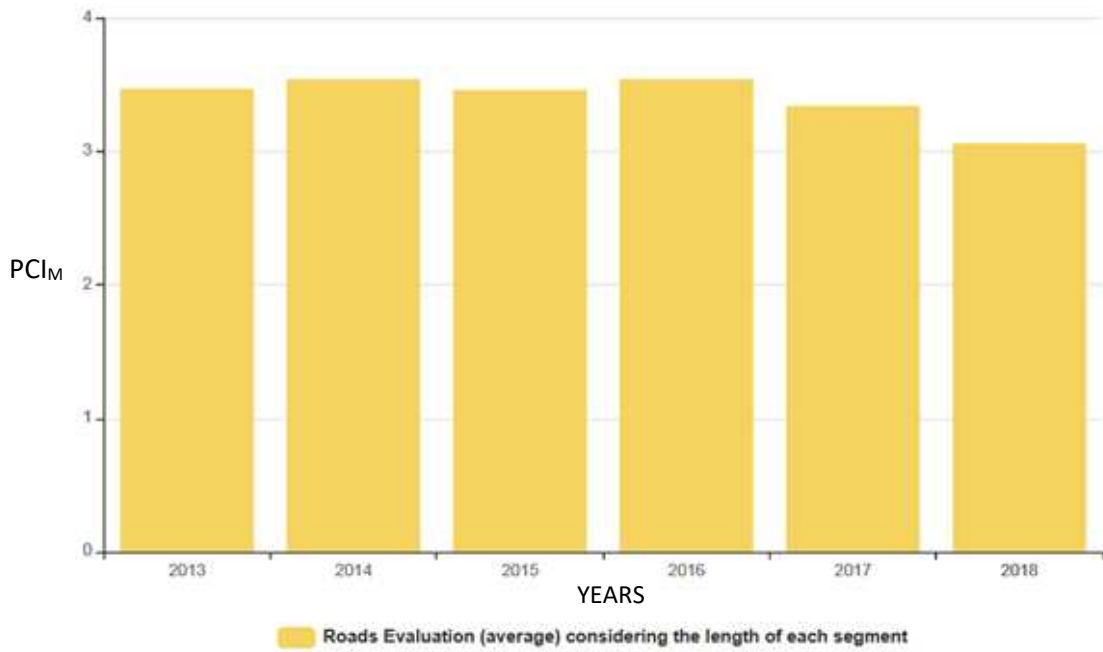


Figure 3: The Average network PCI<sub>M</sub> per year.

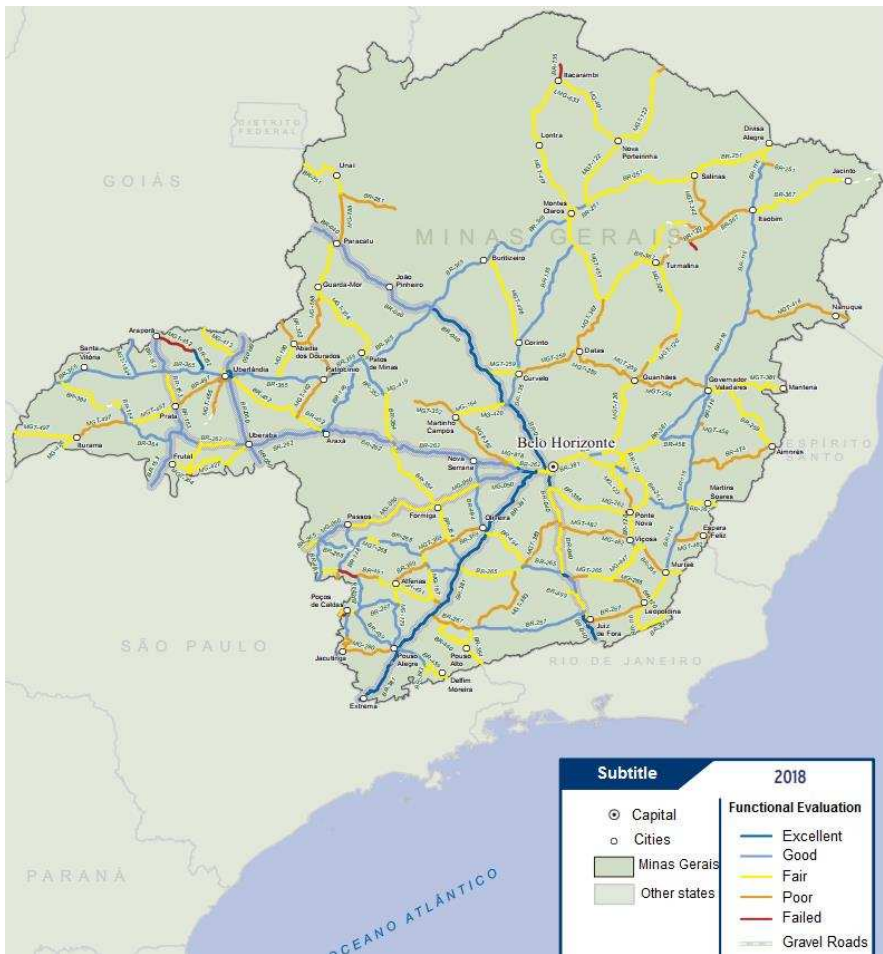


Figure 4: The roads functional condition from Minas Gerais in 2018.

The research CNT (2018) also identified 13 sections with erosions in the lane, 7 with large potholes and 3 with barrier falls that decrease the safety to the driver. The database contained information related to road identification number, the length, and the PCI. Six years of maintenance records from 2013 to 2018 were used in this study. The datasets from 2013 to 2018 was extracted, filtered, and combined to prepare a single database for these roads network.

Based on the standards from AASHTO and DNIT, the CNT methodology for road assessment adopts the following criteria:

- The data was collected and recorded by the evaluator along the roads in a vehicle traveling at a maximum speed of 50 km/h.
- Each road is evaluated according to the visual observation of characteristics in segments with an extension equivalent to a sample unit.
- The sample unit is a road section with a length between 1 and 10 km, unless it is interrupted by an intersection or the end of the road itself.
- The evaluator is trained to carry out the inspection in a continuous way and to identify when a specific distress on the pavement will be considered predominant in a sample unit.
- Data collection occurs only when there is natural light and good visibility conditions for a maximum of eight hours per day. However, in adverse situations as rain or haze, the analysis is suspended until the ideal research conditions are restored.
- If a critical condition is observed along the road segment, the evaluator takes a photo and records the location (using GPS coordinates).

In order to implement the Markovian process, the values of each distress index were grouped based on Table 1.

## **6. DATA ANALYSIS**

This study intends to develop a deterioration model for paved roads in Minas Gerais using the PCI. Table 2 summarizes the data collection from the years 2013 to 2018. The deterioration model was developed using the Markovian chains process. These Markovian processes involves the process of developing three matrices: the transition

probability data table (Table 3), the transition probability matrix (Table 4), and the probability distribution matrices (Table 5).

Six years of pavement condition data (2013 to 2018) were used to develop the transition probability data as shown in Table 2. In this table, Markovian models estimate the transition probabilities data, which is defined as the rate the pavements transit from one state to another. It is possible to visualize through the tables that the pavement conditions of some roadway segments drop from one year to the next by more than a group. However, this type of data was not included on this analysis because this kind of drop is not usual or realistic for a normal track of pavement deterioration.

**Table 2: Road segments with their Pavement Condition using Markovian index ( $PCI_M$ ) from 2013 – 2018.**

Road	Ext. (km)	Pavement Condition Index					
		2013	2014	2015	2016	2017	2018
LMG-633	35	2	2	2	2	2	1
LMG-820	2	3	3	3	3	3	2
MG-050	343	3	4	3	4	3	3
MG-123	45	2	3	3	3	3	3
...		...	...	...	...	...	...
BR-499	15	5	4	5	5	4	3

**Table 3: Road segments with their Transition Probability Data from 2013 – 2018.**

Transition Probability Data from 2013 – 2018						
$PCI_M$	Paved Roads	5	4	3	2	1
		5	25	17	0	0
	4	0	57	31	0	0
	3	0	0	147	51	0
	2	0	0	0	52	11
	1	0	0	0	0	2

Table 3 represents the transition probability matrix for the entire network. A transition matrix of a Markovian process contains information on how the deterioration process moves from one state to another in terms of probabilities. These probabilities are assumed to be constant, i.e., the transition matrix is stationary. From Table 4, it can be seen that the number 0.595 represents the percentage of the roads that stay at level 5, and 0.405 represents the percentage of the roads that deteriorate from level 5 to level 4.

**Table 4: Road segments with their Transition Probability Matrix.**

		Transition Probability Matrix				
Paved Roads		5	4	3	2	1
PCI <sub>M</sub>	5	0.595	0.405	0.000	0.000	0.000
	4	0.000	0.648	0.352	0.000	0.000
	3	0.000	0.000	0.742	0.258	0.000
	2	0.000	0.000	0.000	0.825	0.175
	1	0.000	0.000	0.000	0.000	1.000

Table 5 represents the probability distribution using the Markovian probability process. In this table, the state of the maximum probability is shown in the bold font. For example, comparing the distribution from year 1 to year 5, there is a probability of 0.075 for the segments to stay at level 5 and a probability of 0.024 for the segments to be at level 1. However, the highest probability value is 0.415 for the roads be at level 3 at year 5.

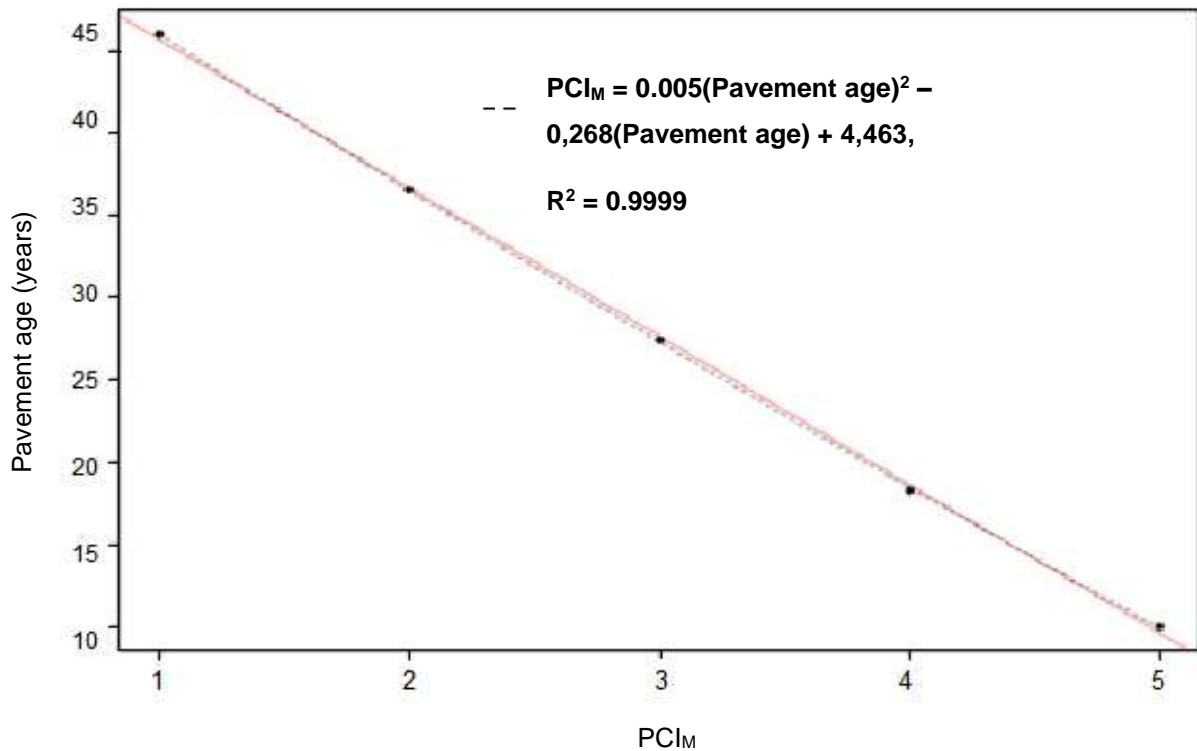
**Table 5: Road segments with their Probability distribution using Markovian process.**

		Probability Distribution					Total
Paved Groups		5	4	3	2	1	
Year	1	<b>0.595</b>	0.405	0	0	0	<b>1</b>
	2	0.354	<b>0.503</b>	0.143	0	0	<b>1</b>
	3	0.211	<b>0.469</b>	0.283	0.037	0	<b>1</b>
	4	0.126	<b>0.389</b>	0.375	0.104	0.006	<b>1</b>
	5	0.075	0.303	<b>0.415</b>	0.183	0.024	<b>1</b>

While Table 5 predicts the distribution for 5 years, Figure 5 shows the deterioration model according to that data set. The deterioration model obtained indicates that the distresses have slow deterioration over the years. Regression techniques have been used to develop the model using the mean obtained from the Markovian distribution as shown in Equation 1:

1

$$PCI_M = 0.005(\text{Pavement age})^2 - 0,268(\text{Pavement age}) + 4,463, \quad R^2 = 0.9999$$



**Figure 5: Roads deterioration model using the Software R.**

This methodology included a pavement optimization maximizing the overall road condition and minimizing life cycle cost on the roadway segments that are selected for preservation projects. As paved roads require different levels of maintenance, the methodology was applied to identify the best mix of road preservation projects over a specific period.

The obtained results can be improved by using more than one year performing the maintenance and revising the process. Also changing the evaluation method from manual to smartphones measurement can highly enhance a better accuracy using reliable subjective ratings and a new feasible way to do the evaluation.

It was demonstrated in this paper that the deterioration models using the Markovian probability process can help manage the pavements in a better way. Accomplishing this, the methodology turns attractive to companies and government due the facilities and good results achieved to better manage their infrastructure with limited budget.

## **7. CONCLUSIONS**

This chapter developed a model using pavement distress data from interstate and highways in the state of Minas Gerais over 6 years (from 2013 to 2018) using the dataset from CNT (2018) survey. The proposed deterioration model was implemented using the statistic computing Software R with the package. The developed Markovian models for performance prediction of each road were characterized in an equation, providing a probabilistic approach tool to the Pavement Management System (PMS) by calculating the future condition states of pavements according to their age. The methodology can be used to find the overall condition state of complete road networks. This helps to identify the appropriate maintenance policy according to a specific budget. It also helps to compare the improvement in overall condition after repair treatment of a road network. The research concluded that the Markovian process is an excellent tool which can be used to design decision support systems for PMS. However, it is more appropriate to be used at a network level, since it is more effective at estimating the number of sections in a particular condition state for a given moment than at predicting the performance of a specific road section and the type of the maintenance to be used there.

## **8. RECOMMENDATIONS**

The Brazilian government and trucking companies that use roads to ship their products are always trying to find new practices to better optimize limited budgets. This chapter has demonstrated that the deterioration models using the Markovian probability process can help organizations better manage their roads. Because the manual data collection process takes a lot of time, energy, and money, it is recommended that a comprehensive study be conducted to determine how to optimize the collection of data using computers and smartphones. It is also recommended to compare Markovian probability processes with other techniques, given the limited historical data available when it comes to predicting the pavement age, allocating maintenance resources, or predicting the future needs to achieve a certain service level.

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## REFERENCES

AASHTO, (2001). AASHTO Pavement Management Guide. Washington, DC: AASHTO.

ADB- Asia Development Bank. (2003) Road Funds and Road Maintenance - An Asian Perspective. July 2003

Baladi, G. Y. (2017) Pavement Performance Measures and Forecasting and the Effects of Maintenance and Rehabilitation Strategy on Treatment Effectiveness. Federal Highway Administration (FHWA). September 2017.

Balbo, J. T. (2007) Pavimentacao Asfaltica: materiais, projeto e restauracao. Sao Paulo: Oficina de Textos, 2007  
Chabot, A., Chupin, O., Deloffre, L., Duhamel, D. (2009). Viscoroute 2.0: a tool for the simulation of moving load effects on asphalt pavement. Road Materials and Pavements Design. Volume X – No X/2009.

Chabot, A., Balay, J.M., Pouteau, B., Larrard, F. (2008) FABAC accelerated loading test of bond between cement overlay and asphalt layers. 6th RILEM International conference on cracking in pavements, Jun 2008, CHICAGO, United States. pp. 671-680. fahal-00399985f

Confederação Nacional do Transporte - CNT. (2019) Anuário CNT do transporte – estatísticas consolidadas 2019. Brasília: 2019.  
<http://anuariodotransporte.cnt.org.br/2018/>.

DelSole, T. (2006) A Bayesian Framework for Multimodel Regression. George Mason University, Fairfax, VA and Center for Ocean-Land-Atmosphere Studies, Calverton, MD. October 20, 2006

DNIT- DEPARTAMENTO NACIONAL DE INFRAESTRUTURA DE TRANSPORTES, (2003a) - Defeitos nos pavimentos flexíveis e semi-rígidos Terminologia. NORMA DNIT 005/2003 – TER.

DNIT - DEPARTAMENTO NACIONAL DE INFRAESTRUTURA DE TRANSPORTES (2003b) - Avaliação objetiva da superfície de pavimentos flexíveis e semi-rígidos – Procedimento. NORMA DNIT 006/2003 – PRO.

DNIT- DEPARTAMENTO NACIONAL DE INFRAESTRUTURA DE TRANSPORTES, (2003c) - Levantamento visual contínuo para avaliação da superfície de pavimentos flexíveis e semi-rígidos Procedimento. NORMA DNIT 008/2003 – PRO.

Domingues, F. A. A (1995) Avaliação de pavimentos: Construção de índices de defeito. In: 27ª reunião anual de pavimentação. São PauloSP. Anais.... p. 84-122. 1995.

FHWA - The Federal Highway Administration (2007) Asset Management Overview. December 2007 FHWA-IF-08-008. [https://www.fhwa.dot.gov/asset/if08008/assetmgmt\\_overview.pdf](https://www.fhwa.dot.gov/asset/if08008/assetmgmt_overview.pdf)

Gupta, A., Kumar, P., Rastogi, R. (2014). Critical review of flexible pavement performance models. *KSCE Journal of Civil Engineering*. 18. 10.1007/s12205-014-0255-2.

Hassan, R., Lin, O., and Thananjeyan, A., (2015). Probabilistic modelling of flexible pavement distresses for network management. *International Journal of Pavement Engineering*. doi:10.1080/10298436.2015.1065989.

Kobayashi, K., Do, M., Han, D. (2010). Estimation of Markovian transition probabilities for pavement deterioration forecasting. *KSCE Journal of Civil Engineering*. 14. 343-351. 10.1007/s12205-010-0343-x.

Leandro, R. P., Beja, I. A., Bessa, I. S., Andrade, L. R. de, Vasconcelos, K., Bernucci, L. L. B., et al. (2015). Desenvolvimento do modelo de deterioração de pavimentos asfálticos com uso de instrumentação e sistema weigh in motion. *Revista ANTT*, 12 p. no2015 (2).

Maaty, Ahmed. (2017). Temperature Change Implications for Flexible Pavement Performance and Life. *International Journal of Transportation Engineering and Technology*. 3. 1. 10.11648/j.ijtet.20170301.11.

Montoya-Alcaraz, M., Mungaray-Moctezuma, A., García, L. (2020) Sustainable Road Maintenance Planning in Developing Countries Based on Pavement Management Systems: Case Study in Baja California, México. *Sustainability* 2020, 12(1), 36; <https://doi.org/10.3390/su12010036>

Moreira, A. V. et al. (2018) An application of Markovian chains to predict the evolution of performance indicators based on pavement historical data, *International Journal of Pavement Engineering*, 19:10, 937-948, DOI: 10.1080/10298436.2016.1224412.

