

Incorporation of Mechanistic-Empirical Pavement Design Guide (MEPDG) into Flexible
Pavement Management System PMS

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Abstract

Incorporation of Mechanistic-Empirical Pavement Design Guide (MEPDG) into Flexible Pavement Management System PMS

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Pavement Management Systems (PMSs) rely heavily on indirect condition indices, such as the International Roughness Index (IRI) and the Pavement Condition Index (PCI), to guide decision-making systems prioritize maintenance and rehabilitation (M&R) at the network level. However, these indices are not structural measures from which signs of decay can be directly recognized; thus, their employment may cause a wrong timing of interventions and higher life-cycle costs. Although there is extensive research on Mechanistic-Empirical Pavement Design Guide (MEPDG) calibration and on PMS optimization, the incorporation of direct distress indicators from MEPDG and their performance within a decision support framework within PMS is missing and needs to be studied and evaluated.

This Thesis develops an approach that tightly links MEPDG-derived distress data, which include rutting and cracking, with PMSs decision-making. Three very different case studies have been implemented for the validation of the methodology. Firstly, in Alaska, distress datasets from 2020-2022 are used to calibrate rutting and cracking models by which more accurate forecasting and anticipatory M&R scheduling can be realized. Secondly, in Uganda, the integration is reformed by the use of AASHTO-based surrogates and a localized IRI progression model that is informed by regression and expert judgment, where limited structural inputs; a 30-year, budget-constrained program is optimized via linear programming, resulting in realistic rehabilitation cycles and credible long-term projections. Lastly, the maturity of a network in Alberta is exploited for the comparison of IRI-triggered and distress-triggered regimens. The development of the distress-based approach results in earlier identification of structural decline, improvement of predicted pavement conditions, and reduction of life-cycle costs.

Across the three different uses, the optimized PMS showed that it could be very effective in both condition control and resource allocation. The Alaska strategy that was optimized was a very good example, as it resulted in more stable spending, thus keeping the annual maintenance costs under \$2.5 million while at the same time it managed to decrease the average rutting from 0.23 to 0.17 inches and also the cracking from 4.6% to ~3.5% over the 30-year horizon. Even though in Uganda some budgetary constraints required front-loaded investments of more than \$70 million in the first few years, the optimized PMS still greatly improved the technical outcomes, as the depth of the ruts was reduced from 9 mm to ~1.5 mm and the cracking from 12% to ~3%, thus, giving a better

performance than the reactive strategies. The optimized-PMS performed better than the baseline IRI-based method in Alberta as it managed to lower the average network rutting from ~5 mm to ~3 inches by the end of the analysis period. Overall, the results that were found here demonstrate that the MEPDG-PMS integration has the capacity to significantly improve the accuracy of the predictions, to reduce the rates of deterioration, and also to optimize the patterns of the expenditures in various regional contexts.

The main contributions encompass: (1) a framework that can be repeated which allows the raising of direct distress measurements to the main decision variables; (2) a clear method for the transfer of knowledge to situations with limited resources; and (3) research findings that strategies initiated by direct distresses perform better in terms of condition outcomes and use of costs than those solely based on indirect damage indicators. Such discoveries promote the progression of PMSs capabilities by facilitating the allocation of resources backed up by the evidence, the improvement of the resilience of the network, and sustainable pavement preservation across diverse data environments for different agencies.

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List of Abbreviations

PMSs	Pavement Management Systems
MEPDG	Mechanistic-Empirical Pavement Design Guide
LCA	Life Cycle Assessment
LCCA	Life-Cycle Cost Analysis
PCI	Pavement Condition Index
IRI	International Roughness Index
SF	Site Factor
PSI	Present Serviceability Index
GIS	Geographic Information System
AASHTO	American Association of State Highways and Transportation Officials
AADT	Average Annual Daily Traffic
SN	Structural Number
LDF	Lane Distribution Factor
DS	Directional Split
LTPP	Long-Term Pavement Performance
M&R	Maintenance and Rehabilitation
TPM	Transition Probability Matrix

1 Introduction

Over the last few decades, the field of pavement engineering has undergone significant advancements with the incorporation of sophisticated tools and techniques in an effort to enhance the design of the road network along with its maintenance and rehabilitation. Pavement Management research presently covers the integration of two major tools in modern pavement engineering, namely Pavement Management Systems (PMSs) and the Mechanistic-empirical Pavement Design Guide (MEPDG).

This integration could be considered a paradigm shift in approach to pavement design and management with the potential for improved efficiency, cost-effectiveness, and sustainability within the road infrastructure. (Monismith & Asce, 2012). Over time, PMSs have developed into advanced tools for transportation agencies, making a complete overhaul of how pavement networks are being maintained and rehabilitated. The importance of a PMSs lies in the systematics and objectiveness it provides to pavement management. It accumulates, stores, and analyzes large quantities of pavement condition data that thus allowing agencies to make informed, data-driven decisions. With PMSs, a clear and overall perspective of the network conditions allows for efficient resource allocation whereby scarce funds are utilized based on where they provide the maximum benefits. Long-term planning can then be realized whereby the future pavement condition is forecasted, thus allowing agencies to develop proactive maintenance strategies alongside corresponding budgeting (Uglova et al., 2018).

PMS provides a current record of pavement performance, which aids professionals in identifying trends, assessing the effectiveness of treatments applied, and often develops refinements in maintenance strategies over time (Bianchini & Bandini, 2010). Ultimately, PMSs schedules intervention at the right time to save life cycle costs on pavement assets by encouraging proactive maintenance (Asres et al., 2022).

The MEPDG is a significant advance in the methodological approach to pavement design, retaining obvious advantages of traditional empirical methods. MEPDG synthesizes mechanistic principles with empirical observations to have more accurate predictions of pavement performance under various conditions (Retherford & McDonald, 2010). It has the flexibility for a wide range of materials used, traffic loads, and environmental conditions, and thus is applicable to any geographical and climatic region (Dan et al., 2022). The MEPDG differs in that it explicitly considers climate conditions in relation to pavement performance, such as temperature, precipitation, and freeze-thaw cycles, which was not the case for most of the methods that preceded it (Zhuang et al., 2023). This guide also provided a full characterization of traffic loads by considering axle configurations and load spectra in addition to vehicle counts. According to Gu et al. (2018), the new MEPDG further introduces reliability concepts, allowing designers for the first time to quantify and manage the uncertainty associated with pavement performance predictions. Together, these advantages contribute to a stronger and more efficient pavement design, which better serves all modern traffic requirements and environmental stressors.

PMSs are designed to serve different needs and objectives and come in various levels. Network PMSs assess the general performance of the pavement network for support of strategic decisions on prioritization and budgeting (Uglova et al., 2018). Project-level PMSs analyse specific pavement sections to assist in selecting detailed maintenance or rehabilitation treatments (Alharbi & Smadi, 2019). Integrated PMSs supports both network and project-level functionalities and is a comprehensive approach to pavement management (Abejide et al., 2021). Moreover, some agencies also use specialized PMSs, focusing on certain types of pavements - which may either be flexible or rigid pavements - or for other special reasons concerning pavement performance such as safety and ride quality (Zhuang et al., 2023). The selected type of PMSs will depend on the needs of the agency, resources, and characteristics of their pavement network (Albayati et al., 2024). Modern PMSs still rely heavily on indirect condition indicators such as IRI and PCI for making investment decisions and policy formulation. These indices are used even though direct damage indicators like cracking and rutting, which reflect the underlying structural deterioration of the pavement, would be more accurate. The use of MEPDG allows PMSs to be able to mechanistically figure out and anticipate the emergence of the most critical distress scenarios such as the development of cracks and rutting and, thus, make a correct structural condition, carry out maintenance at the best time, and plan the long-term investment in an optimal way.

Therefore, it can be said that one of the main areas of research and development includes MEPDG model calibration using data from PMS. The calibration of performance prediction brings the models closer to the local conditions enhancing actual pavement performance within the MEPDG (Retherford & McDonald, 2010). The extensive availability of historical performance data from PMSs enhances the calibration of MEPDG models, enabling agencies to improve predictions for rutting, cracking, or roughness in pavements (Alharbi & Smadi, 2019). This method enhances the interpretive capabilities of MEPDG, providing a more accurate prediction and filling the gap between design assumptions and actual pavement performance (Zhuang et al., 2023). Several studies have demonstrated that the correlation between the predicted and observed pavement performance was significantly improved after calibrating the MEPDG models with local PMS data (Dan et al., 2022).

The integration of MEPDG into the PMSs presents significant opportunities regarding further improvement of both pavement design and management practices. A promising approach for integration involves utilizing the MEPDG performance models (rutting, cracking, and International Roughness Index) to correspond with the condition indicators normally used in PMSs (Abejide et al., 2021). This approach enhances the continuity of information flow between the design and management stages of pavement life. For example, the MEPDG cracking model can be calibrated on cracking measurements recorded in the PMSs to allow for more accurate prediction of crack progression over time (Alharbi & Smadi, 2019). Similarly, the cracking models in MEPDG may be refined to better capture the types and severities of cracking records stored in PMSs (Zhuang et al., 2023). The IRI model, a pavement roughness indicator, may be calibrated utilizing the extensive roughness data commonly found in PMSs (Dan et al., 2022). The integration

of these models may advance realistic design inputs, improved accuracy in performance predictions, and generally better pavement designs that closely relate to long-term management strategies (Albayati et al., 2024).

In line with those advancements this research aims take full advantage of the synergy achievable through the integration of Pavement Management Systems and Mechanistic-Empirical Pavement Design Guide. To date, PMSs as well as the MEPDG have gone a long way independently. However, still, many researchers have not succeeded in combining these two tools into one integrated tool, which makes a crucial gap in the flow of pavement design from maintenance planning based on the condition of the road. The integration of these two major tools would result in a more cohesive system in pavement engineering, addressing both initial design and long-term management elements. This integration may enhance the accuracy of pavement performance predictions, optimize resource allocation, and contribute to the development of more durable, cost-effective, and sustainable road networks. The examination of such features for integration enhances the progress of pavement engineering practice and theory through deliberate efforts.

This research applies this holistic methodological framework to different geographical contexts and diverse operations to pre-appraise comprehensively the PMSs-MEPDG implementation. With this multi-case study approach, the investigation assesses the feasibility under several scenarios of data availability and climatic conditions, thereby handling the crucial gap of cohesive pavement engineering systems.

The outcomes of the study provide a tangible framework that extends beyond theoretical integration to practical application. This research, by integrating the performance data from different environments, ranging from data-rich to data-limited contexts, proves the integrated approach to be the most flexible and reliable under various operational constraints. The analysis depicts the potential of this integration to enable region-specific measures without compromising on the overall methodological framework.

With this model, transportation agencies that work in different conditions can employ the most efficient pavement management plan that is backed by solid evidence, even they may lack sufficient data, or faced with environmental challenges. The methodology addresses the actual limitations faced by the agencies in the design and maintenance process and provides them with adaptable solutions to the different resource levels and technical capabilities. Accordingly, the research produces operational protocols that can be adapted to diverse settings, laying a foundation for the implementation of integrated pavement engineering practice across geographical and institutional variations.

1.1 Thesis Goal

Mechanistic-Empirical considerations are being integrated as part of the effort to significantly improve and update PMSs. The emphasis is mainly on flexible pavements. One of the most important among the changes brought about in PMSs is to turn the evaluation systems, which

depend mostly on indirect damage indicators like PCI and IRI, towards a direct performance assessment that uses damage-specific indicators such as rutting and cracking. This allows the PMS to evaluate the real structural and functional degradation of the pavements by employing direct indicators, thereby greatly improving the accuracy of maintenance planning and design interventions.

The new conceptual design for such a system explicitly incorporates key factors such as climate variability, traffic loading patterns, and material properties, Providing flexibility not only in design but also in performance Prediction. This alignment allows the PMSs decision process to closely reflect MEPDG enabling predictive function that correspond more accurately to actual pavement performance rather than relying solely on condition scores.

Three sets of geographical data from Alaska (USA), Uganda, and Alberta (Canada) are used to substantiate and perfect the suggested PMS paradigm. These places vary significantly in their operational and environmental contexts. While the cold and the freeze-thaw cycles characterize the regions of Alaska and Alberta, the tropics and the traffic requirements characterize Uganda. The comparative analysis of different environmental conditions will prove the usefulness of the direct-indicator-based PMS-indicator method in distinct climatic stressing, loading, and material behavioral areas.

This research is significant in two ways. On the one hand, it innovates the modeling of PMS by incorporating Mechanistic-Empirical performance models and the respective calibrations that connect the changes in surface (rutting and cracking) directly to the measured performance under different conditions. On the other hand, it contributes to the practice of transportation agencies by providing a decision-support tool that can efficiently manage maintenance strategies, budgeting, and design options with trustworthiness and region specificity. Thus, this study qualifies as one that closes the gap between the advanced Mechanistic-Empirical design theory and the practical pavement asset management.

1.2 Specific Objectives

Objective 1: To assess the feasibility of integrating the Mechanistic-Empirical Pavement Design Guide (MEPDG) with Pavement Management Systems (PMSs) in regions with comprehensive distress data.

Objective 2: To adapt the PMSs-MEPDG integration for networks with scarce data and to verify the degree of their efficiency in a long-term budget-constrained scenario of rehabilitation plans.

Objective 3: To estimate the performance and compare the cost-effectiveness of IRI-triggered versus Rutting-triggered maintenance strategies informed by calibrated MEPDG outputs.

2 Literature Review

2.1 Pavement and Its Importance in the Transportation System

Pavement is a crucial component of the transportation infrastructure, serving as the main surface for vehicular traffic. Asphalt pavements, especially, are critical due to their immediate impact on traffic safety and operational efficiency. Liang et al. (2024) point out that asphalt pavements are exposed to repetitive loads and environmental exposures, which inevitably cause surface defects such as cracks and potholes and thus can compromise both safety and efficiency. Deterioration of pavement surface not only impacts the structural integrity of roads but also poses risk to vehicular safety (Chan et al., 2010).

The pavement surface condition is inextricably connected with road safety. In a study by (Alhasan et al., 2018), there are noticeable factors, including pavement roughness and friction, that dictate the likelihood of accidents. Based on their research, the pavement conditions should be kept in a good state to curtail accident occurrences. Likewise, (Chan et al., 2010) examined the relationship between pavement surface conditions and the occurrence of traffic accidents and thereby confirmed that deteriorated pavement quality may be a contributory cause of higher crash frequencies. PMS are important for assessing and maintaining pavement condition to provide safety and operational performance (Ragnoli et al., 2018).

Sustainability in pavement design and construction has been a subject of significant attention in recent years. The use of recycled materials in the construction of pavements is one of the most important ways to enhance sustainability. Zhao et al. (2021) analyzed the benefits of using recycled asphalt pavement materials, pointing out that these methods can reduce environmental effects and save natural resources. In addition, Anis & Abdel-Raheem (2024) investigated the prospects of applying electrically conductive cement concrete pavements for efficient snow removal and de-icing, a field of particular importance in cold climates. Such innovations not only alleviate environmental issues but also improve the operational efficiency of pavements under varying climatic conditions.

The recent technological developments have fundamentally transformed pavement condition assessment and maintenance. The combined application of ground-penetrating radar (GPR) with other non-destructive test methods has been noted by (Elseicy et al., 2022) to be an effective way of assessing pavement integrity. The technologies allow transport authorities to carry out detailed evaluations of pavement conditions, thus stimulating timely maintenance actions. Moreover, the utilization of unmanned aerial vehicles (UAVs) in pavement condition assessment has become a cost-effective method of identifying surface defects, including cracks and potholes (Pan et al., 2018; Romero-Chambi et al., 2020). Incorporation of these kinds of technologies into pavement management systems is improving the precision and efficiency of maintenance activities.

The quality of pavement is directly related to economic growth and development. The capacity of a transport system to facilitate efficient movement of goods and services depends on the quality of

their pavements. Effective maintenance actions are crucial in sustaining pavement conditions, therefore facilitating economic activities (Feitosa et al., 2024). The economic effects associated with pavement management vary from lower vehicle operating costs and enhanced travel efficiency, both being essential for overall productivity improvement (Ragnoli et al., 2018). Additionally, the interconnection between pavement condition and traffic dynamics implies the necessity of deliberate investment in pavement infrastructure to promote economic resilience.

The environmental consequences of pavement construction and maintenance are increasingly becoming a major concern. The use of life cycle assessment (LCA) approaches is increasingly being adopted to evaluate the environmental footprint of different pavement materials and practices. Koh et al. (2024) pointed out that LCA can help policymakers determine more sustainable approaches to pavement management by measuring the environmental costs associated with different materials and construction methods. Also, permeable pavement has been suggested as a way to mitigate stormwater runoff and improve water quality, as explained by Ndon (2017). Such methods are part of larger sustainability objectives in urban planning and infrastructure development.

In summary, pavement is a key component of the transportation infrastructure that influences safety, sustainability, economic efficiency, and environmental effects. Continued advances in research and technology in the areas of pavement assessment and administration highlight the desirability for a comprehensive procedure to pavement system design and care. By stressing sustainable solutions as well as through the application of advanced technologies, transportation departments can improve the usefulness and lifespan of pavement systems towards the end goal of more efficient and safer transport systems.

2.2 Pavement Design

Pavement design is a complex field that integrates numerous engineering fundamentals, material science, climatic conditions, and sustainability strategies. With the increasing urbanization, demands for pavement systems that are efficient, long-lasting, and sustainable have grown manifold. This literature review integrates recent research outcomes related to pavement design, addressing challenges in areas of material selection, structural design, environmental factors, and emerging technologies.

In the last 100 years, design of flexible pavements has gone through a major change. It has moved from empirical practices to performance-based frameworks. This change has already been positively contributed by a number of technologies that have greatly improved the accuracy, reliability, and applicability of pavement design methods around the globe.

One of the initial fundamental methods was the California Bearing Ratio (CBR), invented by Porter (1938). The CBR test was an easy empirical way to determine subgrade strength by measurement of soil penetration resistance against a standard crushed stone which thus, enabled to produce an index value that was used for the decision of pavement thickness. Its ease and low

cost made it generally accepted, especially in early military airfield work and in underdeveloped regions where information was scarce.

Through this empirical approach, pavement design was substantially improved in the 1950s and 1960s as a result of the AASHO Road Test carried out in Illinois from 1958 to 1960. The idea of present serviceability index (PSI) was first introduced in this experiment, which correlated road traffic to pavement deterioration via utilization of quantitative indicators such as present serviceability index (PSI) and moreover, it gave birth to the concept of equivalent single axle loads (ESALs). The obtained empirical equation published by the Highway Research Board in 1962 allowed usage of traffic loads in pavement thickness calculation (Highway Research Board, 1962).

These empirical approaches were effective in the industry for several years; however, the advent of mechanistic principles signified a major change. The Shell 1963 Pavement Design Manual was the first to utilize layered elastic theory for flexible pavement structures. This technique permitted the computation of tensile and compressive strains in pavement layers, and thus, engineers were able to create designs that were resistant to fatigue cracking and rutting by using the analytical stress-strain model. The Shell method not only set the critical strain limits but also introduced the mechanistic-empirical idea, which turned out to be the main approach in later years (Shell International Petroleum Company, 1963).

Simultaneously, the time was marked by attempts to fit pavement design methods to the wide variety of conditions found all over the globe. The UK's Transport Research Laboratory (TRL) put out version 2 of Road Note 31, a manual for the empirical design of roads for tropical and subtropical areas in 1977. The present conference is based on field studies and international collaborations mentioned in a document that provides catalog-based structural designs that are able to reflect the availability of regional materials, climate, and traffic conditions. It is being widely accepted by the countries with the low and middle income as a signal of its most practical and global usage (Transport and Road Research Laboratory (TRRL), 1977).

During the 1980s, the World Bank's Highway Design and Maintenance Standards Model (HDM-III) journeyed further still. HDM-III is not a direct design method; however, it has brought along the idea of incorporating the prediction of pavement performance and the analysis of life-cycle cost into the design process. This instrument, by estimating the deterioration and the road user's cost, allows agencies, especially those in developing countries, to administer the evaluation of design and maintenance strategies in an economic way for a certain period of time (Watanatada et al., 1987).

Utilizing the global progress, Australia and New Zealand became the first to adopt mechanistic-empirical design in the national practice in 1992 through the Austroads Guide to the Structural Design of Road Pavements which is a multilayer elastic analysis-based guide. The guide relied on the use of multilayer elastic analysis and also introduced strain-based failure criteria that were locally calibrated. The method combined theoretical rigor with field calibration and was a major regional commitment to performance-oriented design (Austroads, 1992).

While there was an increasing interest in analytical design, the empirical method was still developing. The AASHTO Guide for Design of Pavement Structures of 1993 is a revised version of the original AASHTO Road Test framework which incorporates reliability-based design, updated material properties, and improved traffic characterization. Although the guide remains essentially empirical, it has however introduced probabilistic thinking and emphasized design variability, and it is now a standard reference in many jurisdictions worldwide (AASHTO, 1993).

The National Cooperative Highway Research Program published the Mechanistic-Empirical Pavement Design Guide (MEPDG) in 2004 which marks the peak of decades of research and efforts in practice. MEPDG was a history breaker in that it basically merged mechanistic response modeling with empirically calibrated performance models. It took into consideration the specific inputs of the local area such as climate, traffic spectra, and detailed material properties to simulate pavement behavior and forecast distresses like fatigue cracking and rutting over time. This guide was instrumental in helping the agencies to look into the long-term pavement performance and to come up with structural design that was optimal with great accuracy (NCHRP, 2004).

Collectively, these innovations outline a definite path in the design of flexible pavement—from the initial empirical indices such as CBR, through the data-intensive AASHTO experiments, the adoption of layered elastic theory, up to the recent mechanistic-empirical frameworks. Each step has been an improvement over the previous one, as it has incorporated new technologies and performance data, which has led to a more reliable, cost-effective and adaptable design process for the pavement in the world.

Pavement design is simply meant to create a road surface that will be resilient to traffic loading while providing smooth and safe driving conditions. Design is typically employed to determine appropriate materials, layer thickness, and environmental impacts on pavement life. Elshahly et al. (2023) states that one of the fundamental goals of pavement design is to make the pavement structure able to withstand expected traffic loads during its defined life cycle while minimizing distress and maintenance requirements. This needs proper understanding of mechanical properties of pavements materials, such as strength, stiffness, and durability under different environmental conditions.

Selection of materials is a very important aspect of pavement design as it directly affects pavement performance and sustainability. Conventional materials like asphalt and concrete are usually utilized, but increasing focus is being given to the utilization of recycled and substitute materials in a bid to promote sustainability. For example, Zhao et al. (2021) noted the need to use recycled asphalt pavement (RAP) materials, which besides saving the use of new materials also saves the greenhouse gas emissions related to pavement construction. Additionally, the use of geopolymers in pavement design has been proposed as an eco-friendly alternative that enhances durability while reducing the carbon footprint of pavement construction (Ikotun et al., 2024).

Recent technological advancements have significantly influenced the techniques used in pavement design. The use of machine learning and artificial intelligence techniques has emerged as an

effective means to enhance pavement design and maintenance. For instance, the use of artificial neural networks (ANNs) in the analysis of flexible pavement layer thickness has exhibited encouraging performance in enhanced design precision (Elsahly et al., 2023). Additionally, the creation of decision-support tools integrating sustainability features into pavement design has been identified, enabling the consideration of environmental effects for varying design scenarios by engineers (Subedi et al., 2018).