Neto, R. S. B. (2004) *Análise Comparativa de Pavimentos Dimensionados Através dos Métodos Empírico do DNER e Mecanístico e Proposta de um Catálogo Simplificado de Pavimentos para a Região de Campo Grande*. (Doctoral dissertation). Universidade de Sao Paulo, 2004.

Nishiyama, E. S.; Domingues, F. A. A. (1995) Atualização de custos e benefícios, para uso em sistemas de gerência de pavimentos. In: 6ª reunião de pavimentação urbana. Anais...Escola Politécnica da Universidade de São Paulo. Departamento de Engenharia de Transportes. Laboratório de Desenvolvimento Tecnológico de Transportes. LDTT/PTR/USP.1995.

Ortiz-García, J., Costello, S., and Snaith, M. (2006) Derivation of transition probability matrices for pavement deterioration modeling. *Journal of Transportation Engineering*, 132(2):141–161, 2006.

- Pardal, M. da C. (2014). Modelos probabilísticos de previsão de fendilhamento em pavimentos rodoviários. (Master's thesis, Universidade Nova de Lisboa, Portugal). Retrieved from: <http://hdl.handle.net/10362/11463>.
- Pulugurta, H., Shao, Q. & Chou, Y.J. (2009). Pavement condition prediction using Markovian process, *Journal of Statistics and Management Systems*, 12:5, 853-871, DOI: 10.1080/09720510.2009.10701426.
- Ragnoli, A., Blasiis, M. R., Benedetto, A (2018). *Infrastructures*, 3(4), 58; <https://doi.org/10.3390/infrastructures3040058>
- Rodrigue, JP. (2020) *The Geography of Transport Systems*. New York: Routledge, 456 pages. ISBN 978-0-367-36463-2
- Saha, P. Ksaibati, K. Atadero, R. (2017). Developing Pavement Distress Deterioration Models for Pavement Management System Using Markovian Probabilistic Process, *Advances in Civil Engineering Volume 2017*, Article ID 8292056, 9 pages DOI: 10.1155/2017/8292056.
- Shahin, M. Y. (1994) *Pavement Management for Airports, Roads and Parking Lots*, Chapman & Hall, London, 1994.
- Sharabah, A., Setunge, S., Zeepongsekul, P. (2007). Use of Markov Chain for Deterioration Modeling and Risk Management of Infrastructure Assets. 2nd International Conference on Information and Automation, ICIA 2006. 384 - 389. 10.1109/ICINFA.2006.374109.
- Sinha, S.K. and McKim, R.A., 2007. Probabilistic based integrated pipeline management system. *Tunnelling and Underground Space Technology*, 22 (5–6), 543–552, *Trenchless Technology*.
- Stewart, W. (2009) *Probability, Markovian Chains, Queues, and Simulation: The Mathematical Basis of Performance Modeling*. Princeton University Press, 2009.
- TRB (2010) *Highway Capacity Manual 2010*. Transportation Research Board, Washington, D.C.
- Tsuda, Y., et al., (2006). Estimating Markovian transition probabilities for bridge deterioration forecasting. *Journal of Structural Engineering and Earthquake Engineering*, 23 (2), 241–256.
- Wilde, WJ., Thompson, L., Wood, TJ. (2014) *Cost-Effective Pavement Preservation Solutions for the Real World*. Minnesota Department of Transportation. MN/RC 2014-33. September 2014.
- Willway, T., Baldachin, L., Reeves, S., Harding, M., McHale, M., Nunn, M. (2008) *The effects of climate change on carriageway and footway pavement maintenance: Technical Report*. TRL Limited, October 2008.
- Yang, J. (2004) *Road Crack Condition Performance Modeling Using Recurrent Markovian Chains and Artificial Neural Networks*. (Master's thesis) University of south Florida, 2004.

## **CHAPTER 4: Developing a Deterioration Model Using Markovian Probabilistic Process for Brazilian Unpaved Roads: Case Study in Viçosa - MG, Brazil**

### **ABSTRACT**

Responsible for more than 60% of shipments and over 90% of travelers, Brazil's road transportation system faces serious problems with the poor infrastructure: 87.6% of the network is unpaved roads. To better preserve these roads, is necessary to understand how these unpaved roads deteriorate and improve the method to select roads to be maintained. Currently, the most cost-effective method is the Unpaved roads Management Systems (GRMS). The GRMS consists in planning the maintenance in order to optimize the surface conditions over the entire network using prediction models to predict the future needs. In this study, 18 segments with 150 m each of unpaved roads were analyzed over nine years at Zona da Mata, Minas Gerais, Brazil. To collect the dataset was used a guide created by Wyoming Technology Transfer Center (Wyoming T<sup>2</sup>/LTAP), because the regular Pavement Condition Index (PCI) evaluation is not sensitive enough to detect the quick changes in unpaved roads. The probabilistic technique Markovian process was used to create a deterioration model for these unpaved road segments, and regression techniques with Software R were used to develop the deterioration paths using the predicted distribution of indices estimated from the Markovian process. Results indicated that unpaved road segments have very fast deterioration over a year. The deterioration model developed had a coefficient of determination ( $R^2$ ) above 0.99. As deterioration models using Markovian process provide more accurate results, it is recommended that these types of models be integrated into the GRMS to be used by the government to maintain the unpaved roads.

Keywords: deterioration model, unpaved roads, unpaved roads management system, Brazilian roads, tropical roads.

### **1. INTRODUCTION**

In Brazil, 87.6% of the roads network is composed of unpaved roads. On the other hand, the traffic volume is increasing every year, jumping 63.6% in six years (2009 – 2017), and exceeding 100 million vehicles in 2017 (CNT, 2018). With the overload, the deterioration is happening faster than before and the maintenance service cannot keep

up the path with the available budget, increasing bad conditions, heavy distresses, and less safety for the drivers. In 2017 alone, 58,176 crashes were reported with 6,243 deaths on the federal highways (CNT, 2018).

In Brazil, Minas Gerais state has the largest road network, equivalent to about 16% of all existing road network in the country. In the state, there are 272,063 km of highways. Of this total, 9,206 km are paved federal roads, 22,286 km are paved state roads, and 24,0571 km are unpaved municipal roads (Rodovias, 2019). In most cases, the offices responsible for the maintenance of unpaved roads in Brazil linked to municipalities do not have adequate financial resources for their maintenance and rehabilitation (Lodge et al., 2017). In addition, the agencies from developing countries lack the technical knowledge and tools to understand how to prioritize these maintenance activities (Pulugurta, Shao, and Chou, 2009).

It is known that the roads are built to match the volume of traffic, and for unpaved roads this traffic is less than 400 vehicles per day (Quadros and Nassi, 2015). However, some roads carry extra-heavy volumes of traffic, usually in a single direction, composed of vehicles with load capacity more than 40 tons, which most of the times exceed their capacity (Shahin, 1994). Five main factors may affect the capacity and quality of unpaved roads: traffic load, subgrade quality, construction practices, water, and maintenance program. To extend this quality and the service life, four types of maintenance are recommended (FHWA, 2015):

- Routine Maintenance: shoulder repairs, side drain repairs and cleaning, manual reshaping, pothole repairs, road grading, side slope repair, road marking, and sign minor maintenance.
- Major Maintenance: maintenance practices used in the case of many distresses in situations where the use of rehabilitation or reconstruction services is not justified.
- Rehabilitation: thin unpaved overlay or chemical stabilization.
- Reconstruction: complete reconstruction.

In developed countries, besides the usual types of maintenance, the advance of the automated models for optimizing unpaved road vertical alignments is one of the main goals of planners and designers before road construction to improve the surface quality and decrease periodic maintenances (Tsuda et al., 2006).

To organize a maintenance program, it is necessary to understand how these unpaved roads deteriorate. They deteriorate not only due to the deformations caused by constant traffic loading, but also by exposure to a variety of environmental and climate conditions (Naik et al., 2017). These climate conditions are increased in variability in tropical countries, which make the pavement deteriorate faster than in moderate climate. The time between maintenances is a big challenge due the relationship between these variables, and the government needs to determine how to prioritize these roads to be maintained. An unpaved roads Management System (GRMS) is widely used in developed countries, and it is a complete method for that (FHWA, 2015).

According to Saha, Ksaibati, and Atadero (2017), a GRMS is a strategic and systematic process to maintain and upgrade the road network, but when the funding is limited, the GRMS identifies the best mix of road preservation projects that provides the most benefit to society in terms of overall lifecycle cost of the road network. A GRMS is composed of seven steps including the “predict condition” which is the most complex one. To predict the conditions, it is necessary to develop deterioration models using the road condition over the years. The established models allow the prediction of the main responses on the road surface, and it can be empirical, mechanistic, or mechanistic-empirical type, which are models calibrated with data observed in the field (Shenghua and Balasingam, 2019).

The GRMS does not have a standardized procedure to determine the surface condition rating nor a deterministic approach to model the surface deterioration. To find the roads condition, is necessary to evaluate the roads and determine the Pavement Condition Index (PCI) (Shohel, 2015). However, the normal PCI does not apply to unpaved roads because the PCI is a detailed examination of paved roads distresses such cracking and potholes (Schnebele et al., 2015). To determine the unpaved roads condition in this work, a guide created by the Wyoming Technology Transfer Center (Wyoming T<sup>2</sup>/LTAP) was used. It was designed to be used in conjunction with the Ride Quality Rating Guide also developed by the Wyoming T<sup>2</sup>/LTAP (WTTC, 2014).

With the roads condition, a GRMS uses probabilistic or deterministic models to predict the future needs (Saha, Ksaibati and Atadero, 2017). In Brazil they are using mostly family and expert opinion curves as a deterministic model, based on the field staff's experience (Martins, 2015). In the deterministic technique, the uncertainties of

pavement deterioration related to traffic and weather are not considered. However, probabilistic models consider these uncertainties and result in more accurate curves (Saha, Ksaibati, and Atadero, 2017).

The probabilistic model using Markovian process have been used to predict deterioration in many infrastructure areas, such as pavements, bridges and pipelines (Jin and Mukherjee, 2014). Surendrakumar, Prashant and Mayuresh (2013) used the Markovian process to develop a decision support system for management systems. The Markovian process is a probabilistic and stochastic model describing a sequence of possible events in which the probability of each event depends only on the state attained in the previous event (Ching and Ng, 2006).

The budget necessary for emergency reconstruction and restoration of unpaved roads is high, and the cities cannot afford to preserve the entire network (Wilde, Thompson and Wood, 2014). However, knowing the budget is not enough to cover all these interventions, an optimization system is a good option to allocate the money effectively. To develop an optimization system, deterioration models must be created. They are necessary to predict the future condition of the roads, allow to select correct rehabilitation treatment and, show the timing to start the repairs.

## **2. OBJECTIVES**

The objective of this study was creating a deterioration model for unpaved roads at Zona da Mata county, Minas Gerais (Brazil) using Markovian process. Over nine years (2011 to 2019) evaluators traveled 2,723 km through the state to determine the general condition of the road network. To determine the roads condition, they were classified according with the amount of distresses on the surface following a guide created by Wyoming T<sup>2</sup>/LTAP. The condition categories are very good, good, fair, poor, and failed.

In order to achieve the main objective, the following specific objectives have been defined:

- Collect and analyze the existing distresses on municipal unpaved roads.
- Use a guide created by Wyoming T<sup>2</sup>/LTAP to evaluate the distresses.
- Create a transition probability matrix with Markovian process using the dataset collected.

- Use regression techniques to predict deterioration paths using indices from the Markovian process and create a deterioration model.

### 3. BACKGROUND

#### 3.1. Unpaved road deterioration and its management system

Roads are only designed to last for a certain period, and comparing paved and unpaved roads, the paved roads lasts in a good condition at least twice more than unpaved roads. The "life cycles", or a period between a good condition and bad condition, is when the surface begins from an optimal condition, declining until it reaches a failed condition. This reduced level in a road condition is known as road deterioration (FHWA, 2015).

Estimating the road deterioration is important to help those responsible for the maintenance with their decision-making process, and aid them in understanding the surface performance offered to drivers. Once the deterioration condition is known, professionals can find techniques that effectively work to control the mechanisms competing to decrease the service-life. The deterioration should be estimated by evaluating the functional deterioration and structural deterioration (Saha, Ksaibati, and Atadero, 2017). There are specific assessment methods to determine each of these components for paved or unpaved roads. Figure 1 shows a data collection from a unpaved county road at Zona da Mata, Minas Gerais (Brazil), which is awaiting maintenance to extend the service life.



Figure 1: County road from Minas Gerais (Brazil) in poor condition.

**Source: The author**

The term Unpaved roads Management System (GRMS) can be understood as the efficient and integrated coordination of the various activities involved in the design, construction and maintenance of unpaved roads that are part of a road infrastructure, in order to allow them to provide acceptable conditions to the user at minimal cost. Fundamentally, the GRMS is a set of tools or methods to assist decision makers to find optimal strategies to construct, evaluate and maintain the surfaces in an acceptable functional condition over a period with a selected budget (Mishra et al., 2015).

These unpaved roads would normally be maintained at approximately 1/3 of the cost per km for maintaining single lane sealed roads and would only carry a fraction of the over-all traffic volumes. However, often these unpaved and unsealed roads are used by a large portion of the agricultural, mining and forestry industries, thus playing an important role in the over-all gross domestic product of any country (Henning et al., 2015).

Although much cheaper to maintain compared to sealed roads, the optimal expenditure on unpaved roads are much more difficult to determine. For example, there are several successful sealed road management systems used around the world. While there are a significant number of management and maintenance guidelines available for unpaved roads, there are only a limited number of well-used maintenance decision guidelines and systems (Austroads, 2009). Research into unpaved road management systems has revealed that one of the main stumbling blocks of the systems is the significant reliance on intensive data collection (Van Zyl, Henderson and Uys, 2007).

To create a good and reliable system, it is important to build a GRMS sooner as possible to understand the road behavior and follow the changes over the years. However, the establishment of a GRMS becomes even more important when the road conditions are bad, and the resources are limited. The main GRMS objective is to use the collected data from the roads to help the managers take decisions to run a maintenance program with an organized methodology (Nishiyama and Domingues, 1995).

According to Van Zyl, Henderson and Uys, (2007) the issues with data sourcing for these management systems are:

- Specific material characteristics normally do not exist for individual unsealed roads.
- The condition of unsealed roads changes rapidly, often leading to existing data being out of date soon after it has been collected.
- In order to make the management system sufficiently robust, more frequent data collection would be required. However, more frequent data collection may not be cost-effective and may be significantly onerous from an administrative perspective.

To build a GRMS, it is necessary to consider three aspects. When considering the project, the methods and procedures to create a system are reviewed, and the implementation plan is developed. At this stage, social impacts are needed in order to obtain political support. During the second aspect, the data collection is implemented, establishing the collection procedures, developing the database and reporting the results. In the third aspect, the analysis is implemented using deterioration models and decision trees, in order to generate priority rehabilitation programs, verifying the effects of varying budget levels, and matching the specified standard requirements for each case. Currently, to implement a GRMS the only issues are the limitation of skilled professionals and availability of material resources (Domingues, 1995).

### **3.2. Deterioration Model and Markovian Chains**

Various methods have been employed by highway agencies and researchers to develop pavement performance prediction models; these can be classified into two categories: deterministic and probabilistic methods (Stewart, 2009). In deterministic models, regression equations are widely used, due to their relative simplicity and well-established procedures for use (Hassan and Thananjeyan, 2015). Both simple and complex function forms, such as straight-line extrapolation, S-shaped curves, and polynomial constrained least squares, have been used in the development of models (Balbo, 2007).

A regression equation can provide accurate predictions if all significant variables have been considered and a reasonable coefficient of determination value has been introduced. The major limitations of the regression methods are (Stewart, 2009):

- Accurate models require accurate inputs, and outliers will significantly affect the accuracy of models.
- The prediction is good only to the range of data that were used to develop the regression model.

The methods commonly used in Brazil are the deterministic ones, elaborated from theoretical and rational extrapolations of observational models obtained by the accumulation of data and experiences (Martins, 2015). However, the application is limited and should only be used when no other advanced technique is available (Balbo, 2007).

For pavements under unexpected conditions, deterministic models may produce unrealistic predictions. Therefore, more and more researchers and engineers have turned to probabilistic methods, such as the Markov process (Neto, 2004).

A Markov process describes a system that can be in one of several states. Each state can pass to another at each time step according to fixed probabilities. Markov-chain model is a special case of the Markov process whose time and state parameters are both discrete. A Markov chain can be treated as a series of state transitions based on certain probabilities. A stochastic process whose transition probability of a future state depends only on the present state is defined as a first-order Markov process (Parzen, 1962).

The transition matrix with dimension  $k \times k$  with the following form is used to evaluate the transition probability of states (Ortiz-García, Costello, and Snaith, 2006):

**2**

$$P_{\Delta t} = \begin{bmatrix} p_{11} & p_{12} & \dots & p_{1k} \\ 0 & p_{22} & \dots & p_{2k} \\ 0 & 0 & \ddots & \vdots \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The unit value presented in this matrix ( $P_{\Delta t}$ ) corresponds to the maximum input value, for each event. The reason for the probability value  $p_{kk}$  is due to the fact that there is no further condition state after the  $k$  state, since it is a limiting value. The transition probability from a state  $i$  to a state  $j$ , for a generic time interval ( $\Delta t$ ), is represented by  $p_{ij}$ , with  $i = j = 1, \dots, k$ , and determined as follows (Yang, 2004):

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

Through this equation, it is possible to demonstrate that the state of the pavement at the moment of evaluation ( $t + \Delta t$ ) depends exclusively on the previous state at the initial moment ( $t$ ).

#### 4. METHODOLOGY

The roads performance can be determined by each distress index or a combined index representing the overall condition. Nonetheless, evaluating and rating unpaved roads requires a different perspective than similar evaluations of asphalt or concrete pavements (called Pavement Condition Index – PCI) due to the nature of unpaved roads and their variability. To properly evaluate these roads, was used the PSI instead of PCI as the Ride Quality Rating Guide (RQRG) created by Wyoming T<sup>2</sup>/LTAP (WTTTC, 2014) described. The RQRG rating scale can be seen on Figure 2.

The dataset was composed by county unpaved roads. To enhance a better understanding, these five surface conditions showed on Figure 2 were divided according to the average speed used by the driver on these roads. The rating scale is presented on Table 1.

Gravel Road Quality Rating	Distresses Adapted from the Gravel - PASER manual
Very Good	Rides like good asphalt pavement. May be hazardous if alignment and shoulders don't allow for safe travel at high speeds.
Good	Dust under dry conditions; Moderate loose aggregate; Slight washboarding
Fair	Moderate washboarding (1" - 2" deep) over 10% - 25% of area; Moderate dust, partial obstruction of vision; None or slight rutting (less than 1" deep); An occasional small pothole (less than 2" deep); Some loose aggregate (2" deep)
Poor	Moderate to severe washboarding (over 3" deep) over 25% of area; Moderate rutting (1" - 3") over 10% - 25% of area; Moderate potholes (2" - 4" deep) over 10% - 25% of area; Severe loose aggregate (over 4")
Failed	Severe rutting (over 3" deep) over 25% of area; Severe potholes (over 4" deep) over 25% of area; Many areas (over 25%) with little or no aggregate

Figure 2: Unpaved roads Quality Rating Scale.

**Table 1: Low volume and unpaved roads rating scale.**

Speed		Condition
mph	Km/h	
>61	>70	Very good
51-60	55-70	Very good
46-50	45-55	Good
41-45	40-45	Good
33-40	35-40	Fair
26-32	30-35	Fair
21-25	25-30	Poor
16-20	20-25	Poor
<15	<20	Failed

**Source: WTTC,2014**

Passenger car speeds are based on surface condition allowed for rider comfort and minimal vehicle wear and tear, assuming no safety or geometric constraints force slower travel. Individual roadways when analyzed may not have all the types of distress listed for any rating (WTTC, 2014). For example, they can have only one or two types.

For each condition state of the road, the repair maintenance must be provided, and the deterioration model must be developed to build the GRMS. For the aim of this work, the probabilistic Markovian process was used to develop the probability transition matrices. Markovian process is a stationary process and considers that the road network will always deteriorate following the transition matrix (Jin and Mukherjee, 2014).

The road condition dataset was appropriately organized according to the defined condition states defined on Table 1. After organizing the dataset according to the unpaved roads rating scale, was created a scale to represent the speed range (RQRG<sub>M</sub>) while using the Markovian process. This new standard can be seen in Table 2.

**Table 2: Grouping distress indices according to RQRG.**

Speed Range	Conditions								
	Excellent	Excellent	Very Good	Very Good	Good	Good	Fair	Fair	Failed
(mph)	>61	60-51	50-46	45-41	40-33	32-26	25-21	20-16	<15
(km/h)	>70	55-70	45-55	45-40	40-35	35-30	30-25	20-25	<20
RQRG <sub>M</sub>	<b>9</b>	<b>8</b>	<b>7</b>	<b>6</b>	<b>5</b>	<b>4</b>	<b>3</b>	<b>2</b>	<b>1</b>

**Source: The author**

Bearing in mind that the deterioration is a natural and continuous process, it is impossible to improve its condition state without any maintenance and rehabilitation operation. It is known that the time interval between two consecutive inspections on paved roads are made to be shorter than the necessary time for a surface section get worse in more than one condition state (ASTM, 2007). However, for unpaved roads in tropical soils which the deterioration increases with the weather, it is possible to happen these drops in more than one condition.

To build the transition matrix, the  $Q$  is null except for the main diagonal and the diagonal above that, meaning that during the deterioration process, in each time interval, the pavement can only advance between adjacent condition states. The worst condition state is designed as absorbing state since there are no transitions from it. For these reasons, all the elements in the last line of matrix  $Q$  are null. In this study, since there are nine different condition states for the unpaved roads evaluation, the intensity matrix  $Q$  is  $9 \times 9$ , as illustrated in Equation 3.

**3**

$$Q = \begin{bmatrix} -\phi_1 & \phi_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -\phi_2 & \phi_2 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -\phi_3 & \phi_3 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\phi_4 & \phi_4 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\phi_5 & \phi_5 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -\phi_6 & \phi_6 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -\phi_7 & \phi_7 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\phi_8 & \phi_8 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

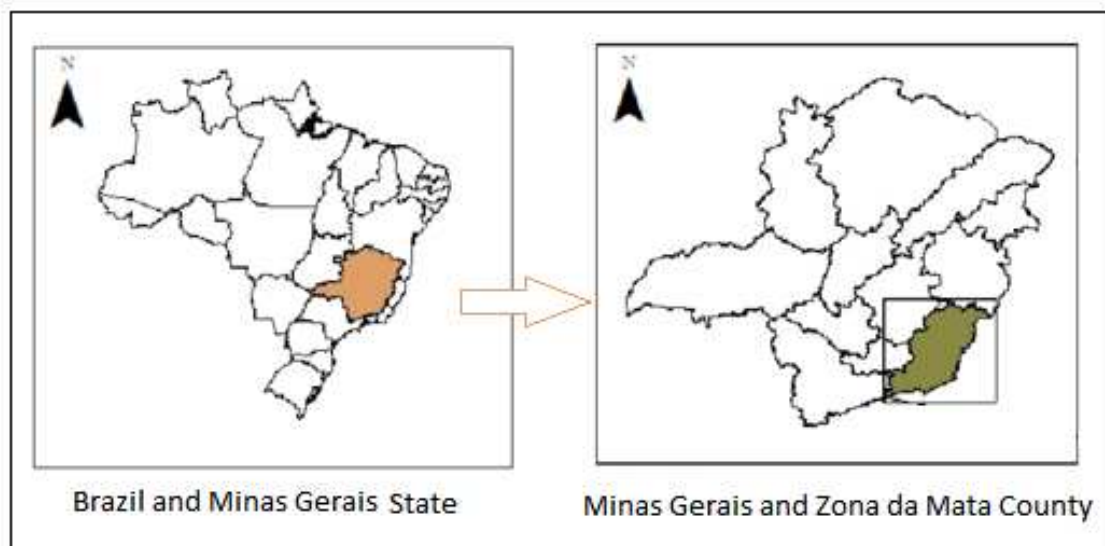
The proposed road deterioration model was implemented using the statistic computing software R. Starting from the data matrix, the transition matrix was calculated to obtain the probability distribution matrix, which was used then to estimate the expected road age according to their condition. Then, these values were used to create the statistical deterioration model specifically for unpaved roads.

## 5. DATA COLLECTION

This case study was conducted on unpaved roads at Zona da Mata County, Minas Gerais state, Brazil in order to develop deterioration models using the Markovian

process. A road condition dataset was collected over nine years by undergraduate students from Federal University of Viçosa. Figure 3 shows the Zona da Mata geographical location.

Approximately 230 km of the state network are in city jurisdiction as unpaved roads. Some of these municipal unpaved roads were selected and segmented by the author, and a total of 18 segments with 150 m each were chosen to be used as sample units. The database is composed by information such as road identification number, year, and the overall functional condition. Nine years of maintenance were recorded (from 2011 to 2019) and used in this study as a single database to develop deterioration models to predict the condition on unpaved roads.



**Figure 3: Geographical location of Zona da Mata County.**

**Source: The author**

While Figure 4 summarizes the annual condition of every segment (from original RQRG methodology) in the network between 2011 and 2019, Figure 5 summarizes the average road network condition per year during the same period. Every year was observed a drop in the functional condition which is due to the reduction in the infrastructure budget that comes from the government which does not match with the road needs. According to CNT (2018), the annual expenditures on infrastructure were R\$8.7 billion in 2016, R\$7.2 billion in 2017 and only R\$5.9 billion in 2018.

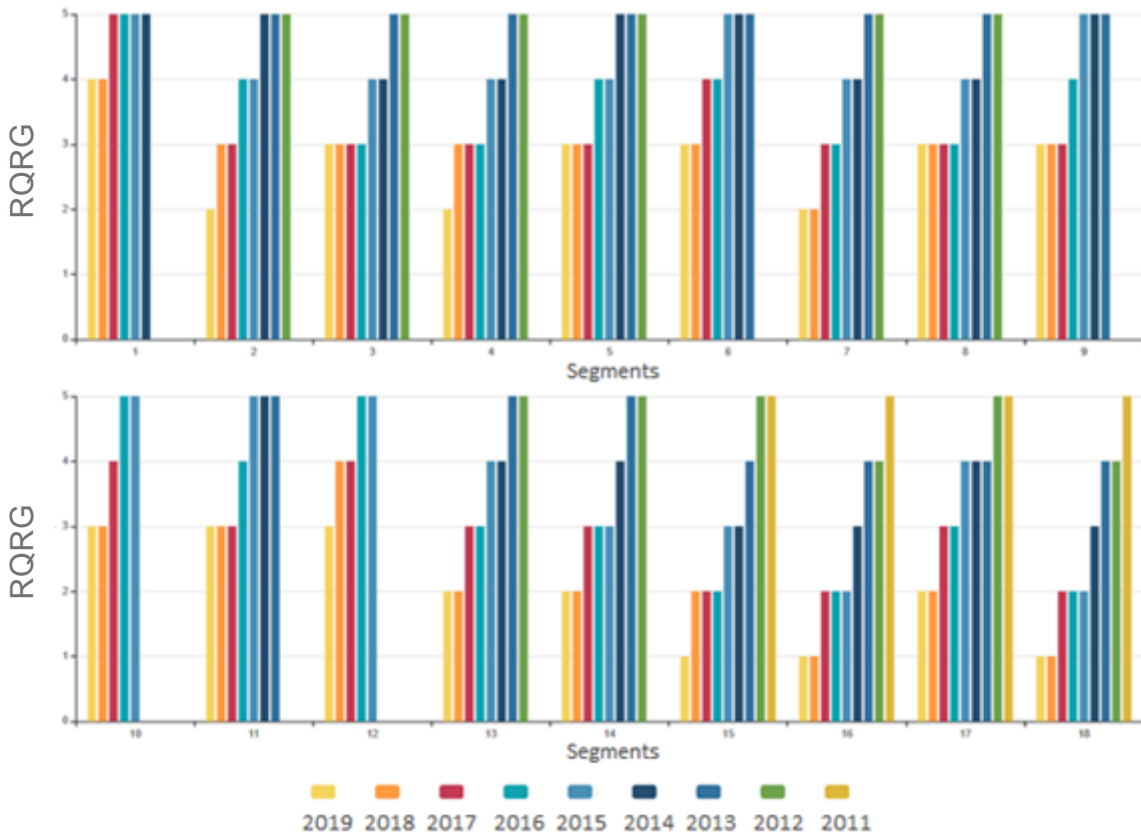


Figure 4: The RQRG conditions of all 18 road segments between 2011 and 2019.

Source: The author

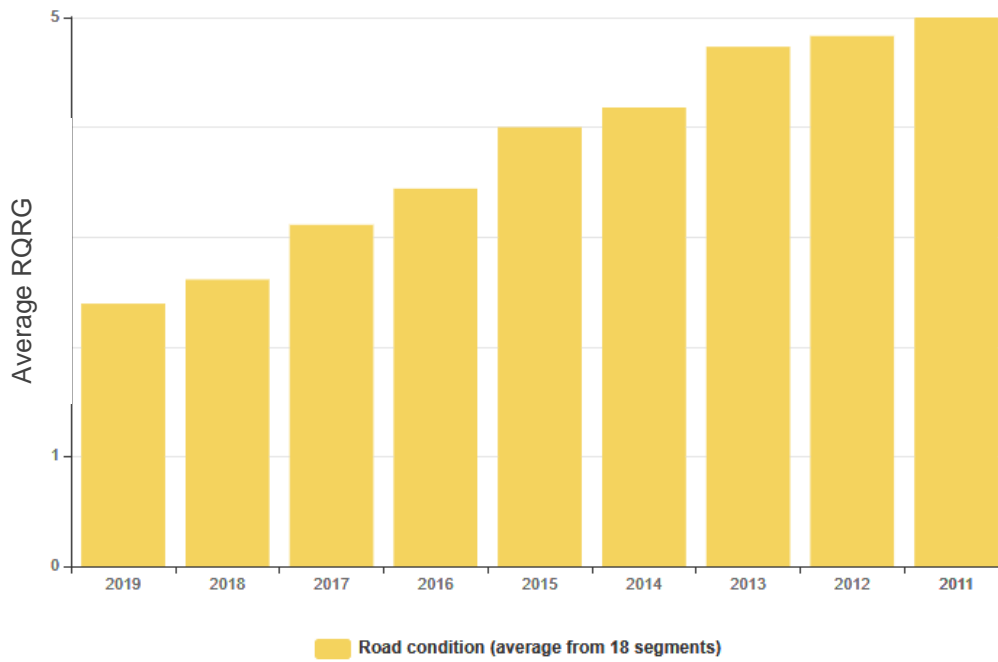


Figure 5: The average RQRG condition of the entire road network per year.

Source: The author

## 6. DATA ANALYSIS

This study developed a deterioration model for unpaved roads at Zona da Mata, Minas Gerais using the Markovian process. To start the Markovian process, nine years of roads condition (2011 to 2019) were used to develop a dataset, which was created using the Unpaved roads Quality Rating Guide (WTTC, 2014). Using the speed values and indexes from Table 2 the dataset was organized in groups as presented in Table 3.

The Markovian process itself, consists of developing three matrices: transition probability data (Table 4), transition probability matrix (Table 5), and probability distribution matrices (Table 6).

Thus, the transition probabilities data were estimated and defined as the rate the roads transit from one state to another (Mizutani et al., 2017). Roads condition of some roadway segments dropped from one year to the next by more than a group and this situation for unpaved roads is normal, because unpaved roads have faster deterioration than paved roads. Table 4 shows the transition probability data.

**Table 3: Road dataset using the RQRG<sub>M</sub> from the last table.**

Segments	2019	2018	2017	2016	2015	2014	2013	2012	2011
1	6	7	8	8	9	9	-	-	-
2	3	4	5	6	7	8	8	9	-
3	4	4	5	5	6	7	8	9	-
4	3	4	5	5	6	7	9	9	-
5	4	5	5	6	7	8	9	9	-
6	4	5	7	7	8	9	9	-	-
7	2	3	5	5	6	7	8	9	-
8	4	5	5	5	6	7	8	9	-
9	4	5	5	7	8	9	9	-	-
10	4	5	7	9	9	-	-	-	-
11	4	5	5	7	8	9	9	-	-
12	5	6	7	9	9	-	-	-	-
13	2	3	4	5	6	7	8	9	-
14	2	3	4	4	5	6	8	9	-
15	1	2	2	3	4	5	6	8	9
16	1	1	2	2	3	5	6	7	9
17	2	3	4	4	5	6	7	8	9
18	1	1	2	2	3	5	6	7	9

Table 4: Transition Probability Data from the road dataset.

		Unpaved roads								
RQRG <sub>M</sub>		9	8	7	6	5	4	3	2	1
RQRG <sub>M</sub>	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

Table 5 represents the transition probability matrix for the entire analyzed network. A transition matrix of a Markov process contains information on how the deterioration process moves from one state to another in terms of probabilities. These probabilities are assumed to be constant. From Table 5, it can be seen that after 1 year the number 0.333 represents the percentage of the roads that stay at level 9, 0.481 represents the percentage of the roads that deteriorate from level 9 to level 8, and 0.185 represents the percentage of the roads that deteriorate from level 9 to level 7.

Table 5: Transition Probability Matrix from the road dataset after 1 year.

		Unpaved roads								
RQRG <sub>M</sub>		9	8	7	6	5	4	3	2	1
RQRG <sub>M</sub>	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 probability distribution using the Markovian probability process. In this table, the state of the maximum probability is shown in the bold font. For

example, comparing the distribution from year 1 to year 5, there is a probability of 0.004 for the segments to stay at level 9 and a probability of 0.037 for the segments to be at level 1 after 5 years. The highest probability value is 0.327 for the roads be at level 5 after 5 years.

**Table 6: Probability distribution from the road dataset using Markov process.**

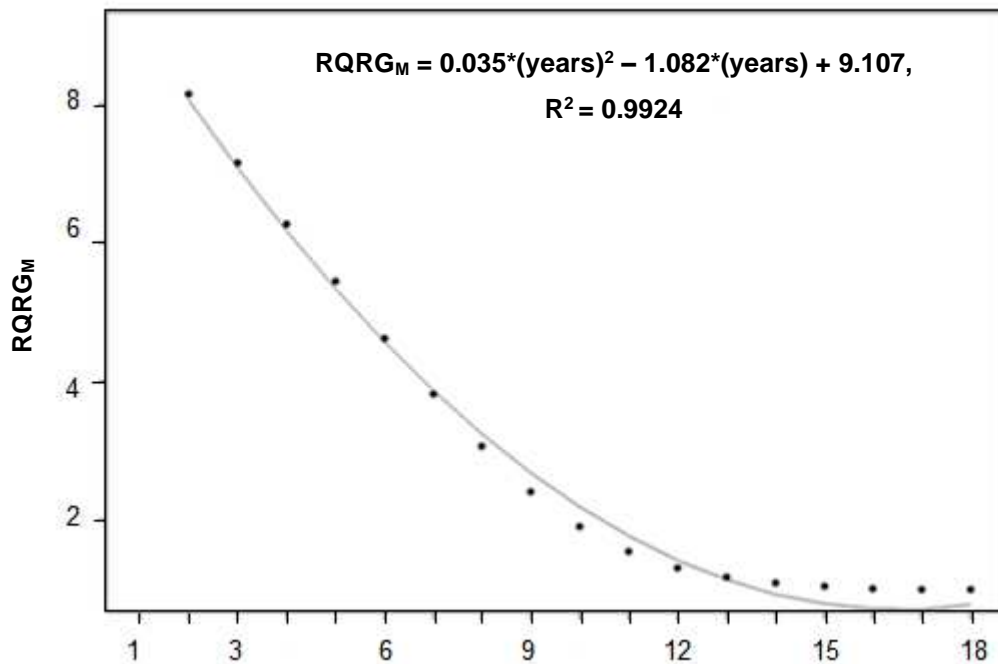
Unpaved roads										
RQRG <sub>M</sub>	9	8	7	6	5	4	3	2	1	Total
1	0.333	<b>0.481</b>	0.185	0	0	0	0	0	0	1
2	0.111	0.194	<b>0.451</b>	0.230	0.011	0	0	0	0	1
<b>Years</b> 3	0.037	0.067	0.272	<b>0.413</b>	0.185	0.021	0.001	0	0	1
4	0.012	0.023	0.123	0.312	<b>0.351</b>	0.134	0.041	0.001	0	1
5	0.004	0.007	0.049	0.173	<b>0.327</b>	0.246	0.152	0.037	0	1

While Table 6 predicts the distribution for 5 years, Figure 6 shows the deterioration model according to that dataset. The deterioration model obtained indicates that unpaved roads have fast deterioration over the years considering how paved roads deteriorate. Regression techniques have been used to develop the model using the mean obtained from the Markovian distribution as shown in Equation 4:

4

$$\text{RQRG}_M = 0.035 * (\text{years})^2 - 1.082 * (\text{years}) + 9.107, R^2 = 0.9924$$

Figure 6 shows that the Equation 4 can be used due its high correlation coefficient. The model accuracy is expressed in terms of years predicting the road condition over almost 20 years, as it can be seen on Figure 6.



**Figure 6: Deterioration model from the road dataset using the Software R.**

Management systems for unpaved roads are often neglected because of the low traffic density on those roads. However, unpaved roads constitute a large portion of the length of the road network and often a large portion of the administration's total maintenance budget. An efficient system for dividing and optimizing that expenditure is therefore justified. Although the model is mathematical, it can be used for dividing funds between maintenance and for setting up the objective maintenance standards for the unpaved road network.

The obtained results can be improved by using more than one-year dataset performing the maintenance and revising the process. Updating the system, accurate maintenances and quality of the projects can be achieved. In addition, changing the evaluation method from manual to smartphones measurement can highly enhance the harmony between the reliable subjective ratings and the practical way to do the evaluation.

## 7. CONCLUSIONS

In this research, probabilistic deterioration models have been developed for unpaved roads over nine years of roads evaluation using Markovian process and the statistical computing Software R. As probabilistic models provide more accurate results, it is

recommended these models to be used to create a GRMS instead using the ranking method. The developed model can be highlighted as follows:

- They are tailored specifically to unpaved roads from Minas Gerais, Brazil.
- As this methodology still incorporates uncertainties about the data collection, the developed models will become every year more accurate if updated with new inputs.
- This methodology can also be implemented on other functional classes or types of roadways.
- Using this probabilistic method to determine the deterioration model, the GRMS can be created as a reliable and cost-effective system to better maintain unpaved roads.