Sustainability is an important keyword in contemporary pavement design, echoing the increasing recognition of environmental problems related to road construction and maintenance. Styer et al. (2024) pointed out that an effective sustainable pavement design ought to take into account the whole life cycle of the pavement, from material extraction through end-of-life disposal. This integrated approach includes the application of life cycle assessment (LCA) techniques to analyze the environmental effects associated with different pavement materials and design alternatives. The use of permeable pavements, for example, has been known to be effective in managing stormwater runoff while improving groundwater recharge (J. D. Lin et al., 2013).

Design of the pavement structure involves finding suitable material layer thicknesses and compositions that are able to resist vehicular traffic stresses and environmental influences. Mechanistic-empirical design has become more popular since it is possible to integrate various factors that influence pavement performance, for example, traffic loading, material characteristics, and environmental factors (Wasanta et al., 2024a). This approach enables pavement performance predictions to be made more precisely under real conditions, hence resulting in better design effectiveness.

Pavement system performance evaluation is necessary to facilitate their sustainability and operational efficiency. Several performance indicators, including roughness, rutting, and cracking, are monitored to assess pavement condition over time. Louhghalam et al. (2015) discussed the need for pavement-vehicle interaction knowledge, which can affect fuel usage and overall pavement performance. Recurring maintenance strategies, as indicated by performance assessment, are essential for maximizing pavements' lives and reducing overall life cycle costs (Giustozzi et al., 2012).

The effect of climate change on pavement design is a new field of research. With an increase in extreme weather events, pavements are required to be designed with the capacity to resist more stresses and strains due to temperature changes, and loss of structural integrity due to water seepage through intense rainfall; drainage systems that are more resilient must also be integrated. Achebe et al. (2021) highlighted the requirement to include flood risks in pavement sustainability assessment, thus ensuring that designs have resilience in the wake of changing climatic conditions. This includes the consideration of material use and design approaches enhancing pavement's capacity to adapt to climate-caused environmental stressors.

Economic considerations strongly influence the choice in pavement design. Life cycle cost analysis (LCCA) method is often applied to determine the cost-effectiveness of various pavement

design choices throughout their anticipated life. A comparison has been conducted between perpetual flexible pavements and conventional rigid pavements on the basis of economic and environmental expenditure, citing the possibility of long-term savings by utilizing more durable design solutions (Kumar & Sharma, 2022). This economic perspective is crucial for resource allocators to plan for pavement construction and maintenance.

As the field of pavement design continues to evolve, future studies will likely focus on integrating innovative materials, new technologies, and environmentally friendly approaches. The study of new materials, including recycled plastics and alternatives to asphalt cement, offers hope for improving the performance of pavement while, in the process, minimizing environmental effects (Mashaan & Ouano, 2024). Furthermore, the creation of smart pavement that integrates sensors and data analytics for real-time monitoring and upkeep is an existing field of study in pavement design (Fameso et al., 2024).

In conclusion, pavement design is a multidisciplinary and dynamic field that encompasses numerous parameters like the selection of materials, structural integrity, sustainability, and financial viability. The integration of advanced technology and sustainable practices is of extreme importance for the design of durable pavement systems that meet the demands of modern transportation infrastructure. As research continues to advance, the focus on creating environmentally friendly and durable pavements will have a profound effect on the future of transportation systems.

2.3 Mechanistic-Empirical Pavement Design Guide

The Mechanistic-Empirical Pavement Design Guide (MEPDG) is an advancement of the approach to pavement design by incorporating mechanistic theory and empirical data to improve the accuracy and reliability of pavement performance predictions. This chapter brings together a compilation of research and findings that pertain to the MEPDG, including its development, implementation, calibration, and application in practice.

MEPDG was conceived to overcome the limitations of the conventional empirical design approaches, which tend to be based on past data and are not necessarily sufficient to deal with the sophistication of current traffic flows and climatic conditions. According to Q. Li et al. (2011), the MEPDG includes mechanistic principles that enable the comprehension of pavement material behavior under different stresses and strains, thus resulting in enhanced design results. This guide makes use of a combination of theoretical frameworks and field data to forecast the performance of pavement subjected to particular conditions, rendering it an invaluable resource for engineers.

The MEPDG was developed under the National Cooperative Highway Research Program (NCHRP) Project 1-37A with the aim of developing a more consistent and scientifically based pavement design method. Ceylan et al. (2009) indicated that the guide has been revised multiple times, with research continuing to refine its frameworks and expand its applicability to various types of pavements and local climatic conditions. Guide development is a move towards an

empirical practice in pavement engineering with enhanced focus on localized calibration and validation of design parameters.

Calibration is one of the most important steps in using the MEPDG since this ensures that performance models reflect local conditions. Research, for instance that of Wu et al. (2013) has shown that the use of condition survey data in calibrating the MEPDG for particular regions significantly increases its predictive capability. Local calibration involves the adjustment of empirical models within the MEPDG to account for local traffic, material properties, and environmental conditions to improve the performance prediction accuracy.

The MEPDG employs a number of performance prediction models to analyze potential pavement distresses like fatigue cracking, rutting, and thermal cracking. The models are mechanistic-based and consider the material properties and loading conditions. As an example, Hu et al. (2017) highlight the importance of axle load spectra for pavement performance prediction, noting that good quality traffic data are crucial for distress predictions that can be trusted. The integration of the models allows for an extensive examination of the influence of various design inputs on the durability of the pavement.

The MEPDG has been implemented over various geographical locations, demonstrating its flexibility to accommodate various climatic and traffic conditions. The use of the MEPDG in Saudi Arabia has been found to be promising in terms of predicting pavement performance for local conditions, according to Fuhaid et al. (2022). Likewise, research in Iowa has been directed towards the regional calibration of the MEPDG for its improved application in the region, solving particular problems concerning traffic loading and environmental conditions (Kim et al., 2014).

Sensitivity analysis is a key component of the MEPDG so that engineers can see how variations in design inputs affect pavement performance. It was demonstrated in a research study by Schwartz et al. (2013) that some parameters like material properties and traffic conditions have a large impact on the outcomes of expected performance. By recognizing these impactful inputs, engineers will be able to focus data collection and calibration, which will eventually result in more efficient pavement designs.

As climate change increasingly affects infrastructure, the MEPDG has been updated to include climate considerations in pavement design. Guest et al. (2020) emphasize the necessity of including climate change in life cycle analysis of pavement performance, with the requirement for design methodologies that can adapt to evolving environmental conditions. The MEPDG's flexibility makes it possible to implement climate data, thus enhancing the development of more resilient pavement designs capable of resisting future climatic stresses.

The MEPDG's flexibility makes it possible to implement climate data, thus enhancing the development of more resilient pavement designs capable of resisting future climatic stresses. MEPDG stands out due to its cutting-edge prediction of mechanical performance and its extensive integration of environmental factors. Recent research has highlighted the necessity of

environmental resilience in contemporary pavement engineering, given that climatic conditions influence the performance of pavement systems. In line with this, the MEPDG methodically integrates a variety of environmental factors influencing the performance of pavement structures and materials throughout their service life cycles.

A significant environmental input included in the MEPDG is temperature. The model considers both the daily and seasonal variations in temperature parameters that are required for estimating the thermal behavior of different asphalt mixtures and pavement structures. Si et al. (2023) averred that thermo-hydro-mechanical coupling simulations form a foundation for predicting pavement response to temperature changes and thus clarifying the difference between transient (daily) and cumulative (seasonal) thermal stresses. Temperature variation affects material properties, like viscosity, rigidity, as well as fatigue resistance, allowing designers to modify mix designs and structure configurations with the aim of providing durability based on dominant thermal conditions (Q. Li et al., 2011).

Moisture sensitivity is another critical component included in the MEPDG system. The manual contains procedures for assessing damage caused by moisture, prioritizing delamination potential in asphalt layers and loss of support from subgrade materials through saturation. Gaspard et al. (2019) highlighted that the model considers the natural vulnerability of pavement materials by quantifying the effects of moisture on subgrade soils' thermal conductivity and resilient modulus. This functionality is critical to forecasting possible deterioration and assessing remedial actions, especially in areas where precipitation and groundwater conditions vary considerably.

The MEPDG is unique in incorporating climate-induced freeze-thaw cycles to mitigate their harmful influence on pavement performance in freezing climates. Experiments by Ma et al. (2015) have improved low-temperature cracking models that reasonably simulate the oscillatory expansion and contraction of pavement material due to freeze-thaw effects. These oscillating mechanisms exacerbate different forms of distress like thermal cracking and fatigue, and their incorporation in the MEPDG allows better prediction of pavement longevity in locations subject to such extreme climatic conditions.

Additionally, MEPDG considers drainage features and precipitation regimes in examining how water distributes itself within and through pavement structures. By using climate-specific inputs from long-term climate data, the guide enables the prediction of water accumulation and infiltration rates, which have great impacts on the drainage adequacy and long-term stability of pavement systems. These inputs are used to predict conditions under which poor drainage would cause water to collect at interfaces of pavement layers or in the subgrade, thereby expediting distress mechanisms (Johanneck & Khazanovich, 2010) .

In all, through the synthesis of daily and seasonal temperature gradients, moisture susceptibility, freeze-thaw activity, and rainfall intensity, the MEPDG incorporates an integrated, climatically sensitive method of pavement design. This integrated framework not only improves the predictive accuracy of distress but also facilitates life-cycle analysis with environmental foot printing,

informing sustainable design solutions and adaptive maintenance protocols. The mention of these environmental factors highlights the necessity to enhance resilience to climate-driven degradation to enable pavement structures to continue being durable, economically viable, and sustainable throughout long service lives (Gaspard et al., 2019; Johanneck & Khazanovich, 2010; Ma et al., 2015; Si et al., 2023; Wasanta et al., 2024).

Several recent Literature highlight significant improvements in MEPDG and compare its benefits against the traditional empirical methods such as the AASHTO 1993. The MEPDG's mechanistic basis and climate-informed models allow for more precise performance predictions, thus providing a solution to the drawbacks of purely empirical designs that were calibrated to limited conditions decades ago. As an example, a recent study that had been done in Laos reined that the MEPDG was applied to flexible pavements and it showed that it is better than the old method because it takes into account local factors such as traffic and climate of the tropical zone. The authors of the paper confirmed that the hot climate in the southern areas was the main reason for the rutting damage that was by far the most severe while the use of hard or polymer-modified binders resulted in the improvement of the service life of the pavement. The research thus promotes MEPDG in Laos, stating that the data-driven (including traffic, material, and climate inputs) approach results in designs that are more durable and cost-effective than those of the current empirical practices (Khamkhanpom et al., 2025). Mursaleen et al. (2025) confirmed that climate changes in different regions continue to influence pavement distresses, while the situation with transverse cracking can change in the range of ~10–40% if temperature and precipitation are altering. They emphasized the necessity of climate-responsive design by such means as making the concrete slab thickness optimal for each climate zone to ensure that the cracking remains within the limits. The results of the research support the use of MEPDG (via Pavement ME Design software) in Pakistan to guarantee sustainable roads under various environmental conditions. Indeed, the assessments of different studies indicate that MEPDG is able to identify failure risks in designs that are still considered satisfactory by empirical methods. Hatoum et al. (2024) have displayed that flexible pavement that were originally designed with AASHTO 1993 (assuming that serviceability criteria are the same everywhere) may have widely different performance after the MEPDG analysis, since the latter factors like overloading and climate inconsistencies that the empirical method does not take into account. To support this, the MEPDG has predicted that the empirically designed road sections would become distressed beyond the permitted limit (e.g., rutting or cracking) before the given service life is finished under heavier traffic and warmer climates in many cases. These comparisons prove yet again that the mechanistic-empirical approach is a more robust and trustworthy basis of contemporary pavement design than the old empirical equations.