## **8. RECOMMENDATIONS**

Agencies are always looking for strategies to optimize the budget of their jurisdictions. In this study that the use of Markovian probability to create deterioration models was demonstrated, and it can be very useful to help manage unpaved roads better. With reliable deterioration models is possible to create a GRMS to improve the management.

However, it is recommended to make a comprehensive and long-term study to determine the benefits and make the model more accurate. It is also recommended that the government consider Markovian probability as an alternative to allocate resources to make the maintenance and rehabilitation strategies within their roads instead using the ranking methodology.

In addition, Markovian probability is more recommended to be used at a network management level, since it works better estimating the number of road sections in a condition state for a specific moment than to predict the performance of a precise road section.

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## REFERENCES

ASTM D6433 -11 (2007) Standard Practice for Roads and Parking Lots Pavement Condition Index Surveys ASTM International, West Conshohocken, PA, 2007, [www.astm.org](http://www.astm.org)

Austrroads (2009) Guide to Pavement Technology Part 6: Unsealed Pavements. Austrroads Publication No. AGPT06/09. Austrroads, Sydney.

Balbo, J. T . (2007) Pavimentacao Asfaltica: materiais, projeto e restauracao. Sao Paulo: Oficina de Textos, 2007.

Ching, W.K. and Ng, M.K., 2006. Markov Chains: Models, Algorithms and Applications. 1st ed. New York: Springer.

Confederação Nacional do Transporte - CNT. (2018) Anuário CNT do transporte – estatísticas consolidadas 2018. Brasília: 2018. <http://anuariodotransporte.cnt.org.br/2017/>. Accessed Sep. 25 2018.

Domingues, F. A. A (1995) Avaliação de pavimentos: Construção de índices de defeito. In: 27ª reunião anual de pavimentação. São PauloSP. Anais.... p. 84-122. 1995.

FHWA - Federal Highway Administration (2015) Unpaved roads. Construction & maintenance guide. US Department of Transportation. August 2015.

Hassan, R., Lin, O., and Thananjeyan, A., (2015). Probabilistic modelling of flexible pavement distresses for network management. International Journal of Pavement Engineering. doi:10.1080/10298436.2015.1065989.

Henning, T., Flockhart, G., Costello, S., Jones, V., Rodenburg, B. (2015). Managing unpaved-roads on the basis of fundamental material properties. Available from: [https://www.researchgate.net/publication/315681196 MANAGING UNPAVED-ROADS ON THE BASIS OF FUNDAMENTAL MATERIAL PROPERTIES](https://www.researchgate.net/publication/315681196_MANAGING_UNPAVED-ROADS_ON_THE_BASIS_OF_FUNDAMENTAL_MATERIAL_PROPERTIES) [accessed May 03 2020].

Jin, Y. & Mukherjee, A. (2014). Markov chain applications in modelling facility condition deterioration. Int. J. of Critical Infrastructures. 10. 93 - 112. 10.1504/IJCIS.2014.062965.

Lodge, M., Stolk, CV., Batistella-Machado, J., Schweppenstedde, D., Stepanek, M. (2017) Regulation of logistics infrastructure in Brazil. RAND Corporation, Santa Monica, Calif., and Cambridge, UK

Martins, L. D. (2015) Levantamento da Utilização de Sistemas de Gerência de Pavimentos no Brasil e Estudo de Caso / Lídia Diniz Martins – Rio de Janeiro: UFRJ/COPPE, 2015.

Mishra, S., Golias, M.M, Sharma, S., and Boyles, S. (2015). Optimal Funding Allocation Strategies for Safety Improvements on Urban Intersections. *Transportation Research Part A: Policy and Practice*, 75, pp. 113-133.

Mizutani D, Lethanh N, Adey B and Kaito K (2017) Improving the Estimation of Markov Transition Probabilities Using Mechanistic-Empirical Models, *Frontiers in Built Environment*. <https://doi.org/10.3389/fbuil.2017.00058>

Naik, B., Matlack, G., Khoury, I., Sinha, G., McAvoy, DS. (2017) Effects of Tree Canopy on Rural Highway Pavement Condition, Safety, and Maintenance: Phase 1. Ohio Department of Transportation

Neto, R. S. B. (2004) Análise Comparativa de Pavimentos Dimensionados Através dos Métodos Empírico do DNER e Mecanístico e Proposta de um Catálogo Simplificado de Pavimentos para a Região de Campo Grande. (Doctoral dissertation). Universidade de Sao Paulo, 2004.

Nishiyama, E. S.; Domingues, F. A. A. (1995) Atualização de custos e benefícios, para uso em sistemas de gerência de pavimentos. In: 6ª reunião de pavimentação urbana. Anais...Escola Politécnica da Universidade de São Paulo. Departamento de Engenharia de Transportes. Laboratório de Desenvolvimento Tecnológico de Transportes. LDTT/PTR/USP.1995.

Ortiz-García, J., Costello, S., and Snaith, M. (2006) Derivation of transition probability matrices for pavement deterioration modeling. *Journal of Transportation Engineering*, 132(2):141–161, 2006.

Parzen, E. (1962) *Stochastic Processes*, Holden-Day Series in Probability and Statistics, Holden-Day, San Francisco, California, USA, 1962

Pulugurta, H., Shao, Q. & Chou. Y.J. (2009). Pavement condition prediction using Markovian process, *Journal of Statistics and Management Systems*, 12:5, 853-871, DOI: 10.1080/09720510.2009.10701426.

Quadros, S. G. R & Nassi, C. D. (2015) “An evaluation on the criteria to prioritize transportation infrastructure investments in Brazil,” *Transport Policy*, vol. 40, pp. 8–16.

Rodovias (2019) Rodovias – Estado de Minas Gerais. Viewed 20/09/2019. <<https://www.mg.gov.br/conheca-minas/rodovias>>

Saha, P. Ksaibati, K. Atadero, R. (2017). Developing Pavement Distress Deterioration Models for Pavement Management System Using Markovian Probabilistic Process, *Advances in Civil Engineering Volume 2017*, Article ID 8292056, 9 pages DOI: 10.1155/2017/8292056.

Shahin, M. Y. (1994) *Pavement Management for Airports, Roads and Parking Lots*, Chapman & Hall, London.

Schnebele, E., Tanyu, B.F., Cervone, G. Waters, N. (2015) Review of remote sensing methodologies for pavement management and assessment. *Eur. Transp. Res. Rev.* 7, 7 (2015). <https://doi.org/10.1007/s12544-015-0156-6>

Shenghua, W. & Balasingam M. (2019) A mechanistic-empirical model for predicting top-down fatigue cracking in an asphalt pavement overlay, *Road Materials and Pavement Design*, 20:6, 1322-1353, DOI: 10.1080/14680629.2018.1443832

Shohel, A. (2015). *The Pavement Performance Modeling: Deterministic vs Stochastic Approaches*. 10.1007/978-3-319-07167-1\_\_5.

Stewart, W. (2009) *Probability, Markovian Chains, Queues, and Simulation: The Mathematical Basis of Performance Modeling*. Princeton University Press, 2009.

Surendrakumar, K. Prashant, N. Mayuresh, P. (2013) "Application of Markovian probabilistic process to develop a decision support system for pavement maintenance management," *International Journal of Scienti+c and Technology Research*, vol. 2, no. 8, pp. 225–303.

Tsuda, Y., et al., (2006). Estimating Markovian transition probabilities for bridge deterioration forecasting. *Journal of Structural Engineering and Earthquake Engineering*, 23 (2), 241–256.

Van Zyl, G. Henderson, M. and Uys, R. (2007) *Applicability of Existing Unpaved-Road Deterioration Models Questioned*. Transportation Research Record. TRB Low-Volume Roads 2007 (Vol. 1 and Vol. 2), Washington DC.

Wilde, WJ., Thompson, L., Wood, TJ. (2014) *Cost-Effective Pavement Preservation Solutions for the Real World*. Minnesota Department of Transportation. MN/RC 2014-33. September 2014.

Wyoming Technology Transfer Center – WTTC (2014). *Unpaved Road Quality Rating Guide*. September 2014.

Yang, J. (2004) *Road Crack Condition Performance Modeling Using Recurrent Markovian Chains and Artificial Neural Networks*. (Master's thesis) University of south Florida, 2004.

## **CHAPTER 5: Optimization Models to Manage Unpaved and Paved Roads**

### **ABSTRACT**

The state of Minas Gerais, Brazil has approximately 272,063 km of the road network, and approximately 90% of this total are unpaved roads. The paved roads deteriorate from excellent to failed conditions usually between 10 and 20 years, and the unpaved roads deteriorates sometimes in less than a year. This deterioration rate needs to be considered when developing a new methodology for managing them efficiently, because when the budget is limited, it is important to identify the best “mix of road” preservation strategies to optimize the lifecycle cost of the road network. This study intends to develop a management system using optimization techniques for managing paved and unpaved roads. Probabilistic deterioration models were created using Markovian process resulting in accurate curves. This optimization system will facilitate a statewide implementation of paved or unpaved roads management system, and the methodology can be easily adopted by other areas interested in the management of all types of roads.

Keywords: unpaved roads, paved roads, tropical roads, roads management system, maintenance, optimization.

### **1. INTRODUCTION**

Despite having such a big network of roads, the quality of the Brazilian roads is still not up to the mark. The existing road network has aged, leading to appearance of different kind of distresses viz. cracking, raveling and potholing on the surface. As a tropical country it deteriorates besides the traffic, due the tropical weather and high humidity. In the state of Minas Gerais, which is the aim of this study, there are a total of 272,063 km of roadway owned and maintained by federal, state, and local entities (CNT, 2018).

Currently, there is no methodology or road maintenance database for the entire road network, however the Brazilian government is trying to develop and implement a management system to restore the roads with a limited budget (Martins, 2015). In the last years, the maintenance management systems have improved significantly due to

the advances in technologies. Many researchers are working on the development of pavement maintenance management system (PMMS) and the effect of road surface deformations. A PMMS is a strategic and systematic process to maintain and upgrade the road network, but when funding is limited, the MS identifies the best “mix of roads” preservation projects that provide the most benefit to society in terms of the overall lifecycle cost of the road network (Leandro, et al., 2015).

The growth of road network, both in terms of capacity and quality has not kept pace with the significant growth in demand for transport in Brazil (Rodovias, 2019). It explains why is necessary to establish a pavement management system (PMS) for local roads, which in Minas Gerais, the roads are mainly supervised by the state or city superintends. Wolters et al. (2011) studied the implementation of a pavement management program in a local agency. The distresses, under the combined action of traffic and environmental factors, have been continuously growing to the extent of severity because of the inability to properly upkeep and maintain the road network within budgetary constraints.

The aim of this research was to develop a methodology to identify the best “mix of road” preservation projects within a certain budget, which contain the current and historical information on road condition, structure, and traffic (Mishra et al., 2015). The methodology will ensure that the overall condition of unpaved roads is maximized, at minimal cost. The cost-factor included in this methodology is determined by the life cycle cost of each treatment type. The integral parts of this optimizing resources are the deterioration model, maintenance decision process, maintenance and rehabilitation cost, and cost-factor associated with the maintenance type (Ragnoli, Blasiis and Benedetto, 2018).

As there in Minas Gerais approximately 90% of unpaved roads with no management system, the focus and first objective of this research was to develop optimization techniques for managing these roads. The second objective was to develop a pavement management system for paved roads following the same structure with simple datasets. This methodology was implemented, to unpaved roads, in Zona da Mata County, located in Minas Gerais state, Brazil, as a case study. To paved roads, was implemented using the entire state of Minas Gerais. This study utilized 18 unpaved

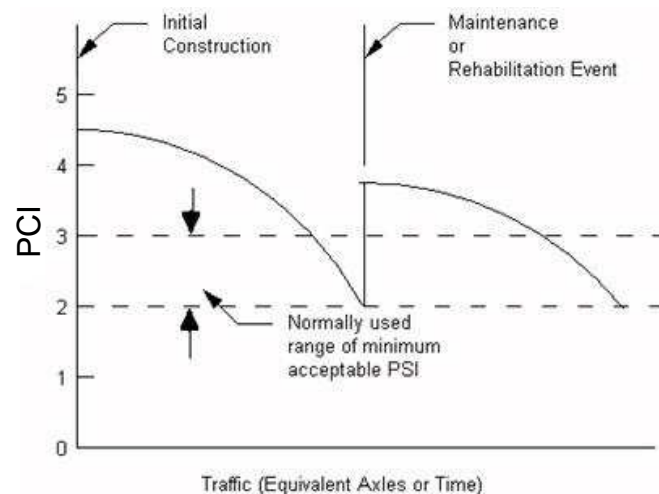
road segments and 88 paved roads, representing the variations of segment length, road width, and traffic counts around the state of Minas Gerais.

## 2. LITERATURE REVIEW

### 2.1. Necessity of Road Maintenance Management

The road deterioration is closely linked to the existent traffic and to the maintenance carried out throughout its useful life, besides the factors previously mentioned. When building a road, paved or not, indexes and variables are used that dimension the road surface to a useful life of  $x$  years (Saha and Ksaibati, 2017). The lack maintenance has caused irreparable damage to economic growth rate, since the poorly maintained roads cause delay, road accidents and higher vehicle operating costs. Any neglect of maintenance activity is self-defeating as \$ 1.00 (dollar) spent on maintenance saves \$ 6.00 in the future cost (WSDOT, 2016). Also, this type of neglect of maintenance accelerates the process of deterioration leading to the higher cost of rehabilitation and reconstruction.

The poor maintenance timings are shown in Figure 1. If proper and timely maintenance measures are not taken, the pavement condition deteriorates very rapidly from “good” (4) to “poor” (2) during a very short period of pavement life, causing the requirement of 4-5 times more fund for rehabilitation of the pavement (Hveem and Carmany, 1948). If maintenance and rehabilitation is performed during the early stages as shows in Figure 2 (WSDOT, 2016), before a sharp decline in pavement condition, over 75% of the maintenance costs can be avoided (Shahin, 1994).



**Figure 1: Concept of maintenance performance (Hveem and Carmany, 1948).**

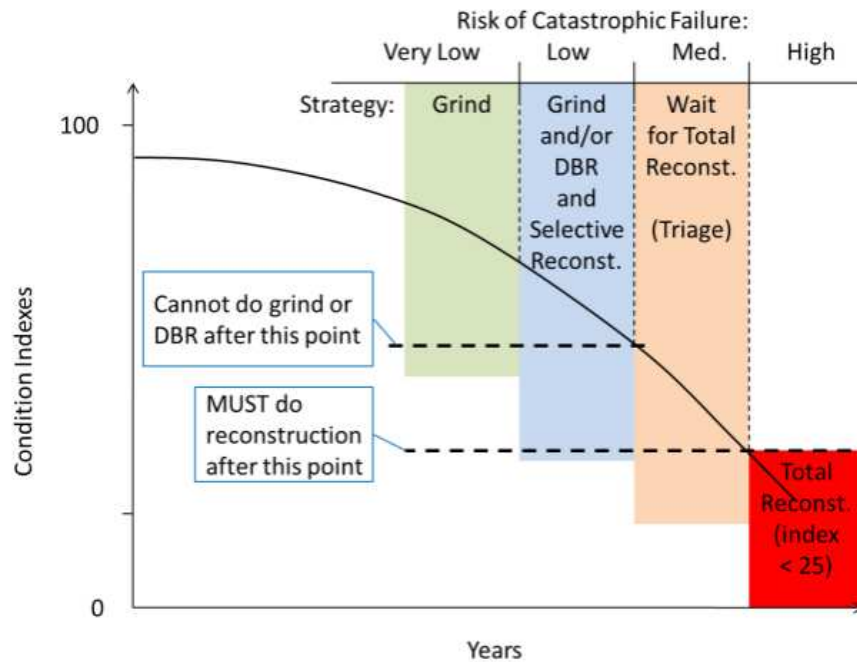


Figure 2: Maintenance possibilities (WSDOT, 2016).

## 2.2. Paved roads assessment method and types of maintenance

Pavements are only designed to last for a certain period. During each of these periods or "life cycles", the pavement begins from an optimal condition, declining until it reaches a failed condition. This decreased level in a pavement condition or service-life is known as pavement deterioration (Shahin, 1994).

Estimating the pavement deterioration is important to help those responsible for maintenance with their decision-making process, and aid them in understanding the pavement performance offered to drivers. Once the deterioration condition is known, professionals are able to find techniques that effectively work to control the mechanisms competing to decrease the pavement service-life. The deterioration should be estimated by evaluating the two main causes: the functional deterioration, and structural deterioration (Saha, Ksaibati, and Atadero, 2017). There are specific assessment methods to determine each of these components. Figure 3, a paved road from Minas Gerais awaits maintenance that will extend its service life.



**Figure 3: Paved road situated at Alfenas, Minas Gerais (CNT, 2018).**

The assessment estimates the condition of the pavement according to the user's perception of detecting surfaces irregularities. It includes surveying aspects which will directly affect the road users in the form of distresses measurement. It depends on the longitudinal roughness, which is generated by the accumulation of permanent deformations under repeated loads in all layers of the pavement (Balbo, 2007). Also, distresses from layers deterioration are measured due to their impact on service level. In other words, an increase in the amount of distresses reduces the service level (Abdalla, 2008).

Based on the standards from AASHTO, the Brazilian methodology for road assessment adopts the following criteria (AASHTO, 2001):

- The data was collected and recorded by the evaluator along the roads in a vehicle traveling at a maximum speed of 50 km/h.
- Each road is evaluated according to the visual observation of characteristics in segments with an extension equivalent to a sample unit.
- The sample unit is a road section with a length between 1 and 10 km, unless it is interrupted by an intersection or the end of the roads itself.
- The evaluator is trained to carry out the inspection in a continuous way and to identify when a specific distress on the pavement will be considered predominant in a sample unit.

- Data collection occurs only when there is natural light and good visibility conditions for a maximum of eight hours per day. However, in adverse situations as rain or haze, the analysis is suspended until the ideal research conditions are restored.
- If a critical condition is observed along the road segment, the evaluator it, takes a photo, and records the location (using GPS coordinates).

Keeping these roads in working condition requires maintenance, and depending on the health of the road, varying degrees of upkeep are required. There are six types of common road maintenance that can be used for each job (Brower, 2018):

- Asphalt Overlays: restore roads to a smooth condition. This resurfacing uses the deteriorating asphalt as a base for which the new layer is added on top of, instead of tearing up the worsening one.
- Patching: is the process of filling potholes or excavated areas in the asphalt pavement. Quick repair of potholes or other pavement disintegration helps control further deterioration and expensive repair of the pavement. Without timely patching, water can enter the sub-grade and cause larger and more serious pavement failures.
- Reshaping: this is necessary when a road surface it too damaged to be smoothed. Using a grader blade and scarifying if necessary, it is possible to rework the unpaved sub-base to eliminate large potholes and rebuild a flattened crown.
- Slab Replacement: this refers to replacing sections of paved roads. It is a good option for when slabs are chipped, cracked, or uneven, and mitigates the need to replace the entire road when just a small section is damaged.
- Smoothing: this is when you lightly rework the unpaved of a road without digging in too far to the sub-base. Typically, a motor grader is used in this operation with an attached blade. Smoothing is done when the road has minor damage or is just worn down a bit from use.
- Reconstruction: when roads have deteriorated to a point that it is no longer cost-effective to maintain, the entire street or road needs to be rebuilt. Typically, this work is done in phases to limit traffic restrictions. As part of reconstruction, the street may be realigned to improve safety or operations, grading may be changed to improve storm water flow, underground utilities may be added, upgraded or

relocated, traffic signals and street lights may be relocated, and street trees and pedestrian ramps may be added.