Other current advancements are related to the introduction of innovative materials and better models that are a part of the MEPDG framework. Researchers are pushing the limits of MEPDG to study how advanced asphalt rubbers, like the one mixed with plastic, affect both performance and sustainability. Farina et al. (2024) combined laboratory-calibrated MEPDG runs of life-cycle assessment to investigate stone roads made with CR-modified asphalt mixtures. The findings of

this study showed that the ability of CR-modified mixtures to be properly designed can reach the same or even better long-term performance than traditional mixtures, thereby facilitating a reduction in the number of rehabilitations needed throughout the 50 years of the lifespan. This goes hand in hand with the large environmental gains it allows for – for instance, using MEPDG-governed performance improvements of CR asphalt can lower life-cycle greenhouse gas emissions about 36–55% compared to traditional pavements. This kind of work is evidence of MEPDG potential to evaluate the structural contribution of new materials and it is in line with the use of sustainable materials without detriment to the pavement lifetime. The same paper, however, identified that the MEPDG's thermal cracking parts were not reliable in some climates (all mixtures in hot or cold regions went beyond the cracking threshold very early), therefore it is suggested that careful local calibration of distress models (especially for thermal cracking) is necessary to improve the accuracy. To conclude, the integration of material innovations into MEPDG together with an environmental impact survey is a new milestone in pavement engineering, that ensures the performance and the sustainability are both taken into consideration.

There is also a strong focus on improving MEPDG by local calibrating and using sophisticated modeling techniques. For example, some of these inputs are based on unsaturated soil mechanics which may affect pavement design. Omenogor et al. (2025) studied how moisture (matric suction) affects subgrade resilient modulus (MR) and came up with empirical correlations to calculate MR from simple CBR tests under different suction conditions. These correlations allow MEPDG to better adapt the design seasonality of support strength by reflecting the loss of stiffness, as soils become wetter. They nevertheless shared those relationships such as these are very soil-specific and thus, more testing and calibration will be required before applying them to different areas. Singh et al. (2025) also expressed the need to adapt MEPDG models to local conditions. They devised a sensitivity-based method which shows which performance transfer function coefficients should be prioritized for calibration if it is impossible to calibrate all of them simultaneously. They calculated scaled sensitivity coefficients in order to find the most influential parameters for flexible and rigid pavements. With this approach they targeted calibration to those parameters which influence flexible and rigid pavement performance the most, such as, fatigue and rutting coefficients. Consequently, extensive calibration can be narrowed down thus allowing maximum accuracy to be achieved with limited calibration resources. On the other hand, regional calibration efforts at full scale are validating MEPDG for new places. The mechanistic-empirical design guide “Medina” is one such example. It was recently developed in Brazil as an alternative to the old 1960s CBR-based design method. Fritzen et al. (2025) updated Medina’s fatigue cracking transfer function based on 45 test sections of Brazil and tested its performance with 15 additional field and accelerated heavy vehicle simulator sets. The calibrated model got along very well with the observations. This achievement highlights the significance of extensive local field monitoring for mechanistic-empirical model development. However, the authors of the study point out that further extending the calibration database and accounting for other factors like binder properties, climate, and traffic speed will definitely help the model to be even more precise. Generally speaking, the worldwide trend reveals that there is a pushing towards the acceptance and enhancement of

MEPDG through regional calibration by climate/material improvements as well as the side-by-side comparison with legacy methods – resulting in a pavement design methodology that is more accurate, adaptable and sensitive to both engineering performance and sustainability.

In spite of its benefits, the implementation of MEPDG is faced with numerous challenges such as the need for comprehensive data collection and calibration programs. Appropriate input parameters that represent local materials and environmental conditions need to be chosen to make the MEPDG effective (Sadek et al., 2014). Moreover, the changeover from conventional empirical procedures to a mechanistic-empirical approach needs extensive training and adjustment within the transportation agencies.

Future studies on the MEPDG will involve strengthening its models, in addition to expanding its use to new pavement types and materials. Studies on recycled materials point to the possibility of incorporating sustainable measures into the MEPDG model (Noureldin & Abdelrahman, 2014). Additionally, continued work on enhancing calibration methods and enhancing data collection techniques will be important in further developing the MEPDG.

The MEPDG is a major development in pavement design procedures through the integration of mechanistic principles and empirical data. Yet, the performance of the MEPDG is inevitably conditioned to calibration to local conditions, where adaptation of the performance prediction models is needed to properly reflect the unique materials, traffic loads, and environmental conditions of a specific location. This literature review synthesizes research on the MEPDG calibration process, covering methodologies, past calibration attempts, and their ensued impacts.

2.4 Mechanistic-Empirical Pavement Design Guide Models Calibration

The MEPDG is an enhanced approach in pavement design methods through the application of mechanistic concepts combined with empirical data. The strength of the MEPDG, however, depends greatly on its calibration to local conditions, as it entails modifying the performance prediction models according to the local materials, traffic, and environmental conditions. The following literature review consolidates work on the process of calibrating the MEPDG, including methodologies, past calibration activities, and the results.

Calibration of the MEPDG entails model parameter curve-fitting into an interval where the predicted performance from the model aligns very well with actual pavement performance data. Calibration at the local scale needs to be implemented because it captures local variations in the properties of the material, traffic loading, and climate conditions that exert important influences on pavement performance (Dong et al., 2020). Calibration entails acquiring local data, analysis of performance indicators, and model parameter adjustment through statistical analyses.

Several methods have been suggested for the calibration of the MEPDG. One such method is the application of historical pavement performance data in informing model parameter adjustments. For example, calibration can be done through sensitivity analyses, which determine the most significant design inputs affecting pavement performance. SHAKHAN et al. (2022) underscored

the need for the application of sensitivity analyses in assessing the impact of changes in input parameters towards predicted responses, hence informing the process of calibration.

The second approach uses advanced statistical methods, including machine learning algorithms and regression analysis, in order to improve calibration parameters. Jadoun & Kim (2012), for instance, implemented a genetic algorithm in order to improve the calibration parameters of the MEPDG in the North Carolina flexible pavements, showcasing the ability of computational methods in enhancing model parameters.

There have been many studies reporting local calibrations for the MEPDG in different locations. For example, K. Hall et al. (2011) calibrated the flexible pavement models in Arkansas. Their work emphasized the need for local calibration because the national and local conditions may vary greatly, causing inferences in the predictions for performance. In the same manner, Kim et al. (2014) studied the calibration of the MEPDG performance models for the pavement systems in Iowa, pointing out the value of local data in enhancing the prediction accuracy.

Ma et al. (2015) calibrated the MEPDG low-temperature cracking model for seasonal frozen areas in Canada, emphasizing the need for the adaptation of the guide in respect of local climatic conditions. Their research reaffirmed the need for the consideration of local environmental conditions in predicting pavement performance.

Local conditions such as traffic patterns, climate, and local properties need to be accounted for in the calibration process of the MEPDG. For example, Fuhaid et al. (2022) presented the successful implementation of the MEPDG in Saudi Arabia, where local calibration was essential for the proper prediction of pavement performance based on local traffic loads and climatic conditions. The presented work demonstrates the ability of local calibration in improving the reliability of the MEPDG in varied environments.

Furthermore, calibration in Ontario has been aimed at modifying the MEPDG rutting models in local Superpave pavements. Gautam (2015) showed that the process greatly enhanced the accuracy in predicting rutting, with local data being proven efficient in updating the MEPDG models.

Albeit the broadening methodologies in calibration, there still exist many challenges. One such significant challenge is the access to high-quality local data, which is necessary for sound calibration. The consistency in the data used in pavement operations can make it difficult to calibrate, and it may require the application of solid data analysis and collection methods (de Salles & Khazanovich, 2021). Complexity in the MEPDG models may result in challenges in the determination of proper calibration parameters.

One such challenge is the need for perpetual updating of the calibration with new technology and materials. There is the need for ongoing research into how the MEPDG can be adjusted for new pavement practices and materials (Beng, 2017). This calls for its approach in calibration to be dynamic in nature, including new findings and methodologies.

Several case studies have given insight into the calibration process for the MEPDG. For instance, the G. E. Jannat (2023) paper centered on the local calibration database for distress models in the province of Ontario, touting the value in regional information having the potential to enhance the predictive ability of the MEPDG. Correspondingly, the efforts of Nantung et al. (2018) illustrated the efficiency in the application of local calibration in enhancing the accuracy in the pavement thickness design for Indiana, evident in the practical application in customized calibration activities.

At a wider level, Ceylan et al. (2009) work analyzed the implementation of the MEPDG in Iowa, determining the important design inputs that need calibration for the prediction of performance. Their work forms part of an increasing body of literature that emphasizes the need for local calibration for successful pavement design.

Future work on MEPDG calibration is expected to feature new, state-of-the-art technologies such as artificial intelligence and big data analysis. However, a lot of research gaps still remain in the applications of these technologies. Machine learning algorithms can potentially help in generating calibration parameters from large datasets, and some studies show the R-squared value of the models related to rutting prediction to be at 0.92 (Wang et al., 2021; Xu et al., 2022). However, these methods do not appear to be systematically integrated with real-time data streams of pavement performance to be able to provide more accurate results at the project specific level.

It is important to understand that currently, the Pavement Management Systems (PMSs) make investment decisions based on indirect damage indicators, i.e., the International Roughness Index (IRI) rather than direct structural damage measures such as rutting and cracking derived from the MEPDG, which must be well-calibrated to increase prediction accuracy so that an effective PMS implementation can be achieved (Al-Omari & Darter, 1995; Leben, 2002). MEPDG AI resources are mostly focused on the detailed examination of the historic data of the MEPDG calibration rather than creating predictive systems that can dynamically modify the calibration parameters due to new performance trends and material property changes.

The issue of how to ensure the consistency and reliability of pavement design when using different machine learning models, which can be regionalized to local conditions while at the same time maintaining the transferability of the model and avoiding overfitting, is at the heart of the problem of standardised calibration across different areas. These concerns are still unresolved by present research. Besides this, as the effects of climate change on infrastructure continue, future calibration measures must go beyond what has been done so far and really bring climate resilience into the MEPDG framework (Barbeau et al., 2020). Guest et al. (2020) already recognize the inclusion of climate data in the calibration process as a necessity if the performance cycle of the pavement system is to be lengthened. Nevertheless, how AI-powered predictive models can be so methodical to allow for the joining of projected climate variables such as temperature, precipitation, and extreme weather events with the traditional calibration parameters to form climate-adaptive, robust pavement design frameworks that account for both present and future climate conditions as well

as the move from indirect performance indicators to direct structural damage assessments for more accurate pavement management decisions remains an area with limited research.

MEPDG calibration is an important process that guarantees the validity and dependability of predictions for pavement performance. From many different methodologies and past research and analyses, it is clear that local calibration is necessary for the implementation of the MEPDG for particular regional conditions. With the passage of time, and in the ongoing advancement in the field, further analysis and technological development will be the decisive factor in defining the practices for calibration, ultimately leading toward enhanced effectiveness and sustainability in the design of pavement.

2.5 Pavement Management Systems

Pavement Management Systems (PMSs) are critical tools for the efficient upkeep and administration of road networks. They give an organized framework for evaluating pavement conditions, forecasting future performance, and planning rehabilitation and maintenance activities. This review brings together multiple elements of PMSs, including their components, widely accepted indicators, methodologies, and outcomes from existing work.

The concept of pavement management was initially introduced in the early 1970s largely due to the new systems approach that brought together the principles of engineering, economics, and decision making for the design and maintenance of pavements. Hudson et al. (1970) from the Texas Transportation Institute were one of the first persons to use systems analysis for flexible pavement design, thus, marking one of the earliest formal descriptions of pavement management as a process.

By the late 1970s, pavement management had become a part of the literature and frameworks were laid down in North America. For instance, Road and Transportation Association of Canada (1977) proposed a network-level management system for the Canadian Good Roads Association, while presented a pavement management approach for highways. These initial steps were very important as they enabled more comprehensive developments to occur in the 1970s.

Pavement management concepts were solidified as official guidelines and textbooks during the 1970s. Road and Transportation Association of Canada (1977) was the first to publish a Pavement Management Guide, which was the first of the manuals to summarize the knowledge and systematic practices available for the management of pavements. This was followed by the first textbook on the subject, Pavement Management Systems, written by Haas & Hudson (1978). This book brought together pavement design, construction, maintenance, and evaluation under a systems methodology framework.

These publications not only consolidated best practices of the time but also reported on some of the first real-world PMSs implementation projects. By the end of the 1970s, the foundational concepts - including the idea of managing pavement networks with coordinated planning and

optimization - were established, setting a baseline for future technological and managerial innovations in the field.

The 1980s was definitely a period for bright ideas and dynamic changes in pavement management all over the world. As computing technology grew, transportation agencies and researchers came up with tools to measure pavement condition and forecast deterioration. A major contribution was the creation of the PAVER system by Shahin & Kohn (1982) which laid down the Pavement Condition Index (PCI) as a uniform, 0–100 numerical scale for describing pavement condition. The PCI, derived from the distress extent surveys, gave engineers' visual inspections an objective format - 100 standing for perfect pavement and lesser numbers indicating different stages of breakdown.

One of the most important developments at the same time was the multiplication of the analytical powers of PMSs through global modeling projects. The World Bank's team led by Watanatada et al. (1987) published the Highway Design and Maintenance Model (HDM-III), a detailed model for pavement performance and life-cycle economic analysis. HDM-III could depict the road surface under traffic and the influence of the environment and calculate the effect of diverse maintenance methods on the agency and road user costs in the future. This novelty was big in that it gave a concrete, finance-based scheme for pavement management decisions especially in developing countries and global applications. The HDM-III model (and its successors) was used extensively and still shapes many national PMS tools and investment models.

Throughout the 1990s, the discipline of pavement management took a great step toward becoming a standard practice for transportation agencies as most agencies began to focus on refining more of the technical and managerial aspects of PMSs. Agencies across the world invested in better data (e.g., automated condition imaging, GIS-based inventories) and undertook several experiments with network-level optimization and predictive modeling to improve budget allocation decisions. The advent of the millennium witnessed the transportation departments having PMS experience spanning several decades and the field moving towards greater institutional integration.

AASHTO (2001) was a remarkable step in outlining best practices in pavement management. In the year 2001, the American Association of State Highway and Transportation Officials (AASHTO) published the 1st edition of a 30-year comprehensive reference for agencies establishing or improving a PMSs. The book consisted of standard definitions, procedures of data collection and analysis, and guidance of PMSs implementation both at the project and network levels.

The new decade began with a heavier focus on performance management. Organizations found formal procedures to set goals for performance targets in pavement condition (ride quality, distress indices, etc.) and use PMSs outputs to back their performance-based budgeting. This movement gained momentum when the Intermodal Surface Transportation Efficiency Act of 1991, enacted in the early 2010s, compelled states to adopt performance measures for pavements (U.S. Congress, 1991). The Pavement Management Guide produced by AASHTO (2012) was the concrete release

of these big ideas that they think will be the next frontier for pavement management. That revision covered the new decade's priorities including: an emphasis on pavement preservation strategies, data quality and integration improvement, and performance measurement and asset management principles incorporation into pavement management. In a nutshell, it was clear to all interested parties in 2012 that good pavement management is not simply about engineering distress models any more but also about managing assets effectively and showing accountability through performance metrics. The amalgamation of traditional PMS and asset management as well as performance-based planning during this era was the starting point for global standards and practices later on.

The 2010s were the formal period of the globalization of asset management concepts, which have greatly affected pavement management systems. The ISO 55000 series was launched in 2014 and has, for the first time, set an international standard for asset management, outlining a framework for infrastructure asset management in a more systematic and value-driven way (ISO, 2014).

The release of ISO 55000 (2014) – based on previous specifications such as PAS 55 – has boosted the extent of *comprehensive asset management approaches* being implemented in the highway sector. Road agencies all around the world started to merge their pavement management programs with broader Asset Management Systems in order to make sure that pavements get managed with the same thoroughness and strategic consistency as the other assets (bridges, facilities, etc.). This integration implied that PMSs data and analyses would become the source of agency-wide investment decisions, risk management, and long-term planning, in line with the ISO 55000 principles of cost, risk, and performance balance throughout the asset lifecycle.

In fact, lots of transportation agencies have come up with Transportation Asset Management Plans that not only include the pavement condition targets and maintenance strategies but also incorporate other assets, following the ISO 55000 focus on cross-asset optimization and executive-level accountability for asset value.

At the same time, pavement management has kept on taking advantage of technological innovations. The new decade offered new instruments for data gathering (high-speed laser scanners, drones), large data analytics, and the starting of artificial intelligence (AI) and machine learning for the task of monitoring pavement and predicting it. The AI-driven image processing can relieve extensively labor-intensive manual tasks in the detection of pavement distresses and, furthermore, machine-learning models are capable of predicting pavement degradation with much higher accuracy.

Along with these developments, the U.S. Department of Transportation, via the Federal Highway Administration (FHWA), updated its Pavement Management Roadmap in 2022 to set the direction for the next generation of PMS (Pavement Management Systems) innovations. The FHWA (2022) is a forward-looking plan that focuses on current and forward-thinking practices, which is intended to assist agencies in maximizing the benefits of pavement management and continuously improving their processes in the coming years without losing sight of the overall picture. Further,

it stresses the significance of automated advanced analytics (e.g., AI-powered decision support) to complement traditional engineering methods in PMSs pursuits.

To sum up, the metamorphosis of Pavement Management Systems from the 1970s to now depicts a path of upsurge in complexity and integration. In terms of technology, the domain has evolved from rudimentary condition evaluations and empirical models to comprehensive indices such as PCI, global models (HDM) and now the data-driven, AI-fueled analytics. Looking at a management strategy angle, the concentration has deepened from project-level engineering choices to network-level optimization, and eventually to asset management and performance management at the organizational level. These global advances – both technical and managerial – have turned modern PMS into a crucial part of infrastructure stewardship, giving agencies the ability to provide safer, more efficient, and cost-effective pavement networks based on both sound engineering data and strategic asset management principles.

Typical PMSs has various indispensable parts which when combined, facilitate effective decision-making. Firstly, data collection involves the gathering of information on road conditions, traffic volume, and environmental factors through such ways as visual surveys, automated sensors, and remote sensing technologies (Chun et al., 2021; Özdemir et al., 2020). Later, condition assessment converts the raw data into standardized indices such as the Pavement Condition Index (PCI), International Roughness Index (IRI), and Present Serviceability Index (PSI) which are the quantitative measures of road health and aid in maintenance activity prioritization (Karim et al., 2016).

On top of that, performance prediction models give the forecast of the road's performance in the future by using historical trends and current condition metrics; the results of artificial neural networks and regression method studies match the ground truth for distress progression thus they can be used as reliable tools for the future projections of condition (Ali & Milad, 2023; Kaya et al., 2020; Osman et al., 2023). Eventually, maintenance and rehabilitation planning are making use of these forecasts to choose the acceptable treatments and the time for intervention with the objective of extending the road's life and getting the best out of the budget (Gao & Zhang, 2008; Radwan et al., 2020).

The Pavement Condition Index (PCI) is a measure that is right at the top of the list of those mostly used in pavement management systems. It is basically a comprehensive numerical rating for pavement health by measuring the scope and the severity of the surface distresses noticed such as cracking, rutting, and potholes during very detailed inspections (Zafar et al., 2019). By using PCI, one can have a clear and uniform idea of how the pavement condition looks like across not only different segments of the network but also different countries. It thus forms the essence of maintenance activities scheduling and issue solving in the most efficient way in terms of resources used.

The International Roughness Index (IRI) is really the heart of getting along with the public part in this line of work which is done by measuring how big the longitudinal profile deviations of the

pavement surface are. Hence, lower IRI values denote smoother and more comfortable rides, and vice versa, so IRI is a major factor when user comfort is going to be assessed together with the smoothness-related maintenance plans (Wang et al., 2013).

Complementing these structural and comfort indicators, the Present Serviceability Index (PSI) comprises a set of key performance indicators from the point of view of the road user. To obtain the performance score, ride quality measurements and subjective user perceptions are the two major components that are integrated. However, despite their widespread use, PCI, IRI, and PSI only furnish indirect proxies of pavement health and, many times, fall short of representing the accurate structural condition of the pavement layers: PCI is a mix of different surface distresses that neglects essential aspects such as load-bearing capacity and sub-surface degradation; IRI does not detect small failures in the area like transverse cracking or the start of shallow rut that can turn very fast into the deep structural breakdown; and PSI is still a subjective gauge that only sees subsurface fatigue and moisture-induced damage mechanisms if they change the surface get affected by them. On the contrary, directly measuring rutting and cracking - if mechanistic-empirical models are engaged for calibration - allow one to pinpoint performance by layer and thus distress progression becomes feasible hence predicting remaining service life and planning maintenance in an accurate manner (Al-0mari & Darter, 1995; Leben et al., 2002).

One of the contemporary PMSs designs that intend to benefit from detailed structural insights, next to using traditional condition indices have, is the inclination to integrate various advanced methodologies. Suitable for handling, analyzing, and visualizing condition data of spatial pavement, Geographic Information System (GIS) became the basic tools, which, with the aid of overlaying distress information with the traffic and environmental layers, allow both macro-level network planning and micro-level intervention targeting (Zagvozda et al., 2019). Correspondingly, a wide range of tools, from a convolutional neural network to support vector machines, i.e. artificial intelligence and machine learning techniques, are reported to be increasingly used for the purpose of large, heterogeneous dataset intake (different kinds of sensor outputs, inspection images, and historical performance records) and the production of distress detection, classification, and performance prediction models with very high accuracy (Ali & Milad, 2023; Chung et al., 2024). In the end, among numerous performance prediction outcomes, thorough-life cost considerations alongside rigorous cost-effectiveness analysis frameworks help to set against the maintenance and rehabilitation alternatives, select projects under the limited budget, and allocate the resources in an approximately optimal manner for the maximum network benefit (Gao & Zhang, 2008a; Guha et al., 2022). Thus, these methodologies complement PMS functions by not only linking the spatial, but also the predictive and economic perspectives into a single, strategic pavement management system.

There have been many studies confirming the efficiency of PMSs in pavement network management. For example, in their analysis, G. Jannat & Tighe (2019) analyzed the rehabilitation and maintenance needs for Ontario highways in relation to traffic flows and types, and identified the need for a methodical approach in decision-making. H. Zhang et al. (2013) also constructed a

network level pavement asset management system incorporating life-cycle analysis, necessitating overall assessments for the sustainability of the pavement.

In another paper, Alhasan et al. (2018) analyzed the effect of pavement surface conditions on roadway departure crash risks, showing the manner in which PMS supports safety-based decisions. The combination of crash data with PMS data supports the handling of the pavement in a holistic manner, in terms of its performance and its safety issues.

Notwithstanding the benefit of PMSs, there are multiple challenges in its implementation. For instance, the availability of quality data is essential in ensuring accurate condition assessments and predictions in performance. Incomplete data may undermine the efficiency of PMSs and result in poor decision-making (Gao et al., 2022). Moreover, the complexity in the deterioration models for pavements and the requirement for recurring updates in response to new conditions remain challenges (Xu & Prozzi, 2023).