### **2.3. Unpaved roads assessment method and types of maintenance**

Normally, roadway functional assessment encompasses the processes of identification and characterization of aspects of its surface linked to the user's comfort and safety, vehicle performance and transportation cost. The assessment includes subjective or objective evaluations (Walker and Unpaved, 1989).

Several agencies and local researchers have suggested other types of subjective rating methods to survey unpaved road condition as PASER, Unpaved-PASER, The Ride Quality Rating Guide (RQRG) or The Unpaved roads Rating System (GRRS) (Huntington and Ksaibati 2015). The GRRS, which is the guide this research is using as a model to follow, provides standard evaluations of seven distresses including: potholes, rutting, washboards, loose aggregate, dust, crown, and roadside drainage (WYDOT, 2014). Figure 4 shows an unpaved road in a bad condition at Zona da Mata County, Minas Gerais, Brazil.



**Figure 4: Unpaved road located at Viçosa, Zona da Mata County.**

**Source: The author**

In the objective assessment, the distresses are quantified with the technical details of its state of deterioration (Almuhanna, Ewadh, and Alasadi, 2018). When the distresses are known, regular maintenance can be applied correctly, and road maintenance is one of the most important engineering services, since it maintains the integrity of the

physical characteristics of the cross-section and contributes to the drainage system (Rabello Quadros and Nassi, 2015).

Unpaved roads are constructed when volume of commercial traffic (gross weight exceeding 3 ton) is less than 400 vehicles per day (Rohith, Srikanth and Chowdary, 2016). In terms of utility, five main factors affecting the quality of an unpaved road can be listed: traffic load, subgrade quality, construction practices, water, and maintenance program (FHWA, 2007). To maintain the roads properly, maintenance practices and the functional condition must be known. According to Kabindra, Pramen, and Thomas (2014), it is recommended to define the types of maintenance of unpaved roads as follows:

- Routine Maintenance: emergency repairs for blocked and ruined unpaved roads as road patrolling, regularization or patching; drainage structures: external cleaning and repair of ditches and drains, external cleaning of bridges, patches of eroded areas, construction of erosion control and repairs to drainage structures.
- Major Maintenance: maintenance practices used in the case of many distresses in situations which the use of rehabilitation or reconstruction services is not justified.
- Rehabilitation: thin unpaved overlay.
- Reconstruction: complete reconstruction.

#### **2.4. Multiobjectives optimization methodology for road management system**

Practices adopted by highway agencies with regards to pavement management have mostly consisted of employing life cycle costs analysis (LCCA) systems to evaluate the overall long-term economic efficiency of competing pavement design and maintenance and rehabilitation (M&R) alternatives activities. This way of supporting the decision-making process, as it relates to pavement management, suggests the need for pavement management decision-support systems, which, by integrating multi-disciplinary and complementary pavement life cycle modelling approaches, enable the decision makers to properly account for, consider and assess the lifetime impacts of their decisions and practices regarding targets (Santos, Ferreira, and Flintsch, 2017). This only can be achieved by employing techniques and tools providing clarity about management system. Below, there are several reasons to explain why the management system is a multiobjectives optimization:

- Engineers or decision makers want to maximize the network road condition within a limited budget (Saha and Ksaibati, 2017; Kamruzzaman, 2010).
- Preventive and minor rehabilitation treatments are more cost-effective than reconstruction (Kamruzzaman, 2010; WYDOT, 2014).
- Budget should be more than a certain amount to achieve maximum benefit to society (Saha and Ksaibati, 2017).
- The best “mix of roads” segments for rehabilitation should include the segments with more traffic volume (Saha and Ksaibati, 2017; Kamruzzaman, 2010).

However, sometimes this system can be considered as a two-levels optimization, since it links two levels of decision makers (Ruuska, Miettinen and Wiecek, 2012). For example, the government is responsible for allocating the budget to every city governor make sure the road condition is going to be maximized. At the same time, the city governor might have different objective functions such as to select the roads with higher traffic volume. So, there are two levels of objectives functions: one is from the government and the other one is determined by the city governor or company’s stakeholders. Both levels will seek to achieve their objectives as much as possible within the allocated budget.

## **2.5. Optimization methodology for URMS and PMS**

The term Management System (MS) can be understood as the efficient and integrated coordination of the various activities involved in the design, construction and maintenance of roads that are part of a road infrastructure (road, airport or urban), in order to allow them to provide acceptable conditions to the user at minimal cost. Essentially, the MS is a set of tools or methods to assist decision makers to find optimize strategies to construct, evaluate and maintain roads in an acceptable functional condition over a period with a selected budget (Wolters, et al., 2011).

This optimization part can be referred to as the mathematical programming related to minimizing or maximizing some quantity. The desired results must lie in a subset of the domain of this function (Mendonça, 2009). The characteristics of the function and subset that contain the solution to the problem define several different types of optimization problems, each requiring a different method to be solved (Zhang and Gao, 2015).

When considering infrastructure, where a network with a significant extension and subject to freight traffic is common, the MS tends to operate at both network and project level in an associated manner. At the network level there is adequate planning of the budget, the resource allocation, and the project selection. On the other hand, at the project level it is possible to find the most cost-effective repair maintenance for each road section (Santos, Ferreira, and Flintsch, 2017).

## **2.6 Unpaved Roads Management System (URMS)**

According to Saha, Ksaibati, and Atadero (2017), an URMS is a strategic and systematic process to maintain and upgrade the road network, but when the funding is limited, the URMS identifies the best “mix of road” preservation projects that provides the most benefit to society in terms of overall lifecycle cost of the road network. A URMS is composed of seven steps including the “predict condition” which is the most complex one. To predict the conditions, it is necessary to develop deterioration models using the road condition over the years. The established models allow the prediction of the main responses on the road surface, and it can be empirical, mechanistic, or mechanistic-empirical type, which are models calibrated with data observed in the field (Shenghua and Balasingam, 2019).

The URMS does not have a standardized procedure to determine the surface condition rating nor a deterministic approach to model the surface deterioration. To find the roads condition, it is necessary to evaluate the roads and determine the pavement condition index (PCI). However, the normal PCI does not apply to unpaved roads because the PCI is a detailed examination of paved roads distresses such cracking and potholes (Shohel, 2015). To determine the unpaved roads condition in this work, a guide created by the Wyoming Technology Transfer Center (Wyoming T<sup>2</sup>/LTAP) was used. It was designed to be used in conjunction with the Ride Quality Rating Guide also developed by the Wyoming T<sup>2</sup>/LTAP (WTTTC, 2014).

With the roads condition, a URMS uses probabilistic or deterministic models to predict the future needs. In Brazil they are using mostly family and expert opinion curves as a deterministic model, based on the field staff's experience. In the deterministic technique, the uncertainties of pavement deterioration related to traffic and weather are not considered. However, probabilistic models consider these uncertainties and result in more accurate curves (Saha, Ksaibati and Atadero, 2017).

## **2.7 Pavement Management System (PMS)**

The establishment of a PMS becomes even more important when the road conditions are bad and with a limited availability of resources. The main objective is to use historical data to make a careful decision to run a pavement maintenance program with an organized methodology. Thus, a good PMS seeks to define maintenance strategies looking to minimize the cost and to obtain an ample return on the applied resources increasing the service life (Nishiyama and Domingues, 1995)

A quality PMS should seek to increase the efficiency of decision-making while informing of the consequences of decisions made at various levels. Additionally, PMS must ensure consistency between the decisions made, define the maintenance strategy that minimizes the cost of road transportation, obtain the best return for the resources applied by means of a safe, comfortable and economical transportation, and optimize the use of the attributes destined to the maintenance of the road infrastructure. To achieve all of these objectives, a PMS must have the ability to constantly update itself considering alternative strategies, being able to determine the optimal option, and to use feedback to improve overall decision-making (Domingues, 1995)

Prior to starting the implementation process, it is recommended that the government consider forming a steering committee to work as a group in establishing a process to meet the needs. The development of a systematic and repeatable pavement management process is a key component in the effective planning and management of a PMS. Seven steps serve as a guide for customizing a pavement management process that fits the needs of each local agency. The steps define the roadway network and collect inventory data, collect condition data, predict condition, select treatments, report results, select pavement management tool, and keep the process current (Pulugurta, Shao, and Chou, 2009).

To predict the condition, it is necessary to understand the pavement performance and the differences when it is analyzed at the network or project level. At the network level, the entire network is analyzed to identify the appropriate type of maintenance and the road sections to be repaired. At the project level, only the selected sections are analyzed to determine the right treatment types (material and thickness) to be applied (Maaty, 2017).

These performance models derived from all the pavement characteristics (functional condition, width, length, rut) allow the prediction of the main pavement distresses caused by the traffic loads and the climatic conditions, such as deflections, tensions, deformations, thermal tensions, moisture content, and temperature. With this performance (or deterioration) models, it is possible to implement a reliable and cost-effective PMS that provides a reasonable and practical number of maintenance and rehabilitation plans consistent with the number of deployed condition states according to the limited budget.

### **3. METHODOLOGY**

The PASER manual describes that the surface of unpaved roads is rated on a five points scale, where 5 represents an excellent condition from the roads and 1 is for a failed condition from the unpaved roads. In Minas Gerais, these five points scales were transformed into a nine points scale as the GRRS, which is the guide this research is following, realized (Huntington and Ksaibati, 2015). This decision to go from a five to nine points scale was ended to try to decrease the error when human raters need to choose a condition.

These nine points scales are going to be used in this research as Overall Road Condition Index, called ORCI. According to this rating method, the primary variables of this model are the road condition distresses roadside drainage, crown, rutting, potholes, loose aggregate, dust, and corrugation. The ride quality is the result, and the extreme values 9 and 1 represent the best and worst conditions, respectively (Mendonça, 2009). Depending on these indices, a decision table with figures and standards is used to identify the appropriate treatment type.

On the other hand, the surface of paved roads was rated according to AASHTO methodology, ranking the condition from 0 to 100, where 100 represents a brand-new constructed road and 0 is for a failed road. According to this rating method, the primary variables of this model are the distresses rutting, fatigue cracking, longitudinal cracking, transverse cracking, patches, potholes, raveling, bleeding, and roughness (AASHTO, 2001)

In this section, the deterioration model used in this methodology is discussed first. Then, the algorithm for identifying the best mix of road preservation projects is

explained. It is important to mention that this model does not consider political factors but purely life cycle cost of unpaved and paved roads.

### 3.1. Unpaved and Paved Road Deterioration Model

While the typical life of paved roads without maintenance is around 10 and 20 years, unpaved roads typical service life is in the range of several months to 1 year. This faster deterioration of unpaved roads is affected by many factors: permeability, materials, construction, traffic, environment, and drainage (Walker and Unpaved, 1989). Among them, the most important factor is the permeability and weather (Maaty, 2017). Because of these, tropical roads deteriorate faster, and unpaved road surface is more permeable than paved surface which causes significant damage due to moisture. Huntington and Ksaibati (2015) developed the deterioration model for roads in Wyoming, USA, which have been used as a guide to create the Brazilian deterioration model. Using this model as a guide, an average deterioration was estimated based on overall road conditions. The deterioration is represented in points per day on a 10-point scale. From this model, the time to go from excellent condition (10) to failed condition (1) can be projected. Equation 1 and 2 shows the deterioration model to unpaved and paved roads respectively where URCI indicates unpaved roads condition index, PCI indicates pavement condition index, and Age is represented in years.

1

$$\text{URCI} = 0.035 * (\text{Road age})^2 - 1.082 * (\text{Road age}) + 9.107$$

2

$$\text{PCI} = 0.005 * (\text{Pavement age})^2 - 0,268 * (\text{Pavement age}) + 4,463$$

### 3.2. Treatment Types

The five possible treatment options for county unpaved roads are summarized in Table 1 along with the estimated cost, while Table 2 shows the six possible treatment options for paved roads with their costs. The cost of these treatment types was obtained from county engineers and road superintends from Minas Gerais state (CNT, 2018). If the costs of maintaining unpaved roads are compared with the county paved roads, it was found that full rehabilitation costs of county paved roads are approximately 10 times higher than unpaved roads for a km roadway segment. On the other hand, the frequency of applying maintenance treatments for unpaved roads is approximately 4 times higher (every 3 months to unpaved and every 12 months to paved roads).

**Table 1: The treatment types and costs for unpaved roads.****Source: The Author**

<b>Treatment Type</b>	<b>Details and Applications</b>	<b>Est. Cost (R\$/km)</b>
GM General Maintenance	General Maintenance Procedure (2x per year)	R\$ 600,00
1-R Chemical and Mechanical Stabilization	Cement or lime	R\$ 20.000,00
2-R Preventive Rehabilitation	According to DNIT	R\$ 31.800,00
3-R Preventive Rehabilitation with Shoulder Needs	According to DNIT	R\$ 71.387,00
4-R Full Paving the roads	Complete pavement construction	R\$ 400.000,00

**Table 2: Treatment types and costs for paved roads.****Source: The Author**

<b>Treatment Types</b>	<b>Details and Application</b>	<b>Est. Cost (R\$/km)</b>
GM General Maintenance	General Maintenance Procedure Asphalt Patching Pothole Repair Crack Sealing Road Striping	R\$ 1.875,00
1-R Preventive Rehabilitation	Chip Seal Micro-surface Thin Overlay (<2")	R\$ 51.800,00
2-R Minor Rehabilitation	Surface Preparation (mil scale, full-depth reclamation or combination thereof) Seal Coat and Thick overlay (> 2")	R\$ 100.000,00
<b>Continued</b>		

Treatment Types	Details and Application	Est. Cost (R\$/km)
3-R Preventive Rehabilitation	1-R plus shoulder or widening requirements Applicable on roads in good conditions with shoulder needs	R\$ 150.000,00
4-R Major Rehabilitation	2-R plus shoulder or widening requirements Applicable on narrow roads with shoulder or widening needs	R\$ 200.000,00
5- R Full Reconstruction	Complete Reconstruction	R\$ 300.000,00

The decision information used to identify the appropriate treatment types for unpaved and paved roads in Minas Gerais can be seen in Figures 5 and 6 respectively. Appropriate treatment is selected based specific distresses for unpaved or paved roads using the service level and distress condition. Basically, as the service level increases the maintenance priority also increases and, comparatively an expensive treatment type is selected to upgrade the condition.

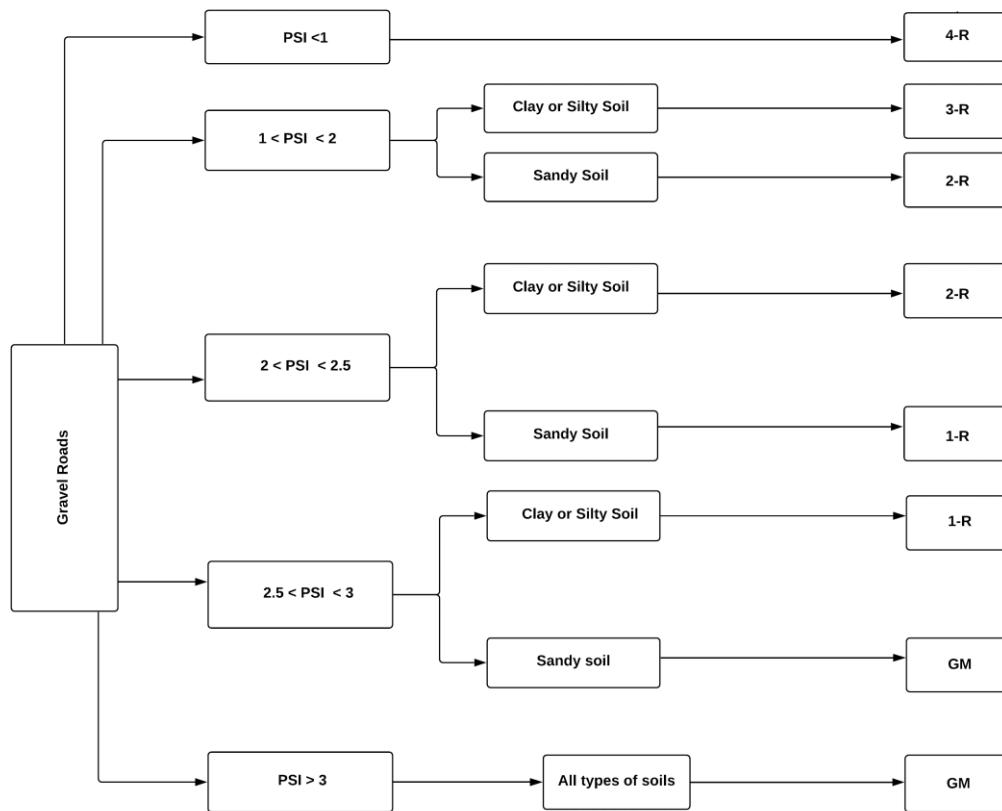


Figure 5: Decision tree for unpaved roads.

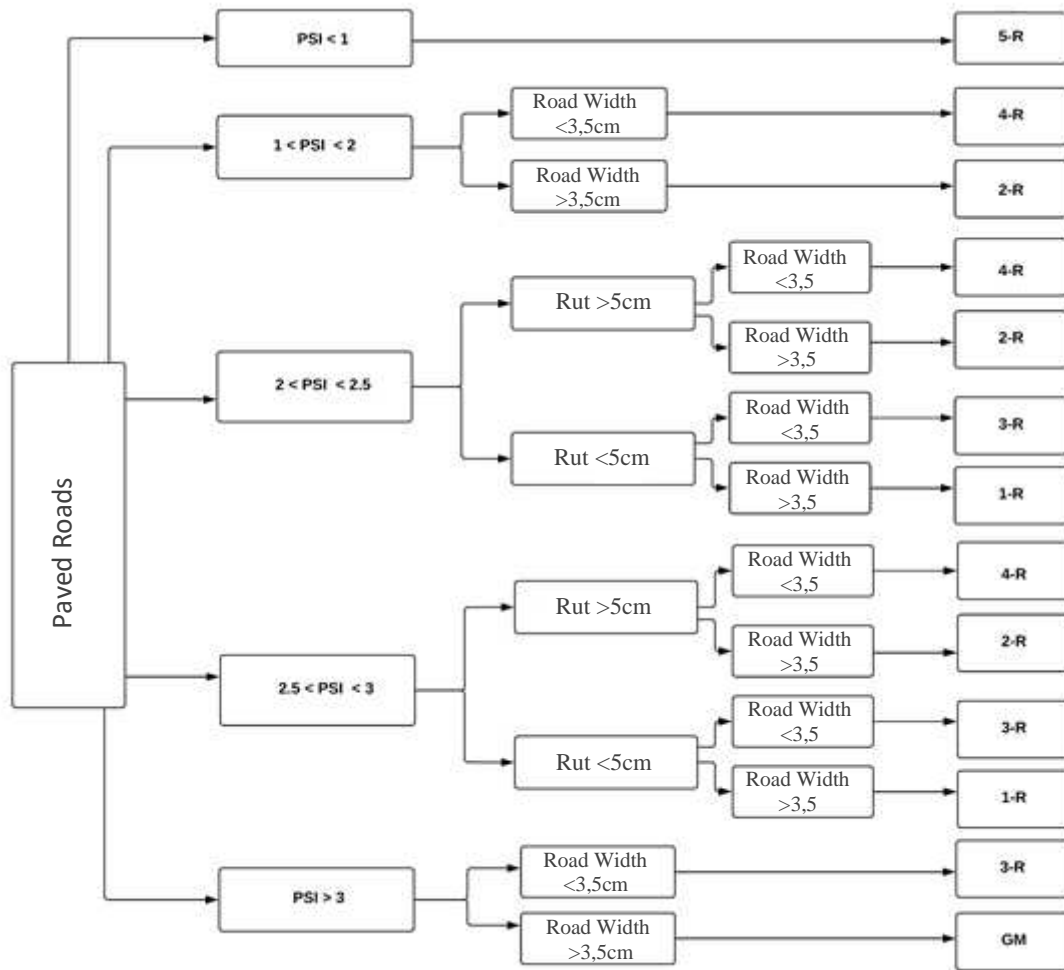


Figure 6: Decision tree for paved roads.

Source: The Author

### 3.3. Unpaved and Paved Road Management System

The proposed Unpaved Roads Management System (URMS) and Pavement Management System (PMS) consider not only the cost factor but also local conditions such as ORCI and average daily traffic (ADT). The objective of the developed model is to maximize a function that considers 3 independent parameters: road condition, ADT, and cost-factor as showed in Equations 3 and 4:

3

$$\text{Maximize } \sum_{i=1}^n \frac{ORCI * ADT_i}{\text{Cost-Factor}_i(\text{treatment type})} * x_i,$$

$$\text{Subject to } \sum_{i=1}^n \text{Treatment Cost}_i * x_i \leq \text{budget},$$

$$x_i \in \{0, 1\},$$

where  $ADTi$  expresses the average daily traffic for road  $i$ ,  $\text{Cost-Factor}_i$  is the function of treatment type,  $x_i$  is an integer equal to one if the project is selected and 0 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 constraint.

#### 4. CASE STUDY

##### 4.1. Data Collection

Four types of data were used to develop this research. There are roadways segmentation, traffic counts, road width, and road condition data. All the unpaved roads dataset was collected by different students from Universidade Federal de Viçosa over the years. The paved roads dataset was collected from CNT (2018) survey, which is managed by the Brazilian federal government. These datasets were then combined into the comprehensive database shown in Table 3 and 4. The following subsections will discuss the datasets briefly.

**Table 3: Unpaved roads dataset from Viçosa city, Brazil.**

**Source: The Author**

Seg	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
PSI	1	1,8	2,8 1	2,5 1	1,5	0,8 8	1,6 3	0,8 9	1,8	1,0 3	1,1 9	3,0 6	1,2 2	1,6 3	0,9	0,9 3	1,2 2	3,2 4
Length	1,9 4	0,9 1	0,6 2	0,6 5	1,0 2	0,1 3	0,2 7	1,5 2	0,5 7	1,1 8	1	2,6 5	0,2 6	0,5 6	0,1 3	0,9	0,6	1,3
Type of Soil	3	2	1	3	2	1	2	2	3	2	1	2	2	1	1	3	3	2

\*Where 1: clay, 2: silt and 3: sand.

Table 4: Paved Roads dataset from the state of Minas Gerais, Brazil.

Source: The Author

<b>Seg</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>6</b>	<b>7</b>	<b>8</b>	<b>9</b>	<b>10</b>	<b>11</b>	<b>12</b>	<b>13</b>	<b>14</b>	<b>15</b>	<b>16</b>	<b>17</b>	<b>18</b>
<b>PSI</b>	1	2	3	3	2	3	2	1	2	3	2	2	2	2	2	2	1	2
<b>Length</b>	35	9	6,5	45	10	32	17	23	7	10 3	29 1	3	60	26	75	33	11	97
<b>Width</b>	7	7	7	7	7	3,8	6,5	3	7,2	7,2	7,2	7,2	7,2	7,2	7,2	3,7	6,6	4
<b>Rut</b>	0,4	0,4	0,4	0,4	0,5	0,5 1	0,5 3	0,4 5	0,7 7	0,4 3	0,5 1	0,5 1	0,5 1	0,5 1	0,5	0,4 8	0,5	0,5 4
<b>Seg</b>	<b>19</b>	<b>20</b>	<b>21</b>	<b>22</b>	<b>23</b>	<b>24</b>	<b>25</b>	<b>26</b>	<b>27</b>	<b>28</b>	<b>29</b>	<b>30</b>	<b>31</b>	<b>32</b>	<b>33</b>	<b>34</b>	<b>35</b>	<b>36</b>
<b>PSI</b>	3	3	2	2	3	1	2	3	2	2	2	2	1	2	2	2	1	2
<b>Length</b>	50	6,5	91	6,5	5	43	10 5	19	21	28	15	14	11	29	10	17 7	24 7	26 8
<b>Width</b>	6,5	8	3,7	3,7	4,2	4,2	3,6	3,6	3,6	8	4,5	4,1	6,6	6,6	6,6	4,2	4,1	4,1
<b>Rut</b>	0,5 1	0,4 8	0,7 7	0,7 7	0,7 7	0,4 8	0,5	0,4 5	0,5 1	0,5 1	0,4 3	0,5	0,5 4	0,5 4	0,5 4	0,4 5	0,4 5	0,7 7
<b>Seg</b>	<b>37</b>	<b>38</b>	<b>39</b>	<b>40</b>	<b>41</b>	<b>42</b>	<b>43</b>	<b>44</b>	<b>45</b>	<b>46</b>	<b>47</b>	<b>48</b>	<b>49</b>	<b>50</b>	<b>51</b>	<b>52</b>	<b>53</b>	<b>54</b>
<b>PSI</b>	2	3	2	1	2	2	1	3	3	2	2	3	4	4	4	3	2	4
<b>Length</b>	91	10 9	17	49	16 0	49	6	12 4	59	69	17	23 9	83 1	20 9	82 3	34 1	41	67 0
<b>Width</b>	3,8	3,8	8	8	8	8	8	3,8	4,4	3,4	3,3	3,8	3,8	5,5	5,5	5	5	3,7
<b>Rut</b>	0,4 5	0,5	0,7 6	0,7 7	0,2 5	0,4 3	0,4	0,4 8	0,2 5	0,7 6	0,7 7	0,5 6	0,5 7	0,5 3	0,5 4	0,5 3	0,5	0,4
<b>Seg</b>	<b>55</b>	<b>56</b>	<b>57</b>	<b>58</b>	<b>59</b>	<b>60</b>	<b>61</b>	<b>62</b>	<b>63</b>	<b>64</b>	<b>65</b>	<b>66</b>	<b>67</b>	<b>68</b>	<b>69</b>	<b>70</b>	<b>71</b>	<b>72</b>
<b>PSI</b>	4	4	4	3	3	3	2	3	2	3	3	2	4	4	3	2	4	3
<b>Length</b>	33 8	24 6	11	54 7	31 1	89 0	41 7	45 7	77	26 8	73	20 2	15 4	87 5	32 4	13 7	94 6	14 0
<b>Width</b>	5,2	5,2	5,2	5,2	5	5	5	5	5	5	5	5	5	5	5	5	5	5
<b>Rut</b>	0,5 5	0,5 1	0,4	0,4	0,5 7	0,5 8	0,5 7	0,8 1	0,5 4	0,5 8	0,8 6	0,8 6	0,7 9	0,5 8	0,8 4	0,9 9	0,7 6	0,8 4
<b>Seg</b>	<b>73</b>	<b>74</b>	<b>75</b>	<b>76</b>	<b>77</b>	<b>78</b>	<b>79</b>	<b>80</b>	<b>81</b>	<b>82</b>	<b>83</b>	<b>84</b>	<b>85</b>	<b>86</b>	<b>87</b>	<b>88</b>		
<b>PSI</b>	4	2	3	4	3	3	3	2	4	2	1	3	4	1	3	3		
<b>Length</b>	48	17 9	30	27	78	21 2	79	4	25	15 1	14 2	25 6	19 8	13 5	86	15		
<b>Width</b>	3,7	3,4	4,7	4	4	4	4	4	4	4	4	4	4	4	4	4		
<b>Rut</b>	0,5 5	0,4 9	0,4 5	0,2 5	0,7 7	0,7 7	0,2 5	0,2 5	0,2 5	0,5	0,7 6	0,4 8	0,4 8	0,5 8	0,5 5	0,5 8		

## **4.2. Segmentation**

Roadway segmentation was performed by the author. The segments begin and end where there are new construction and intersect with other roads or other changes in the road. A total of 18 unpaved different roads and 88 paved segments were established. Each segment was mapped with ArcGIS. The traffic counts were made, and all the unpaved segments had less than 400 vehicles per day, and approximately 20% of the paved segments had more than 400 vehicles per day. The road widths of these segments vary between around 3 and 7 meters.

## **4.3. Road Condition Data**

The unpaved road conditions are characterized by seven parameters: cross section/crown, roadside drainage, rutting, potholes, loose aggregate, dust, corrugation. The author performed the data collection effort on the 18 selected segments. The parameters were ranked on a scale of 1 to 9 where 1 represents the worst condition and 9 is for the best condition.

The paved roads that were evaluated include federal highways, relevant county roads, and important local roads. These characteristics were analyzed according to condition, distresses, and safety levels. The evaluation result was published in a report, using the AASHTO guide to road classification as Excellent, Good, Fair, Poor, and Failed (AASHTO, 2001).

## **5. DATA ANALYSIS**

A preliminary analysis was conducted on the datasets used in the research to summarize the road condition with budget needs. There are 18 unpaved different roads in the study area, and 88 paved roads segments counting 15,236 km. Four different scenarios were summarized in Figure 7 for unpaved roads: average road conditions at existing conditions, conditions after 4 cycles of 3 months without any maintenance, and conditions after applying treatments required with no limited budget, and conditions after applying treatments required to maintain the condition. The reason of considering 3-month period is that the unpaved roads decrease their level without any maintenance approximately every 3 months based on existing condition (Aleadelat, 2018).

Segment	CURRENT CONDITION				DO NOTHING		NO BUDGET CONSTRAINTS		LIMITED BUDGET	
	PSI	Length	Type of Soil	PSI*L	PSI	PSI*L	PSI	PSI*L	PSI	PSI*L
1	1	1,94	3	1,940	0,919	1,783	4,100	7,954	0,919	1,783
2	1,8	0,91	2	1,638	1,718	1,564	4,000	3,640	1,718	1,564
3	2,81	0,62	1	1,742	2,728	1,692	3,900	2,418	3,900	2,418
4	2,51	0,65	3	1,632	2,428	1,578	2,510	1,632	2,510	1,632
5	1,5	1,02	2	1,530	1,418	1,446	4,000	4,080	1,418	1,446
6	0,88	0,13	1	0,114	0,798	0,104	4,100	0,533	0,798	0,104
7	1,63	0,27	2	0,440	1,549	0,418	4,000	1,080	1,549	0,418
8	0,89	1,52	2	1,353	0,808	1,228	4,100	6,232	0,808	1,228
9	1,8	0,57	3	1,026	1,718	0,979	4,000	2,280	1,718	0,979
10	1,03	1,18	2	1,215	0,949	1,119	4,000	4,720	0,949	1,119
11	1,19	1	1	1,190	1,108	1,108	4,000	4,000	1,108	1,108
12	3,06	2,65	2	8,109	2,978	7,892	3,060	8,109	3,060	8,109
13	1,22	0,26	2	0,317	1,138	0,296	4,000	1,040	4,000	1,040
14	1,63	0,56	1	0,913	1,549	0,867	4,000	2,240	1,549	0,867
15	0,9	0,13	1	0,117	0,819	0,106	4,100	0,533	0,819	0,106
16	0,93	0,9	3	0,837	0,848	0,763	4,100	3,690	0,848	0,763
17	1,22	0,6	3	0,732	1,138	0,683	4,000	2,400	1,138	0,683
18	2,34	1,3	2	3,042	0,915	1,190	4,000	5,200	4,000	5,200
		Sum		Sum		Sum		Sum		Sum
		14,91		24,85		23,63		56,58		25,37
<b>Overall PSI</b>				<b>1,67</b>		<b>1,58</b>		<b>3,79</b>		<b>1,70</b>
<b>R\$</b>				-		-		R\$ 17.640.909,00		R\$ 46.900,62

Figure 7: Unpaved roads treatment decision process from Viçosa city, Brazil.

To paved roads, the Figure 8 presents also four scenarios: average road conditions at existing conditions, conditions after 12 months without any maintenance, and conditions after applying treatments required with no budget constraints, and conditions after applying treatments required to maintain the condition. The reason of considering 12-month period is that the paved roads decrease their level without any maintenance approximately every 12 months based on existing condition (Aleadelat, 2018).

Segment	CURRENT CONDITION					DO NOTHING		NO BUDGET CONSTRAINTS		LIMITED BUDGET	
	PSI	Length	Road Width	Rut	PSI*L	PSI	PSI*L	PSI	PSI*L	PSI	PSI*L
LMG-633	1	35	7	0,40	35	0,95	33,41	4,30	150,50	0,95	33,41
LMG-820	2	9	7	0,40	18	1,86	16,70	4,00	36,00	4,00	36,00
MG-050	3	6,5	7	0,40	19,5	2,80	18,19	3,90	25,35	2,80	18,19
MG-123	3	45	7	0,40	135	2,80	125,94	3,90	175,50	2,80	125,94
G-123/BR-262	2	10	7	0,50	20	1,86	18,56	4,00	40,00	4,00	40,00
MG-129	3	32	3,8	0,51	96	2,80	89,56	4,00	128,00	2,80	89,56
G-129/BR-120	2	17	6,5	0,53	34	1,86	31,54	4,00	68,00	1,86	31,54
MG-164	1	23	3	0,45	23	0,95	21,95	4,30	98,90	0,95	21,95
BR-460	3	79	4	0,25	237	2,80	221,10	3,90	308,10	2,80	221,10
BR-462	2	4	4	0,25	8	1,86	7,42	4,00	16,00	1,86	7,42
BR-464	4	25	4	0,25	100	3,75	93,87	4,00	100,00	4,00	100,00
BR-474	2	151	4	0,50	302	1,86	280,19	4,00	604,00	1,86	280,19
BR-482	1	142	4	0,76	142	0,95	135,53	4,30	610,60	0,95	135,53
BR-491	3	256	4	0,48	768	2,80	716,47	3,90	998,40	2,80	716,47
BR-494	4	198	4	0,48	792	3,75	743,47	4,00	792,00	4,00	792,00
BR-496	1	135	4	0,58	135	0,95	128,85	4,30	580,50	0,95	128,85
BR-497	3	86	4	0,55	258	2,80	240,69	4,00	344,00	2,80	240,69
BR-499	3	15	4	0,58	45	2,80	41,98	4,00	60,00	2,80	41,98
		Sum			Sum	Sum		Sum		Sum	
		14011,5			42949	40246,29		56155,60		41254,94	
<b>OVERALL PSI</b>					<b>3,07</b>	<b>2,87</b>		<b>4,01</b>		<b>2,94</b>	
<b>R\$</b>					-	-		R\$ 48.057.320,00		R\$ 19.883.100,00	

Figure 8: Paved roads (18 of 88 segments showed below) treatment decision process from the state of Minas Gerais, Brazil.

The overall road condition of each segment is defined as the minimum rating among the 7 distress parameters. The average condition of all segments is defined as the condition weighted by length of segments. Based on the traffic counts and distress conditions of those segments, a specific treatment type with associated cost for each segment was identified.

The optimization model developed in this study was based on the principles that preventive and minor rehabilitation treatments are more cost-effective than reconstruction, high traffic volume roadways should have higher priority when selecting treatments, and the only constraint in this model is the budget.

In the objective function, the budget was determined by the cost of a single project applying the most expensive treatment for the current maintenance scheme. From the unpaved roads dataset used in this research, it was found that to maintain the roads condition, it is necessary to spend R\$ 46.900,92 per year to maintain the 18 roads. It is important to note that, in this research, every 3 months the road condition needs to be reevaluated as the unpaved roads require next level of rehabilitation approximately every 3 months. In order to obtain yearly budget, the optimization model was performed every 3 months in a year and then the budget was accumulated for the entire year. From the paved roads dataset, was found that to maintain the roads condition, it is necessary to spend R\$ 19.883.100,00 per year for the entire state analyzed network of Minas Gerais. As the unpaved roads, after every cycle (12 months to paved roads) the road condition needs to be reevaluated.

To optimize the budget, different counties might be interested in optimizing different parameters. For example, engineers might want to maximize the network road conditions with unrestricted budget. In this research, the following two possible options for unpaved roads and two for paved roads were analyzed to demonstrate to counties the potential of the proposed model:

- Option 1: maximize network road condition.
- Option 2: minimize cost.

In any roadway network, segments are different in length, traffic volumes, and road conditions. When results are summarized for the model proposed, the variables were weighted based on segment lengths to represent the overall network condition. In this

model, the objective functions should be achieved within the allocated budget. Since the budget was determined by the cost of a single project based on the most expensive treatment for every 3 months for unpaved roads and every 12 months for paved roads, the allocated budget changes every 3 months/12 months. Using this methodology, the overall road conditions will improve while decreasing cost-factor and increasing traffic volume on the selected projects.

## **6. CONCLUSIONS**

In the state of Minas Gerais, there is a total of 15,236 km of roadway owned and maintained by federal, state, and local entities. The government utilizes its ranking to maintain their condition. However, a pavement management system (PMS), for managing county paved roads, and an unpaved roads management system (URMS) are being creating to optimize the process. This study developed an optimization methodology to develop a management system for unpaved and paved roads. The methodology developed identifies the best “mix of roads” preservation projects that uses limited available resources.

The methodology was applied as a case study on the unpaved roadway network consisting of 18 roadway segments in Viçosa, Zona da Mata County, Minas Gerais, and of 88 paved roads segments over the entire state of Minas Gerais, Brazil. This methodology included a multilevel optimization maximizing the overall road condition and minimizing life cycle cost. As unpaved roads require next level of maintenance every 3 months, the methodology was applied to identify the best mix of road preservation projects over a similar period of time. The budget of 3 months was determined by the cost of a single project applying the most expensive treatment. The same methodology was applied to paved roads, however, instead of 3 months of cycle, paved roads have 12 months. To determine the budget for the entire year for unpaved roads, the methodology was applied 4 times in a year and the total budget was accumulated over 12 months. Results show that the maintenance cost for a year is expected to be approximately R\$ 46.900,92 for unpaved roads network analyzed and R\$ 19.883.100,00 for the paved roads network analyzed, to maintain the roads conditions. It also can be noticed that when a major treatment is applied, only minor treatments are required for the next several years in both situations.

The developed methodology can be highlighted as follows:

- (i) The unpaved model is tailored specifically to Zona da Mata county, and the paved model is tailored to the entire state of Minas Gerais, Brazil.
- (ii) This methodology considers that preventive and minor rehabilitation treatments are more cost-effective than reconstruction.
- (iii) This methodology can be implemented in any county in the state of Minas Gerais and can be used by other states for developing a management system for unpaved roads. However, for other states, some minor changes in the methodology may be needed to reflect local conditions.
- (iv) The government can use the findings of a statewide optimization to allocate the appropriate resources to manage the roads in Minas Gerais.

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## **REFERENCES**

- AASHTO (2001). AASHTO Pavement Management Guide. Washington, DC: AASHTO.
- Abdalla, M. (2008). Effect of Subgrade Properties on Pavement Performance. Gulf Conference on Transportation. 23-24 January 2008 , Dubai, UAE.
- Aleadelat, W. (2018) Establishing a Methodology for Unpaved roads Management System, Ph.D. Dissertation. Department of Civil and Architectural Engineering, University of Wyoming.
- Almuhanna, R.R.A., Ewadh, H.A., Alasadi, S.J.M. (2018) Using PAVER 6.5.7 and GIS program for pavement maintenance management for selected roads in Kerbala city. Case Studies in Construction Materials Volume 8, June 2018, Pages 323-332
- Balbo, J. T . (2007) Pavimentacao Asfaltica: materiais, projeto e restauracao. Sao Paulo: Oficina de Textos, 2007.
- Brower, A. (2018) 6 Types of Road Maintenance. Road maintenance website Milling Tools, Graders on June 26, 2018. <http://info.winterequipment.com/blog/types-of-road-maintenance>

Confederação Nacional do Transporte - CNT. (2018) Anuário CNT do transporte – estatísticas consolidadas 2018. Brasília: 2018.  
<http://anuariodotransporte.cnt.org.br/2018/>.