Amador-Jiménez & Mrawira (2009) vigorously confront a typical obstacle faced in pavement management: how to find reliable performance models with the minimum historical data. A Costa Rican case study published by them illustrates beyond doubt that only two years of network level condition data (IRI for surface roughness and FWD for structural capacity) are enough for them to calibrate an initial historical Markov Chain-based deterioration model.

The key methodological advances they have made include developing a locally weighted Pavement Condition Index (PCI) that takes into account structural adequacy (60% weight) and roughness (40%) to represent local priorities; applying an “apparent age” moving average technique to derive a rate of deterioration from a set of condition states when longitudinal data are unavailable; and obtaining recovery effectiveness directly from those segments that exhibit PCI improvement. Importantly, their optimization sample analysis shows that preventive methods - such as maintaining roads in good condition - both sustainably improve network-wide PCI (achieving values above 90 within 11–20 years) and are the most cost-effective, whereas “worst-first” approaches, even with higher budget allocations, merely accelerate pavement decay.

Such an effort gives the replicable GIS-integrated framework to agencies in data-scarce areas for starting evidence-based management though they still have to continuously gather data to improve transition probability matrices.

Future PMSs research will most probably revolve around improving the methods for collecting data, adopting advanced technology, and enhancing prediction models. Remote sensing and automated data collecting methods can simplify the process of assessment and yield real-time data on road conditions (Chun et al., 2021; Roberts et al., 2020). In addition, the incorporation of climate resilience into the PMS framework will be important, given the rising challenges for transportation agencies in dealing with climate change (Qiao et al., 2020).

The Pavement Management Systems perform an important function in the proper maintenance and control of the road network. Combining data collection, condition evaluation, performance

forecasting, and maintenance planning, PMSs help the highway agencies make well-informed decisions for improving the distribution of resources and the performance of the pavement. With the ongoing advance in the area of research, the incorporation of new methodology and technology will continue to enhance the efficiency and sustainability of the PMSs.

2.6 Integration of the Mechanistic-Empirical Pavement Design Guide (MEPDG) in Pavement Management Systems (PMSs)

The integration of the MEPDG into PMSs is an important development in pavement engineering. This review of the literature examines the state of existing research on this integration and discusses what has already been achieved and gaps in the literature identified so far as well as reports authoritative and extensive findings from existing research studies.

The MEPDG is a contemporary pavement design approach that integrates mechanistic concepts and empirical observations to forecast pavement performance under a myriad of conditions. It offers a framework for comprehending behavior of various materials and structural forms subjected to traffic loads and environmental aspects (Q. Li et al., 2011). Conversely, PMSs is a methodical approach employed by transportation agencies for efficiently managing pavement networks through data collection, condition evaluation, performance estimation (Alharbi & Smadi, 2019).

The application of MEPDG in PMSs will make possible the predictive insight of pavement management so as to make better-informed decisions on maintenance and rehabilitation planning. The MEPDG offers specific performance models that can be adopted in PMSs for enhancing the precision of forecasting pavement conditions, as indicated by J. Li et al. (2009).

Numerous studies have investigated the incorporation of MEPDG in PMSs through different aspects including data compatibility, performance prediction, and decision-making procedures. A case in point is the study by G. Jannat & Tighe (2019), which sought to investigate the implementation of MEPDG models in Ontario's PMSs, underscoring the essence of local calibration in making realistic performance predictions. The study elucidated the imperative of sound data collection techniques for facilitating the integration properly.

Another study, by Gao & Zhang (2008), established a framework through which MEPDG performance models could be integrated with PMSs decision tools and shown to maximize maintenance strategies and allocations of resources. The study served to highlight the value of applying MEPDG-derived data to guide PMSs activity and achieve better pavement performance and lower life-cycle costs.

The integration of MEPDG in PMSs typically entails the application of a number of key performance indicators (KPIs) in the evaluation of pavements and forecasting future performance. Some of the most highly utilized of those indicators are the Pavement Condition Index (PCI), which gives a numerical rating of the pavement based on noted distresses and is an essential input for PMSs (Zafar et al., 2019); the International Roughness Index (IRI), which evaluates the surface

smoothness of the pavement and relates directly to ride quality, making it a key measure for assessing the user experience; and Remaining Service Life (RSL) models, which forecast the time when a pavement will reach a specific threshold level of deterioration, allowing agencies to prioritize maintenance work (Kaya et al., 2020). These measurements play a key role in assessing the success of the integrated MEPDG-PMSs system and guaranteeing maintenance plans conform to actual pavement conditions.

A number of research studies have taught us a lot about the benefits of applying MEPDG in PMSs. For instance, the study by Alhasan et al. (2018) proved that the integration of MEPDG performance models in Iowa's PMSs enhanced the precision of estimating roadway departure crashes linked to pavement conditions significantly. Through integration, the pavement management became more holistic and embraced both performance and safety aspects.

H. Zhang et al. (2013) also conducted a study where they constructed a network-level pavement asset system that incorporated life-cycle analysis coupled with MEPDG performance prediction. The research established that coupled approaches yielded better results in allocation of resources as well as enhanced sustainability in pavement management.

Also, the contributions of G. Jannat & Tighe (2019) aimed at emphasizing local calibration as a means of improving the predictive capacity of MEPDG models in PMSs. The research by the authors identified that specific customization efforts yielded enhanced performance prediction accuracy and eventually better maintenance planning and implementation.

Albeit the progress made in the integration of MEPDG in PMSs, numerous gaps in the existing literature persist. The extent of the gap lies in the absence of a standardized methods for integration frameworks. Xu & Prozzi (2023) observe that variations in data collection methodologies and performance prediction models may cause inconsistencies in outcome and delay effective decision making.

Furthermore, there remains a requirement for extensive studies assessing the long-run effects of the incorporation of MEPDG in PMSs. Whereas numerous studies have concentrated on short-run performance enhancement, minimal studies examine the effects of integration on pavement performance in the long-run as well as under differing traffic and environmental conditions (Qiao et al., 2020). No research has look into the integration to support enhanced treatment effectiveness prediction.

Future studies would aim at formulating standardized approaches for the integration of MEPDG in PMSs so as to maintain consistency and reliability in regions and agencies. Studies would also investigate the long-term pavement performance and life-cycle cost effects of this integration so as to better understand the benefits.

Furthermore, integration of advanced technology, including machine learning and big data analysis, in the integrated MEPDG-PMSs system may also expand predictive insight and enhance decision-making efforts. More research in this direction could result in more efficient and better

decision-making strategies for road pavements adaptable and sensitive to changing conditions and demands.

The integration of the MEPDG into PMSs is a valuable step in pavement engineering. Much progress has already been achieved in this field, and although standardization and long-range evaluation gaps persist, ongoing research and cooperation between transportation agencies, engineers, and researchers will be required in order to maximize the benefits of the integration and enhance general pavement network management.

2.7 Pavement Treatment Effectiveness

The literature on road construction has been grouped under three main classes of work: preventive maintenance, rehabilitation, and reconstruction. Preventive methods, are those which aim at small surface defects, as they are the main cause of the rest of the problems (Ahmed et al., 2013; Labi et al., 2005; Saeed et al., 2018). Preventive treatments such as crack sealing, chip seals, micro-surfacing, and thin overlays, besides closing the existing cracks, can also add like skid resistance and be a kind of refreshment for the surface texture, thus giving again a service life to the road in a very cost-effective way. Rehabilitation works, i.e., thin hot-mix asphalt overlays and full-depth reclamation, are the ones that reconstruct or add strength to the pavement layers thus, return the structural capacity and make the serviceability of the road up to standard again (Khurshid et al., 2011). Whereas these classifications have their merit in providing a way of sorting different treatment options, they are usually portrayed as somewhat less detailed in the decision process, ignoring factors such as traffic loading, environmental exposure, and material variability, and as a result, future research must take these parameters into account in treatment selection frameworks for better treatment intervention tailored to local conditions.

Road treatment is measured by means of performance indicators (PCI, IRI, road life), statistical methods (e.g., regression, Markov chains), and life-cycle cost analysis (LCCA) that aim to quantify improvements in condition and thus, project the long-term benefits of these works (Ahmed et al., 2013; P. Lin et al., 2019; Mandiartha et al., 2017; Pittenger et al., 2012). On the other hand, present-day methods for treating road distress are open to criticism with regard to data quality, methodological consistency, and their ability to identify structural improvements beyond surface roughness. For example, TPM-based approaches can accurately locate variations in IRI and deflection parameters (Amador-Jimenez & Afghari, 2015) but reliance on small sample sizes and limited traffic conditions seemingly restrict their generalizability. Furthermore, LCCA typically ignores a number of subsidiary advantages such as moisture control and reduced subsurface fatigue, and therefore, preventive treatments are not valued to the extent as they should be. Closing these holes in the referred issues of concern necessitates the coming together of standardized data collection protocols, the application of structural performance indicators, and an expanding cost model that would encompass both the direct and indirect benefits of treatment.

Treatment performance studies through comparative analyses have been a major source of both converging and divergent insights. Long-Term Pavement Performance (LTPP) data analysis

reveals that thin overlays as well as chip seals are very effective in raising overall pavement service life (Ahmed et al., 2013). On the other hand, short-term effectiveness models highlight the importance of post-treatment prognosis in longevity of the surface (Luo et al., 2022). Studies of cost-effectiveness have in common identifying the treatment as a source of savings over the lifecycle period as the main point of convergence of rigid pavement restoration (Khurshid et al., 2011) and low-volume road treatments (Hafez et al., 2019). Still, these studies are often depicted as separate worlds focusing on single treatments or performance metrics without delivering a unified conceptualization for network-level prioritization. It is suggested that future research should be oriented towards combining performance results from different treatment types and conditions to create more cohesive decision-making tools which will facilitate better direct confrontation of alternative treatments based on their structural and financial impacts.

Several studies that have developed prediction models for treatment efficacy have long performance data gaps and face problems integrating into the PMSs decision support. Most of the research concentrates in the improvements within quite short durations (e.g., 4–15 years for micro-surfacing)(Bashar et al., 2019; Nair & McGhee, 2022), but only a few studies go beyond that time frame to confirm the durability of the surface under changing traffic and climate conditions. The lack of longitudinal studies imposes limitations on giving treatment life-cycle projections and weakens the process of deciding how to distribute funds. It is necessary to have extensive field monitoring stretched over long periods and be accompanied by sound statistical studies that link treatment types to pavement aging trajectories under varying operating environments to fill this gap.

Ultimately, despite cost-benefit analyses being a key input in deciding treatment by balancing the initial and maintenance costs, they usually exclude the environmental effects and the benefits of the structure, such as increased water resistance or decreased fatigue cracking (Pittenger et al., 2012). While agencies are working towards eco-friendly methods, further research will have to broaden the cost-benefit frameworks to account for carbon emissions throughout the life cycle, resource consumption and user delay costs. Decisions models by using these inclusive metrics can not only achieve better congruence of treatment options with environmental targets and community values but also mark a crucial step in harnessing the role of this research for such a move.

3 Methodology

This chapter briefly outlines the conceptual framework created to comprehensively and properly explore the integration of mechanistic-empirical pavement design and management systems in different regional contexts. The research work has taken a comparative multi-case study approach to handle or deal with totally different climatic conditions, availability of resources, and quality of data, which in turn are factors that affect these different regional contexts. The study has used Alaska, Uganda, and Alberta as its case study examples and thus developed the methodologies of each case study to be consistent with the environmental and operational constraints for each region.

Such a deployment of methodology choices realizes the direct linking of the study's three research objectives and thus facilitates a detailed and layered understanding of the potential and practicability of pavement performance modeling and optimization technologies in varied contexts.