Domingues, F. A. A (1995) Avaliação de pavimentos: Construção de índices de defeito. In: 27ª reunião anual de pavimentação. São PauloSP. Anais.... p. 84-122. 1995.

FHWA - The Federal Highway Administration (2007) Asset Management Overview. December 2007 FHWA-IF-08-008.  
[https://www.fhwa.dot.gov/asset/if08008/assetmgmt\\_overview.pdf](https://www.fhwa.dot.gov/asset/if08008/assetmgmt_overview.pdf)

Hveem, F. N. and Carmany, R. M. (1948) The Factors Underlying a Rational Design of Pavements. Proceedings. Highway Research Board, 1948.

Huntington, G. and Ksaibati, K. (2015) 'Visual Assessment System for Rating Unsealed Roads', Transportation Research Record, 2474(1), pp. 116–122. doi: 10.3141/2474-14.

Kabindra, S., Pramen, S. & Thomas, K. (2014) A Road Maintenance Management Tool for Rural Roads in Kenya. 2014 289-298. DOI: 10.1061/9780784413517.030.

Kamruzzaman, M. (2010) Heuristic Rules to Achieve Pavement Performance Profile Objectives, [Doctoral dissertation], 2010.

Leandro, R. P., Beja, I. A., Bessa, I. S., Andrade, L. R. de, Vasconcelos, K., Bernucci, L. L. B., et al. (2015). Desenvolvimento do modelo de deterioração de pavimentos asfálticos com uso de instrumentação e sistema weigh in motion. Revista ANTT, 12 p. no2015 (2).

Maaty, A. (2017). Temperature Change Implications for Flexible Pavement Performance and Life. International Journal of Transportation Engineering and Technology. 3. 1. 10.11648/j.ijtet.20170301.11.

Martins, L. D. (2015) Levantamento da Utilização de Sistemas de Gerência de Pavimentos no Brasil e Estudo de Caso / Lídia Diniz Martins – Rio de Janeiro: UFRJ/COPPE, 2015.

Mendonça, M. W. (2009) Multilevel Optimization: Convergence Theory, Algorithms and Application to Derivative-Free Optimization, Dissertation presented to Facultes Universitaires Notre-Dame de la Paix. Belgium: Facultes Universitaires Notre-Dame de la Paix, 2009  
 Mishra, S., Golias, M.M, Sharma, S., and Boyles, S. (2015). Optimal Funding Allocation Strategies for Safety Improvements on Urban Intersections. Transportation Research Part A: Policy and Practice, 75, pp. 113-133

Mishra, S., Golias, M.M, Sharma, S., and Boyles, S. (2015). Optimal Funding Allocation Strategies for Safety Improvements on Urban Intersections. Transportation Research Part A: Policy and Practice, 75, pp. 113-133.

Nishiyama, E. S.; Domingues, F. A. A. (1995) Atualização de custos e benefícios, para uso em sistemas de gerência de pavimentos. In: 6ª reunião de pavimentação urbana. Anais...Escola Politécnica da Universidade de São Paulo. Departamento de Engenharia de Transportes. Laboratório de Desenvolvimento Tecnológico de Transportes. LDTT/PTR/USP.1995.

Pulugurta, H., Shao, Q. & Chou. Y.J. (2009). Pavement condition prediction using Markovian process, *Journal of Statistics and Management Systems*, 12:5, 853-871, DOI: 10.1080/09720510.2009.10701426.

Ragnoli, A., Blasiis, M. R., Benedetto, A. di. (2018) Pavement Distress Detection Methods: A Review. *Infrastructures* 2018, 3(4), 58; <https://doi.org/10.3390/infrastructures3040058>

Rabello Quadros, S.G. and Nassi, C.D. (2015) "An evaluation on the criteria to prioritize transportation infrastructure investments in Brazil," *Transport Policy*, vol. 40, pp. 8–16, 2015.

Rodovias (2019) Rodovias – Estado de Minas Gerais. Viewed 20/09/2019. <<https://www.mg.gov.br/conheca-minas/rodovias>>

Rohith, D., Srikanth, K., Chowdary, V. (2016) Performance Evaluation of Unpaved Road Sections Sealed Using Open Graded Premix Surfacing with Bitumen and Bitumen Emulsion as the Binders. *Transportation in Developing Economies* 2: 13. 2016. DOI: 10.1007/s40890-016-0019-4

Ruuska, S., Miettinen, K. and Wiecek, M.M. (2012) Connections between single-level and bilevel multiobjective optimization, *Journal of Optimization Theory and Applications*, vol. 153, no. 1, pp. 60–74, 2012.

Saha, P., and Ksaibati, K. (2017) A risk-based optimization methodology for pavement management system of county roads, *International Journal of Pavement Engineering*, pp. 913–923.

Saha. P., Ksaibati, K. (2017) Developing an Optimization Model to Manage Unpaved Roads. *Journal of Advanced Transportation*. Article ID 9474838. <https://doi.org/10.1155/2017/9474838>

Saha, P. Ksaibati, K. Atadero, R. (2017). Developing Pavement Distress Deterioration Models for Pavement Management System Using Markovian Probabilistic Process, *Advances in Civil Engineering* Volume 2017, Article ID 8292056, 9 pages DOI: 10.1155/2017/8292056

Santos, J.M., Ferreira, A., Flintsch, G. (2017) A multi-objective optimization-based pavement management decision-support system for enhancing pavement sustainability. *Journal of Cleaner Production*, Elsevier, 2017, 164, pp.1380-1393. [ff10.1016/j.jclepro.2017.07.027](https://doi.org/10.1016/j.jclepro.2017.07.027)ff. fffhal-01644474f

Shahin, M. Y. (1994) Pavement Management for Airports, Roads and Parking Lots, Chapman & Hall, London, 1994.

Shenghua, W. & Balasingam M. (2019) A mechanistic-empirical model for predicting top-down fatigue cracking in an asphalt pavement overlay, Road Materials and Pavement Design, 20:6, 1322-1353, DOI: 10.1080/14680629.2018.1443832

Shohel, A. (2015). The Pavement Performance Modeling: Deterministic vs Stochastic Approaches. 10.1007/978-3-319-07167-1\_\_5.

Walker, D. Unpaved (1989) PASER Manual: Pavement Surface Evaluation and Rating. Wisconsin Transportation Information Center, Madison, 1989.

Wolters, K. Zimmerman, K. Schattler, and A. Rietgraf, Implementing Pavement Management for Local Agencies, Illinois Center for Transportation, 2011.

WYDOT (2014), Transportation Asset Management Plan, Retrieved June 17, 2014, from <http://www.tamptemplate.org/wp-content/uploads/tamps/021wyomingdot.pdf>.

Wyoming Technology Transfer Center – WTTC (2014). Unpaved Road Quality Rating Guide. September 2014.

WSDOT – Washington State Department of Transportation. (2016) Pavement Asset Management. 47p. 2016.

Zhang, G. Lu, J. and Gao, Y. (2015) Multi-Level Decision Making Models, Methods and Applications, Springer, 2015.

## **CHAPTER 6 – Conclusions and Recommendations**

### **6.1. Final Conclusions**

Based on the studies produced in the previous chapters, the following conclusions are presented:

The second chapter presented two different road assessments methods to identify unpaved roads distresses. The hypothesis adopted in tropical countries is that the subjective method, which is based on individual perceptions, is more suitable in reflecting road serviceability than the objective functional assessment which is based on standardized measures of defects. The models included only five of the seven distresses which are included in both methodologies, subjective and objective. With current pavement condition index assessed using the models, agencies are equipped with the information needed to predict the future condition of a segment, and to create performance prediction models.

The third chapter presents a study which a practical application of Markovian chains to predict pavement performance based on its age and the PCI was presented. The research relied on a significant amount of historical data - from 2013 to 2018, that was further transformed from PCI to five condition states following the AASHTO methodology. The proposed deterioration model was implemented using the statistic computing Software R. The methodology can be used to find the overall condition state of complete road networks and then, helps to identify the appropriate maintenance policy according to a specific budget. The research concluded that the Markovian process is an excellent tool which can be used to design decision support systems for PMS. However, it is more appropriate to be used at a network level, since it is more effective at estimating the number of sections in a particular condition state for a given moment than at predicting the performance of a specific road section and the type of the maintenance to be used there.

In the fourth chapter, to optimize the decision-making, developed countries are using a management system which consists in develop deterioration models according to the surface condition. In this research, probabilistic deterioration models have been developed for unpaved roads over nine years of roads evaluation using Markovian process and the statistical computing Software R. The developed models were tailored specifically to unpaved roads from Minas Gerais, Brazil. As this methodology still

incorporates uncertainties about the data collection, the developed models will become every year more accurate if updated with new inputs. This methodology can also be implemented on other functional classes or types of roadways. And, using this probabilistic method to determine the deterioration model, the GRMS can be created as a reliable and cost-effective system to better maintain unpaved roads.

And the fifth chapter, in the state of Minas Gerais, there is a total of 15,236 km of roadway owned and maintained by federal, state, and local entities. The methodology developed identifies the best “mix of roads” preservation projects that uses limited available resources. Results showed that the maintenance cost for a year is expected to be approximately R\$ 46.900,92 for the unpaved roads network analyzed and R\$ 19.883.100,00 for the paved roads network analyzed, to maintain the state roads conditions. The unpaved model was tailored specifically to Zona da Mata county, and the paved model was tailored to the entire state of Minas Gerais, Brazil. The methodology considers that preventive and minor rehabilitation treatments are more cost-effective than reconstruction. It can be implemented in any county in the state of Minas Gerais and can be used by other states for developing a management system for unpaved roads. However, for other states, some minor changes in the methodology may be needed to reflect local conditions.

## **6.2. Future Work**

At this stage, the current methodology to obtain the data collection is a process which require efforts to be more technological and feasible. More experimental work is required to enhance the reliability of this method. For example, the actual functional condition of a unpaved or paved road is determined manually using an established referenced guide from DNIT (DNIT, 2003). However, in developed countries, smartphones are being used in the data collection process (through images and correlations between roughness and texture of roads) as a new, feasible and low-cost method (Forslof, 2015). More experimental work is required to enhance the reliability of this method to tropical soils to calibrate the system (Aleadelat, 2018). Furthermore, different types of smartphones and fixing locations (e.g., drivers’ pocket) should be tested using different vehicles to simulate real time circumstances

The deterioration models associated with functional conditions using Markovian Chain method must be updated to be more reliable every year. The model was created

just to Minas Gerais state, and the other states should be included in any future estimates. This will generate specific scenarios for every Brazilian state, and provide decision makes a better understanding and eventually enhance the planning and the decision-making process. Using a smartphone, this can be achieved by weekly monitoring a representative sample of unpaved roads for a year. Then, this new historical database can be used to establish more accurate performance prediction equations.

Lastly, the developed system uses the evolutionary method to solve the optimization problems presented in this work. However, genetic algorithms (GA) are being introduced to update management systems (Pinninghoff, Contreras, and Atkinson, 2008). GA are robust search algorithms which are stochastic in nature. This mean that these algorithms might be vulnerable to be trapped in a local minima or maxima. Therefore, future work will be focusing on enhancing the developed tools and dealing with the stochastic nature of the implemented algorithm.

## REFERENCES

Aleadelat, W. (2018) Establishing a Methodology for Unpaved roads Management System, Ph.D. Dissertation. Department of Civil and Architectural Engineering, University of Wyoming.

DNIT- DEPARTAMENTO NACIONAL DE INFRAESTRUTURA DE TRANSPORTES, (2003c) - Levantamento visual contínuo para avaliação da superfície de pavimentos flexíveis e semi-rígidos Procedimento. NORMA DNIT 008/2003 – PRO.

Forslofp, L. (2015). Automated collection of road condition data with smartphones. Roadroid WRC 2015. Accessed: [https://www.roadroid.com/common/References/roadroid\\_-\\_accuracy\\_and\\_use\\_trv\\_project.pdf](https://www.roadroid.com/common/References/roadroid_-_accuracy_and_use_trv_project.pdf)

Pinninghoff J.M., Contreras, R., Atkinson, J. (2008). Using Genetic Algorithms to Model Road Networks. IEEE Computer. 41. 60-67. 10.1109/MC.2008.543.

## APPENDIX A-1: Instructions on How to Use the Unpaved Roads Management System (URMS)

The following instructions provide the necessary steps to run the maintenance tool.

1. Prepare a CSV file with the required inputs as shown exactly in Figure 1.

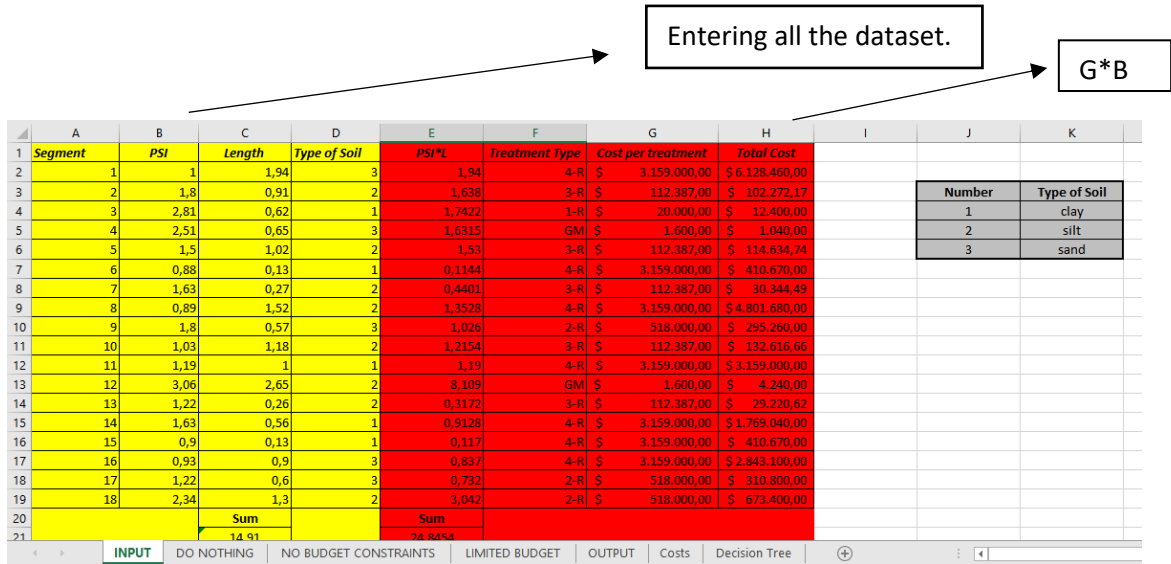


Figure 1: Sample CSV File to Run the Maintenance Tool.

2. Please go to “DO NOTHING” spreadsheet and select the option GOAL SEEK according to the deterioration model. It also shows the roads overall PSI after one year without maintenance.

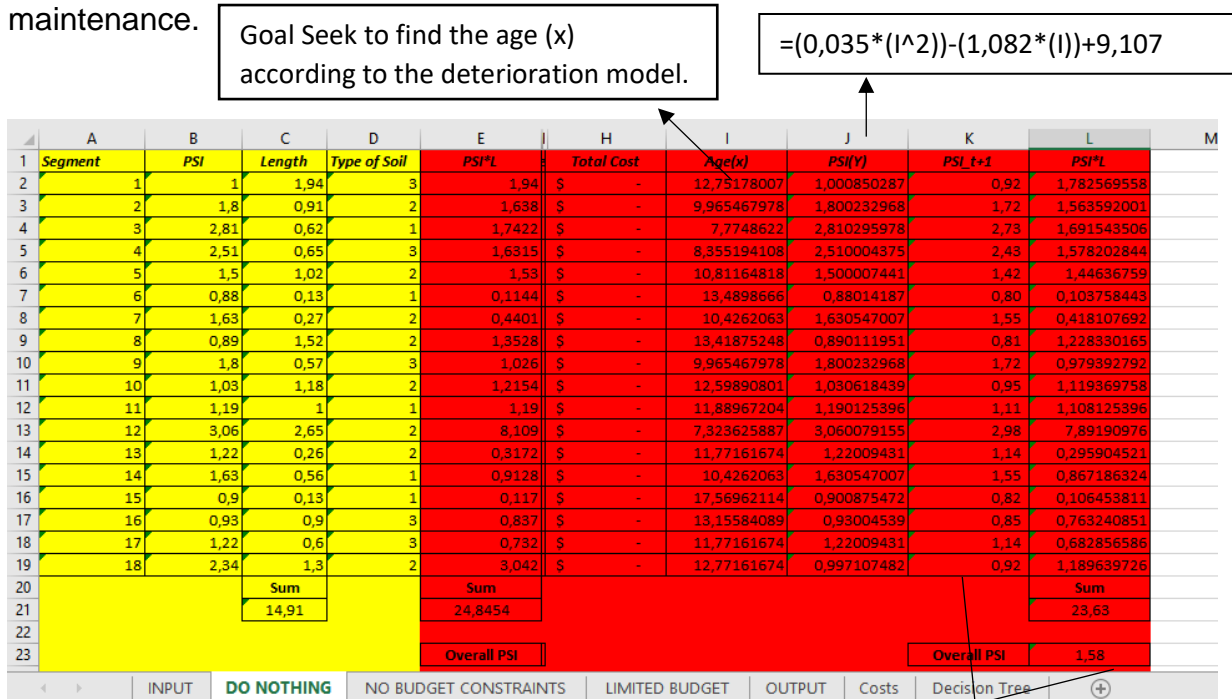


Figure 2: Sample running the “DO NOTHING” spreadsheet.

PSI after 1 year if you decide DO NOTHING

$$=(0,035*(I^2)+1)-(1,082*(I+1))+9,107$$

3. If was decided to realize any maintenance at the roads surface, it is necessary to consider the constraints. If there is no constraint, please go to “NO BUDGET CONSTRAINTS” spreadsheet and select the decision (column E) as 1\* as shows Figure 3.

- \* Decision 0 = no maintenance
- Decision 1 = maintenance

The result will give you the overall PSI after all the maintenances and its total cost.