To address the first objective - evaluating the feasibility and validity of integrating MEPDG with PMSs in regions with comprehensive distress data - Alaska, USA was chosen as the case study due to its extensive pavement performance database that contains detailed data of pavement conditions, traffic loading patterns, and climatic factors such as freeze-thaw conditions. The comprehensive dataset of Alaska allows for a seamless implementation of mechanistic-empirical methods into PMS, thus making the framework sufficiently adaptive to the challenges of cold climate and simultaneously serving as a reference for areas with well-documented and quality data. To accomplish the second objective-adapting and evaluating PMSs-MEPDG integration using AASHTO-based structural surrogates and localized progression models for networks with scarce data while testing their efficiency in long-term budget-constrained rehabilitation scenarios - Uganda was appointed to represent the data restrictions that are typical of the developing regions. This method reveals the new ways of dealing with missing data that are discussed in the presentation, such as the use of surrogate indicators, predictive models, and low-cost collection strategies, whereas the tropical climate of Uganda is a perfect example of environmental adaptation testing because of its added difficulty in resource-poor settings. To address the third objective - estimating and comparing the performance and cost-effectiveness of IRI-triggered versus rutting-triggered maintenance strategies informed by calibrated MEPDG outputs - the pavement performance database of Alberta, Canada, over considerable multiple years was utilized to allow direct validation of predicted versus measured pavement performance. The different areas with varying geographical and climatic conditions in Alberta provide the possibilities of a thorough study of the benefits, sustainability, and life-cycle cost advantages of the maintenance trigger strategies on a network-wide application.

3.1 Introduction to the three Case Studies

This chapter introduces three different methodologies constructed to attain the foremost aim of the study: the incorporation of PMSs in the MEPDG. Owing to the immense variability in the availability and quality of the data in different areas, a single method will not be adequate to fulfill the complexities of the incorporation. Rather, three different approaches have been formulated, each of which suits the unique aspects of different geographic areas and sets of data. The regions of focus - Alaska, Uganda, and Alberta - were selected based on their dissimilar attributes and the information they reveal regarding overcoming the challenges and opportunities of incorporating PMS in MEPDG.

The first case study targets the state of Alaska, which was selected because it has all the components necessary to enable the seamless incorporation of the Mechanistic-Empirical Pavement mechanism into PMS. Alaska's thorough pavement performance database has detailed

histories of pavement conditions, traffic loading patterns, and climate factors including freeze-thaw conditions and permafrost. These data points are significant to the study of how pavements react to conditions of extreme cold. Utilizing the sound dataset in Alaska, this approach maximizes the capability of incorporating PMS into MEPDG to make the framework adequately adaptive to the peculiar challenges of cold climate conditions. This method acts as a standard for areas with equally documented and quality data.

The second case study focuses on Uganda, chosen to test the process of integrating the MEPDG with missing or incomplete information, as a result of economic limitations. In most developing parts of the world, including Uganda, a lack of funds usually implies sparse or obsolete pavement information, further making MEPDG integration a daunting task. This approach discusses new ways to handle missing information, including the use of surrogates, predictive models, and low-cost collection strategies. Through the simulation of the integration process at these limitations, the approach seeks to establish a stronger and flexible framework to be applicable even in limited-resource environments. The tropical climate of Uganda, with its intense rains and heat, adds another layer of intricacy to the analysis, with lessons on how to handle environmental conditions in information-poor areas.

The third case study makes use of Alberta, Canada, which has been selected for the large multi-year databases of pavement performance. Alberta's database has the advantage of allowing for direct comparisons between the results produced by the integrated PMS-MEPDG framework and the measured performance of pavements in the database. The large body of past performance data allows for the integration process to be validated accurately to reflect reality. The geography of Alberta, which comprises urban areas, rural, and a range of climatic zones, makes the results of this method even more applicable. By contrasting predicted results with measured performance values, the method makes it possible to pinpoint potential differences and tune the process to make it even better.

The approaches utilized emphasize the need to adapt pavement design principles to the environmental, economic, and operating conditions of the various regions. The choice of Alaska, Uganda, and Alberta represents a deliberate attempt to take on a broad range of challenges and opportunities related to incorporating PMS into MEPDG. Alaska stands for regions with extensive information and developed infrastructure systems, Uganda for regions with constraints in terms of available information and economic capabilities, and Alberta provides a solid platform to test and refine the incorporation process. Combined, these approaches emphasize the need for a flexible, all-encompassing approach to the development of a universally applicable pavement design and management framework. Addressing the variations in available information among territories, the current study seeks to improve the adaptability and performance of the MEPDG framework to be relevant to various global contexts.

In the following sections, the results obtained from each methodology will be presented in detail, accompanied by an interpretive discussion that contextualizes these findings within the broader

framework of the study's goals. This dual approach - presenting empirical data alongside critical analysis - not only highlights key outcomes but also explores their implications, limitations, and connections to existing literature. By structuring the chapter in alignment with the study's objectives and methodologies, this discussion aims to provide a clear, coherent narrative that underscores the significance of the findings and their contribution to the field.

3.2 Proposed Approach for the First Objective

The major goal of this study is to establish mechanistic-empirical deterioration curves for rutting and cracking distresses for situations where the capability of the pavement structure is not known. In these situations, the AASHTO 1993 design procedures are employed to estimate the pavement structure under the existing traffic loads, and the resulting imputed pavement structure is thereafter matched with the realized level of distress to yield the current apparent age of the pavement. Through this framework, the study seeks to overcome the shortcoming of pavement performance and deterioration assessment in situations where the underlying pavement structure data are not available, allowing transportation authorities to evaluate pavement condition and project future deterioration trends, even in situations where the original pavement design parameters are not available.

As shown in Figure 3-1, to accomplish this a data collection is performed to obtain the current level of distress of the pavements, and to group them into homogenous groups of pavements according to truck loading conditions. Then pavement thickness is designed. An analytical assessment is used to estimate stresses and strains for each typical pavement representative of each pavement family. Deterioration curves are then created using the MEPDG and incorporated within the PMS which in turn is used to prioritize the scheduling of Maintenance and Rehabilitation (M&R) according to cost effectiveness of treatments seeking the preservation and/or rejuvenation of the pavement.

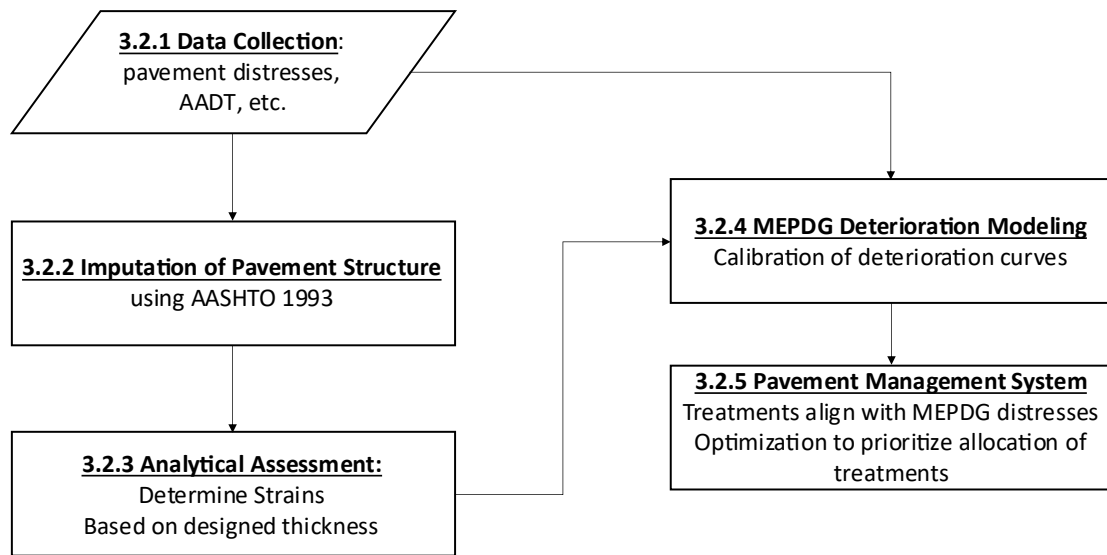


Figure 3-1: Methodology for the First Objective

3.2.1 Data Collection

The dataset utilized in this case study is publicly available from the State of Alaska and comprises two distinct sets of pavement damage data collected for the years 2020 and 2022 (Alaska Department of Transportation & Public Facilities, n.d.). Each dataset encompasses segmented information, where segments are uniformly divided into 0.1-mile intervals. Within each segment, diverse pavement attributes such as rutting (inches), cracking (%area), IRI (inch/mile), and AADT (vehicles per day), alongside the percentage distribution of various truck types, are meticulously documented. Through a process of data integration, these datasets were merged to create a continuous series spanning two years. Table 3-1 provides a summary of data features for ESALs, which are divided into four homogeneous traffic volume groups. The average ESAL value was taken as the main parameter for the estimation of the pavement thicknesses corresponding to each type of traffic in the design process for every group, i.e., Low, Moderate, High, and Very High ESALs. Besides the averages, the table offers the standard deviation as well as the lowest and the highest recorded ESALs for each group to indicate the distribution and range of the data, so that the analysts have a complete picture of the loading environment they work with in the pavement analyses.

Table 3-1: ESALs Data Characteristics

	Average	Standard Deviation	Lowest	Highest
Low ESALs	73,366	66,020	422	249,362
Moderate ESALs	346,596	71,030	250,036	497,982
High ESALs	663,495	125,741	501,332	945,511

Very High ESALs	1,422,786	380,898	1,003,010	2,526,040
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Table 3-2 displays essential pavement distress characteristics related to rutting and cracking, which were reported in the years 2020 and 2022. For every distress type and year, along with the average, the standard deviation, the minimum, and the maximum values, the table outlines not only the central tendency but also the spread of the observed pavement performance metrics. It can be observed that the relatively low averages and upper limits for rutting (inches) and cracking (percentage) in both monitoring periods attest to the fact that the pavement network is still in a very good condition.

Table 3-2: Pavement Distresses Characteristics

	Average	Standard Deviation	Lowest	Highest
Rutting (Inches) 2020	0.191	0.1723	0.04	1.43
Rutting (Inches) 2022	0.187	0.1193	0.04	0.92
Cracking (%) 2020	2.496	4.667	0	40.18
Cracking (%) 2022	3.105	5.199	0	37.16

One of the key goals behind conducting this study was to build a pavement deterioration curve and evaluate its deterioration rate, with a special focus on cracking and rutting. Segments were divided into homogeneous categories first based on traffic intensity and the current status of the pavement. Segmentation created 16 homogeneous categories for each of the pavement indicators, based on different traffic intensities (very high, high, moderate, and low) and pavement conditions (Excellent, Good, Intermediate, and Bad). These categories were later used to compare against reference deterioration rates from the MEPDG.