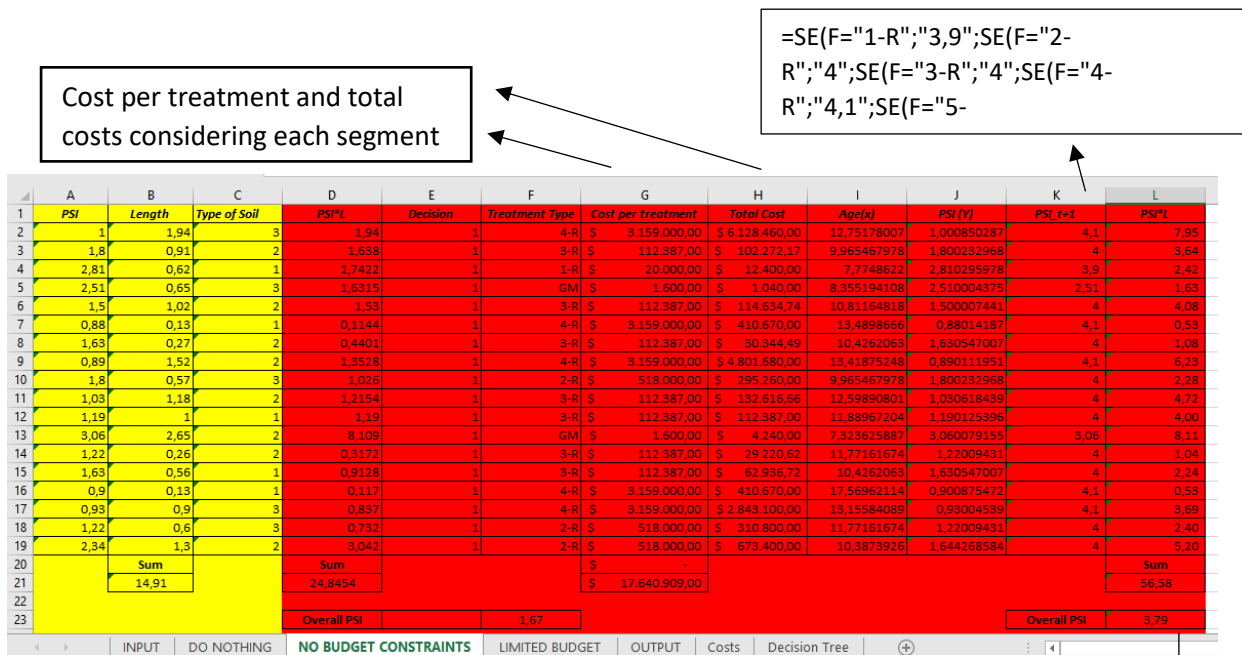


Figure 3: Sample running the “NO BUDGET CONSTRAINTS” spreadsheet.

PSI after 1 year if you decide to maintain the roads with NO BUDGET CONSTRAINTS

4. If was decided to realize any maintenance at the roads surface, it is necessary to consider the constraints. If there is a budget constraint, please go to “LIMITED BUDGET” spreadsheet, then go to data tab and SOLVER. Select the options as shows Figure 4 with the available budget and press SOLVE.

- \* Decision 0 = no maintenance
- Decision 1 = maintenance

The result will give you the overall PSI after all the maintenances and its total cost considering the constraints as shows Figure 5.

Parâmetros do Solver

Definir Objetivo:  ↑

Para:  Máx.  Mín.  Valor de:

Alterando Células Variáveis:  ↑

Sujeito às Restrições:

- 
- 
- 

Tornar Variáveis Irrestritas Não Negativas

Selecionar um Método de Solução:

Método de Solução

Selecione o mecanismo GRG Não Linear para Problemas do Solver suaves e não lineares. Selecione o mecanismo LP Simplex para Problemas do Solver lineares. Selecione o mecanismo Evolutionary para problemas do Solver não suaves.

This budget value will represent the overall maintenance budget.

Figure 4: Solver inputs.

Solver to decide if the segments will be maintained (1) or not (0).

=SE(E=0;'DO NOTHING'!K;SE(F="1-R";"3,9";SE(F="2-R";"4";SE(F="3-R";"4";SE(F="4-R";"4,1";SE(F="5-R";"4,3";SE(F="GM";A;))))))

	A	B	C	D	E	F	G	H	I	J	K	L	
1	PSI	Length	Type of Soil	PSI*L	Decision	Treatment Type	Cost per treatment	Total Cost	Age (X)	PSI(Y)	PSI_t+1	PSI*L	
2	1	1,94	3	1,94	0	0	\$ -	\$ -	12,75178007	1,000850287	0,92	1,78	
3	1,8	0,91	2	1,638	0	0	\$ -	\$ -	9,965467978	1,800232968	1,72	1,56	
4	2,81	0,62	1	1,7422	1	1-R	\$ 20.000,00	\$ 12.400,00	7,7748622	2,810295978	3,9	2,42	
5	2,51	0,65	3	1,6315	1	GM	\$ 1.600,00	\$ 1.040,00	8,355194108	2,510004375	2,51	1,63	
6	1,5	1,02	2	1,53	0	0	\$ -	\$ -	10,81164818	1,500007441	1,42	1,45	
7	0,88	0,13	1	0,1144	0	0	\$ -	\$ -	13,4898666	0,88014187	0,80	0,10	
8	1,63	0,27	2	0,4401	0	0	\$ -	\$ -	10,4262063	1,630547007	1,55	0,42	
9	0,89	1,52	2	1,3528	0	0	\$ -	\$ -	13,41875248	0,890111951	0,81	1,23	
10	1,8	0,57	3	1,026	0	0	\$ -	\$ -	9,965467978	1,800232968	1,72	0,98	
11	1,03	1,18	2	1,2154	0	0	\$ -	\$ -	12,59890801	1,030618439	0,95	1,12	
12	1,19	1	1	1,19	0	0	\$ -	\$ -	11,88967204	1,190125396	1,11	1,11	
13	3,06	2,65	2	8,109	1	GM	\$ 1.600,00	\$ 4.240,00	7,323625887	3,060079155	3,06	8,11	
14	1,22	0,26	2	0,3172	1	3-R	\$ 112.387,00	\$ 29.220,62	11,77161674	1,22009431	4	1,04	
15	1,63	0,56	1	0,9128	0	0	\$ -	\$ -	10,4262063	1,630547007	1,55	0,87	
16	0,9	0,13	1	0,117	0	0	\$ -	\$ -	17,56962114	0,900875472	0,82	0,11	
17	0,93	0,9	3	0,837	0	0	\$ -	\$ -	13,15584089	0,93004539	0,85	0,76	
18	1,22	0,6	3	0,732	0	0	\$ -	\$ -	11,77161674	1,22009431	1,14	0,68	
19	2,34	1,3	2	3,042	2	2-R	\$ 518.000,00	\$ 673.400,00	10,3873926	1,644268584	4	5,20	
20		Sum		Sum			Sum	Sum				Sum	
21		14,91		24,85			\$	46.900,62				25,37	
22													
23				1,67								Overall PSI	1,70

Figure 5: Sample running the “LIMITED BUDGET” spreadsheet.

PSI after 1 year if you decide to maintain the roads with LIMITED BUDGET. In this case, the goal was to maintain the PSI and find the minimal cost to it.

## APPENDIX A-2: Instructions on How to Use the Pavement Management System (PMS)

The following instructions provide the necessary steps to run the maintenance tool.

1. Prepare a CSV file with the required inputs as shown exactly in Figure 1.

Entering all the dataset.

H\*B

	A	B	C	D	E	F	G	H	I
1	Segment	PSI	Length	Road Width	Rut	PSI*L	Treatment Type	Cost per treatment	Total Cost
2	LMG-633	1	35	7	0,40	35	5-R	\$ 2.334.000,00	\$ 81.690.000,00
3	LMG-820	2	9	7	0,40	18	2-R	\$ 308.000,00	\$ 2.772.000,00
4	MG-050	3	6,5	7	0,40	19,5	1-R	\$ 518.000,00	\$ 3.367.000,00
5	MG-123	3	45	7	0,40	135	1-R	\$ 518.000,00	\$ 23.310.000,00
6	G-123/BR-262	2	10	7	0,50	20	2-R	\$ 308.000,00	\$ 3.080.000,00
7	MG-129	3	32	3,8	0,51	96	2-R	\$ 308.000,00	\$ 9.856.000,00
8	G-129/BR-120	2	17	6,5	0,53	34	2-R	\$ 308.000,00	\$ 5.236.000,00
9	MG-164	1	23	3	0,45	23	5-R	\$ 2.334.000,00	\$ 53.682.000,00
10	MG-167	2	7	7,2	0,77	14	2-R	\$ 308.000,00	\$ 2.156.000,00
81	BR-462	2	4	4	0,25	8	2-R	\$ 308.000,00	\$ 1.232.000,00
82	BR-464	4	25	4	0,25	100	GM	\$ 1.380,00	\$ 34.500,00
83	BR-474	2	151	4	0,50	302	2-R	\$ 308.000,00	\$ 46.508.000,00
84	BR-482	1	142	4	0,76	142	5-R	\$ 2.334.000,00	\$ 331.428.000,00
85	BR-491	3	256	4	0,48	768	1-R	\$ 518.000,00	\$ 132.608.000,00
86	BR-494	4	198	4	0,48	792	GM	\$ 1.380,00	\$ 273.240,00
87	BR-496	1	135	4	0,58	135	5-R	\$ 2.334.000,00	\$ 315.090.000,00
88	BR-497	3	86	4	0,55	258	2-R	\$ 308.000,00	\$ 26.488.000,00
89	BR-499	3	15	4	0,58	45	2-R	\$ 308.000,00	\$ 4.620.000,00
90			Sum			Sum			
91			14011,5			42949			
92									
93						Overall PSI	3,07		

INPUT
DO NOTHING
NO BUDGET CONSTRAINTS
LIMITED BUDGET
OUTPUT
Costs
Decision Tree
+

**Figure 1: Sample CSV File to Run the Maintenance Tool.**

2. Please go to “DO NOTHING” spreadsheet and select the option GOAL SEEK from the data tab. The result as Figure 2 shows will be the age according to the deterioration model. It also shows the roads overall PSI after one year without maintenance.

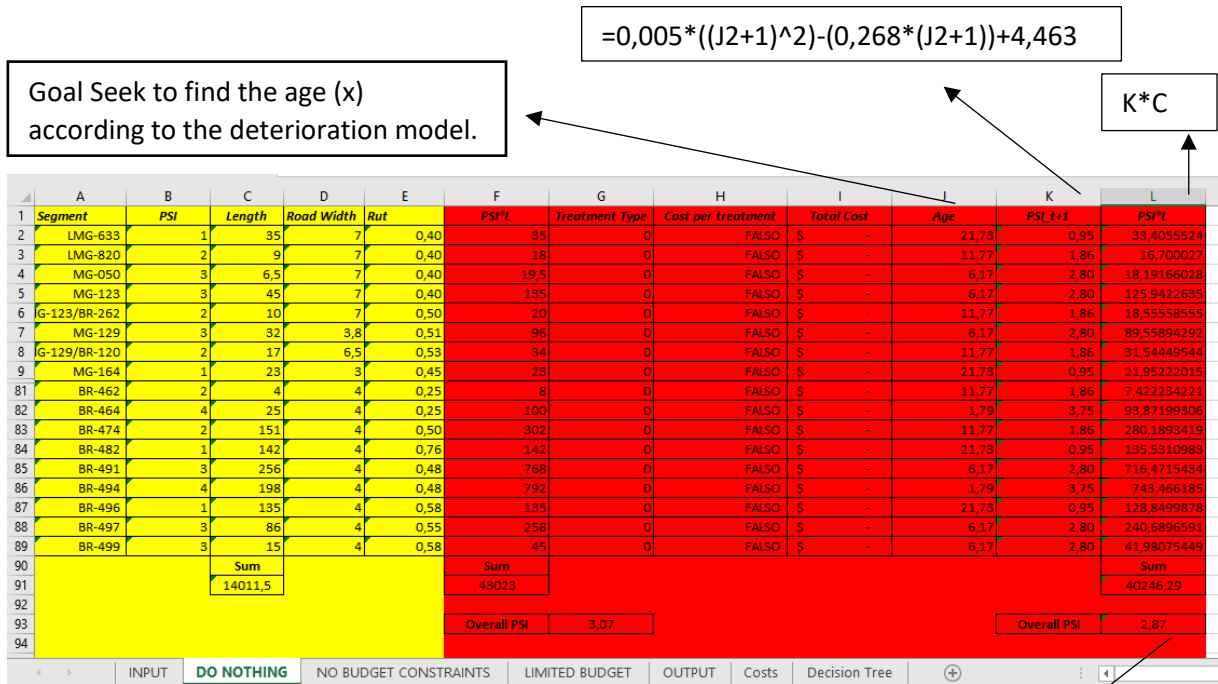


Figure 2: Sample running the “DO NOTHING” spreadsheet.

PSI after 1 year if you decide DO NOTHING

3. If was decided to realize any maintenance at the roads surface, it is necessary to consider the constraints. If there is no constraint, please go to “NO BUDGET CONSTRAINTS” spreadsheet and select the decision (column E) as 1\* as shows Figure 3.

- \* Decision 0 = no maintenance
- Decision 1 = maintenance

The result will give you the overall PSI after all the maintenances and its total cost.

=SE(G="1-R";"3,9";SE(G="2-R";"4";SE(G="3-R";"4";SE(G="4-R";"4,1";SE(G="5-R";"4,3";SE(G="GM";A;))))))

Cost per treatment and total costs considering each segment

K\*B

	A	B	C	D	E	F	G	H	I	J	K	L
1	PSI	Length	Road Width	Rut	PSI <sup>t</sup> L	Decision	Treatment Type	Cost per treatment	Total Cost	Age	PSI <sub>t+1</sub>	PSI <sup>t</sup> L
2	1	35	7	0,40	35	1	5-R	\$ 2.334.000,00	\$ 81.690.000,00	21,73	4,3	150,50
3	2	9	7	0,40	18	1	2-R	\$ 308.000,00	\$ 2.772.000,00	11,77	4	36,00
4	3	6,5	7	0,40	19,5	1	1-R	\$ 518.000,00	\$ 3.367.000,00	6,17	3,9	25,35
5	3	45	7	0,40	135	1	1-R	\$ 518.000,00	\$ 23.310.000,00	6,17	3,9	175,50
6	2	10	7	0,50	20	1	2-R	\$ 308.000,00	\$ 3.080.000,00	11,77	4	40,00
7	3	32	3,8	0,51	96	1	2-R	\$ 308.000,00	\$ 9.856.000,00	6,17	4	128,00
8	2	17	6,5	0,53	34	1	2-R	\$ 308.000,00	\$ 5.236.000,00	11,77	4	68,00
9	1	23	3	0,45	23	1	5-R	\$ 2.334.000,00	\$ 53.682.000,00	21,73	4,3	98,90
81	2	4	4	0,25	8	1	2-R	\$ 308.000,00	\$ 1.232.000,00	11,77	4	16,00
82	4	25	4	0,25	100	1	GM	\$ 1.380,00	\$ 34.500,00	1,79	4,0	100,00
83	2	151	4	0,50	302	1	2-R	\$ 308.000,00	\$ 46.508.000,00	11,77	4	604,00
84	1	142	4	0,76	142	1	5-R	\$ 2.334.000,00	\$ 331.428.000,00	21,73	4,3	610,60
85	3	256	4	0,48	768	1	1-R	\$ 518.000,00	\$ 132.608.000,00	6,17	3,9	998,40
86	4	198	4	0,48	792	1	GM	\$ 1.380,00	\$ 273.240,00	1,79	4,0	792,00
87	1	135	4	0,58	135	1	5-R	\$ 2.334.000,00	\$ 315.090.000,00	21,73	4,3	580,50
88	3	86	4	0,55	258	1	2-R	\$ 308.000,00	\$ 26.488.000,00	6,17	4	344,00
89	3	15	4	0,58	45	1	2-R	\$ 308.000,00	\$ 4.620.000,00	6,17	4	60,00
90		Sum			Sum			Sum				Sum
91		14011,5			43023			48.057.320,00				56155,60
92												
93					Overall PSI		3,07				Overall PSI	4,01
94												

Figure 3: Sample running the “NO BUDGET CONSTRAINTS” spreadsheet.

PSI after 1 year if you decide to maintain the roads with NO BUDGET CONSTRAINTS

4. If was decided to realize any maintenance at the roads surface, it is necessary to consider the constraints. If there is a budget constraint, please go to “LIMITED BUDGET” spreadsheet, then go to data tab and SOLVER. Select the options as shows Figure 4 with the available budget and press SOLVE.

- \* Decision 0 = no maintenance
- Decision 1 = maintenance

The result will give you the overall PSI after all the maintenances and its total cost considering the constraints as shows Figure 5.

Parâmetros do Solver

Definir Objetivo:

Para:  Máx.  Mín.  Valor de:

Alterando Células Variáveis:

Sujeito às Restrições:

- \$F\$2:\$F\$89 <= 1
- \$F\$2:\$F\$89 = número inteiro
- \$I\$91 <= 20000000

Tornar Variáveis Irrestritas Não Negativas

Selecionar um Método de Solução: Evolutionary

Método de Solução

Selecione o mecanismo GRG Não Linear para Problemas do Solver suaves e não lineares. Selecione o mecanismo LP Simplex para Problemas do Solver lineares. Selecione o mecanismo Evolutionary para problemas do Solver não suaves.

Ajuda Resolva Fechar

This budget value will represent the overall maintenance budget.

Figure 4: Solver inputs.

Solver to decide if the segments will be maintained (1) or not (0).

=SE(F=0;'DO NOTHING'!K;SE(G="1-R";"3,9";SE(G="2-R";"4";SE(G="3-R";"4";SE(G="4-R";"4,1";SE(G="5-R";"4,3";SE(G="GM";A;))))))

	A	B	C	D	E	F	G	H	I	J	K	L	M	
	PSI	Length	Road Width	Rut	PSI'L	Decision	Treatment Type	Cost per treatment	Total Cost	Y (psi)	Age (X)	PSI_t+1	PSI'L	
2	1	35	7	0,40	35	0		FALSO	\$ -	1,0001	21,73	0,95	33,41	
3	2	9	7	0,40	18	1	2-R	\$ 308.000,00	\$ 2.772.000,00	2,000827	11,77	4	36,00	
4	3	6,5	7	0,40	19,5	0		FALSO	\$ -	3,000029	6,17	2,80	18,19	
5	3	45	7	0,40	135	0		FALSO	\$ -	3,000029	6,17	2,80	125,94	
6	2	10	7	0,50	20	1	2-R	\$ 308.000,00	\$ 3.080.000,00	2,000827	11,77	4	40,00	
7	3	32	3,8	0,51	96	0		FALSO	\$ -	3,000029	6,17	2,80	89,56	
8	2	17	6,5	0,53	34	0		FALSO	\$ -	2,000827	11,77	1,86	31,54	
9	1	23	3	0,45	23	0		FALSO	\$ -	1,0001	21,73	0,95	21,95	
81	2	4	4	0,25	8	0		FALSO	\$ -	2,000827	11,77	1,86	7,42	
82	4	25	4	0,25	100	1	GM	\$ 1.380,00	\$ 34.500,00	4,000008	1,79	4,00	100,00	
83	2	151	4	0,50	302	0		FALSO	\$ -	2,000827	11,77	1,86	280,19	
84	1	142	4	0,76	142	0		FALSO	\$ -	1,0001	21,73	0,95	135,53	
85	3	256	4	0,48	768	0		FALSO	\$ -	3,000029	6,17	2,80	716,47	
86	4	198	4	0,48	792	1	GM	\$ 1.380,00	\$ 273.240,00	4,000008	1,79	4,00	792,00	
87	1	135	4	0,58	135	0		FALSO	\$ -	1,0001	21,73	0,95	128,85	
88	3	86	4	0,55	258	0		FALSO	\$ -	3,000029	6,17	2,80	240,69	
89	3	15	4	0,58	45	0		FALSO	\$ -	3,000029	6,17	2,80	41,98	
90		Sum			Sum				Sum		4,463		Sum	
91		14011,5			43023,00				\$ 19.883.100,00				41254,94	
92														
93			Overall PSI		3,07								Overall PSI	2,94
94														

Figure 5: Sample running the "LIMITED BUDGET" spreadsheet.

PSI after 1 year if you decide to maintain the roads with LIMITED BUDGET. In this case, the goal was to maintain the PSI and find the minimal cost to it.