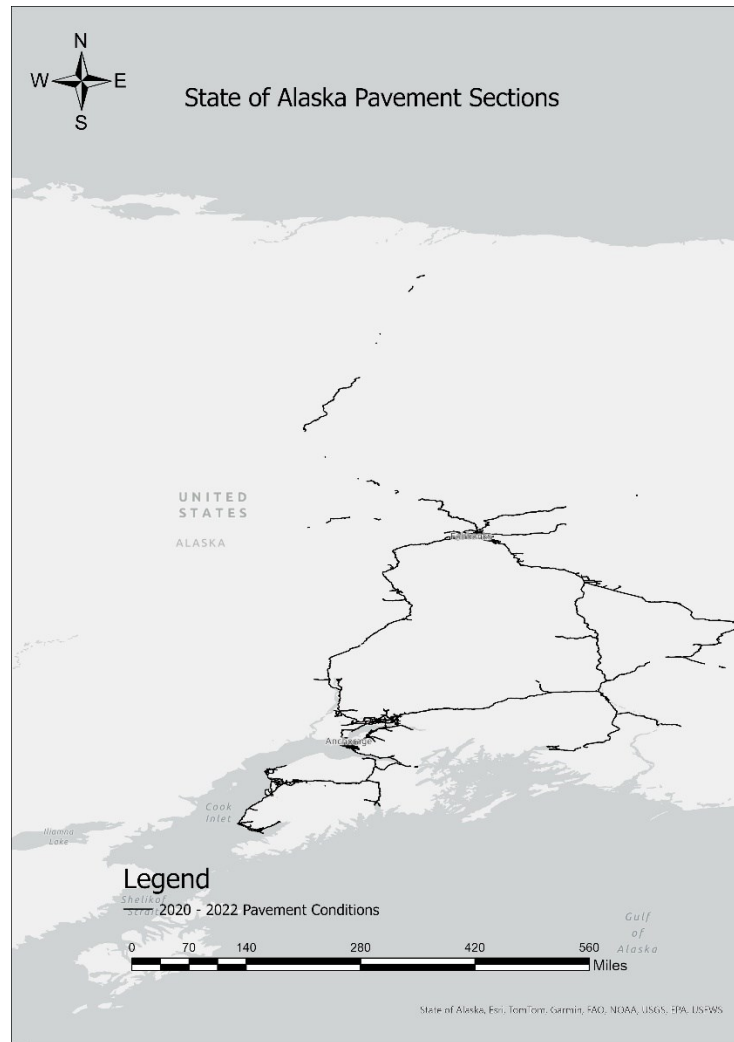


Figure 3-2: Map of State of Alaska pavement sections

3.2.2 Imputation of Pavement Structure

The thickness of the pavement layers was not available and was required to develop the MEPDG deterioration curves. A design procedure was applied to deduce the anticipated layers' thickness (Error! Reference source not found.). The AASHTO (1993) method was applied by the pavement design process. The method allowed the determination of the required thicknesses of the pavements to enable subsequent strain calculations required by the MEPDG. The KENPAVE Software was used to achieve that. The derivation of the strain values was achievable with the aid of the program. As the dataset did not contain information on pavement thickness, four different designs were prepared to suit the differential intensities of traffic as per the dataset. Groups by traffic intensity based on expert criteria were created to illustrate the approach (Table 3-3). Of notable importance, certain parameters that were vital in the design procedure, including resilient modulus and layer characteristics, were assumed to adopt recommended values that are relevant to applying pavement design in Alaska; recommended values from AASHTO (1993) were retained in this case study (Table 3-5 & Table 3-6). The applied thicknesses by design were crucial in the follow-up analyses

and were used to gain insights into how the pavement was to perform under varying traffic conditions.

Table 3-3 : Traffic Levels groups

Traffic Level	ESALs
Low Traffic	≤ 250000
Moderate Traffic	>250000 and ≤ 500000
High Traffic	>500000 and ≤ 1000000
Very High Traffic	>1000000

Table 3-4: Average IRI for each traffic intensity (from dataset)

Traffic Intensity	IRI	
	Year 2020	Year 2022
Low	145	197.89
Moderate	151	164.11
High	136	125.38
Very high	141	140.45

$$\log_{10}(W_{18}) = Z_R \times S_0 + 9.36 \times \log_{10}(SN + 1) - 0.2 + \frac{\log_{10}(\frac{\Delta PSI}{4.2 - 1.5})}{0.40 + \frac{1094}{(SN + 1)^{5.19}}} + 2.32 \times \log_{10}(M_R) - 8.07 \quad \text{Eq. 1}$$

Where:

W_{18} : Represents the number of 18-kip equivalent single-axle loads (ESALs).

Z_R : The reliability factor or reliability coefficient, to ensure the probability of failure does not exceed a certain threshold.

S_0 : The standard deviation in material properties, traffic loading, or other uncertainties in the design.

SN : Structural number represents the overall strength of the pavement structure.

ΔPSI : The change in the Present Serviceability Index (PSI).

M_R : Resilient modulus representing the stiffness of the pavement material.

Table 3-5 : Assumptions for pavement design purpose (AASHTO, 1993)

Assumption	Value
DS	0.5

LDF	0.8
Growth rate	0.03
Reliability	90%
Design Life	25
Δ PSI	1.9
S_0	0.35

Table 3-6 : Layers' properties assumptions (AASHTO, 1993)

Assumption\Layer	Surface Layer	Base	Subbase	Subgrade
Resilient Modulus	450000	30000	15000	50000
Layer Coefficient	0.44	0.14	0.11	-----

*Note: Further adjustments of the above assumptions are required if the methods and estimations presented are taken into practical applications

Based on the AASHTO (1993) design methodology, the required thicknesses of the pavement layers were determined. Table 3-7 presents the calculated layer thicknesses corresponding to each traffic intensity group.

Table 3-7: Layer Thicknesses for Each Traffic Group

Traffic Level \ Layer	Surface (Inches)	Base (Inches)	Subbase (Inches)
Low	3	4	8.5
Moderate	3.5	5.5	12
High	4	5.5	13.5
Very High	4.5	6.5	14.5

3.2.3 Analytical Assessment of Pavement Designs

Pavement analysis within this research depended heavily on KENPAVE software (Huang, 1993), which was used to perform vertical and radial strain calculations vital to the design process based on the MEPDG. The KENPAVE program allowed the creation of detailed strain data, which is needed by subsequent design phases (Figure 3-3). A direct correspondence of these strain values was used to derive the design criteria needed for the MEPDG to ensure that the designed pavement meets set standards. The values of the obtained strains also played a pivotal role in the derivation of the rutting and cracking deterioration curves. By comparing the obtained curves to those of actual trends found in the data set, a sound assessment of pavement behavior under varying conditions was achieved. Lastly, the incorporation of MEPDG concepts within the PMS was a key aim of this research. Through the realization of theories based on a comparison of calculated versus observed degradation curves, the PMSs were augmented to embed MEPDG methodologies. A

holistic method not only created a clearer perception of how pavements behave but also set the stage for smarter and sustainable roadway management practices.

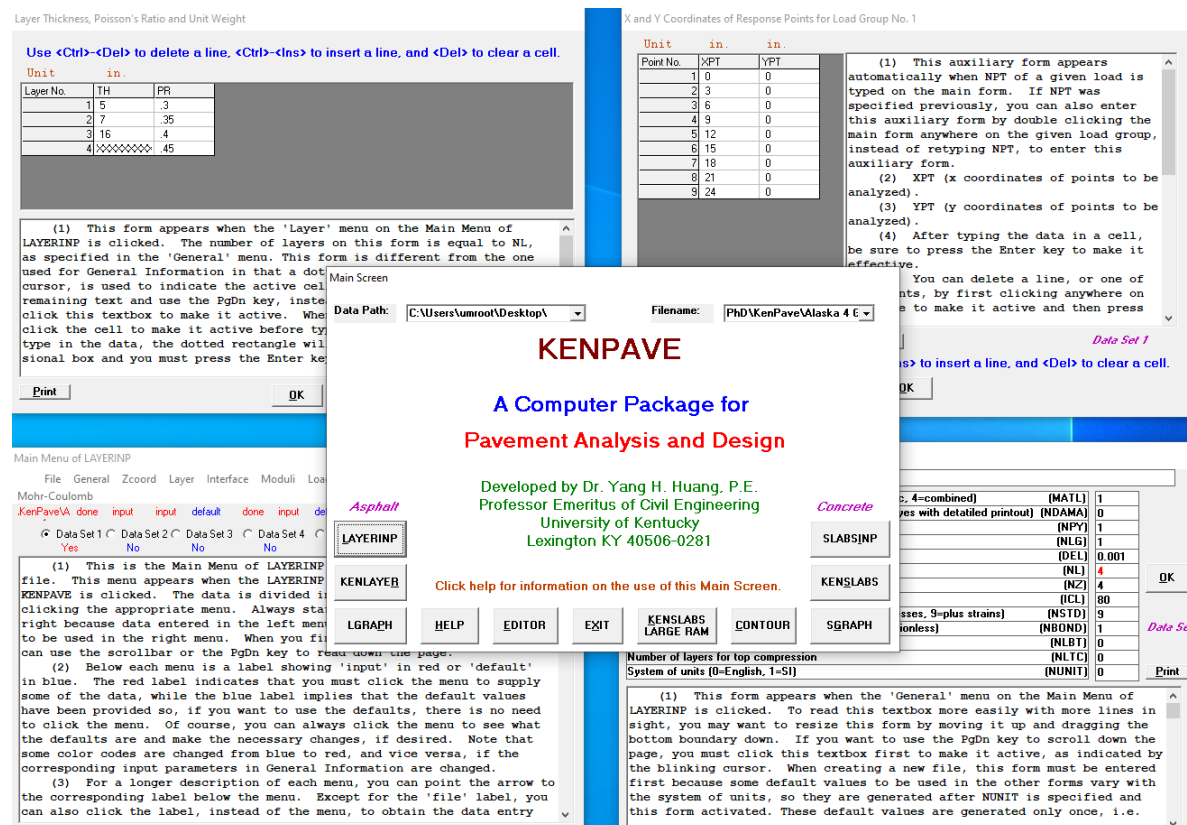


Figure 3-3 : KENPAVE software interface with used data

3.2.4 MEPDG Deterioration Modeling

The available data from Alaska were insufficient to construct a pavement deterioration curve. Therefore, to comprehensively assess pavement deterioration, Amador-Jiménez & Mrawira (2009) method was applied to build deterioration curves, taking advantage of the dataset that contains observations from two consecutive years. This method provided insights into the rate of deterioration within the pavement over this period, with particular focus on rutting and cracking as key indicators. Therefore, the MEPDG models was utilized to predict pavement deterioration over its lifespan. Using MEPDG, a forward-looking analysis was conducted, predicting future pavement performance based on assorted designs. Cracking and rutting remained focal points throughout this predictive analysis, enabling a comprehensive understanding of long-term deterioration patterns and informing decision-making processes regarding pavement maintenance and rehabilitation strategies.

MEPDG measures the rutting depth (Δ_P) as the sum of permanent strains in the pavement layers caused by repeated traffic loading. The rutting prediction model in a general way is represented by an empirical-mechanical transfer function as illustrated in Eq. 2 to Eq. 9.

Where:

$$\Delta_P = \varepsilon_{P(AC)} h_{AC} = \beta_{1r} k_z \varepsilon_{r(AC)} 10^{k_{2r} n} k_{3r} \beta_{3r} T^{k_{2r} \beta_{2r}} \quad \text{Eq. 2}$$

$$k_z = (C_1 + C_2 D) 0.328196^D \quad \text{Eq. 3}$$

$$C_1 = -0.1039(H_{AC})^2 + 2.4868H_{AC} - 17.342 \quad \text{Eq. 4}$$

$$C_2 = 0.0172(H_{AC})^2 - 1.7331H_{AC} + 27.428 \quad \text{Eq. 5}$$

$$\Delta_{P(Soil)} = \beta_{s1} k_{s1} \varepsilon_v h_{soil} \left(\frac{\varepsilon_o}{\varepsilon_r} \right) e^{-\left(\frac{\rho}{n} \right)^\beta} \quad \text{Eq. 6}$$

$$\log \beta = -0.61119 - 0.017638(W_c) \quad \text{Eq. 7}$$

$$\rho = 10^9 \left\{ \frac{C_o}{1 - (10^9)^\beta} \right\}^{\frac{1}{\beta}} \quad \text{Eq. 8}$$

$$C_o = \ln \left(\frac{a_1 M_r^{b_1}}{a_9 M_r^{b_9}} \right) = 0.0075 \quad \text{Eq. 9}$$

- Δ_P : Accumulated permanent or plastic vertical deformation in the AC layer/sublayer, in.
- $\varepsilon_{P(AC)}$: Accumulated permanent or plastic axial strain in the AC layer/sublayer, in/in.
- $\varepsilon_{r(AC)}$: Resilient (elastic) strain calculated by the structural response model at the mid-depth of each AC sublayer, in/in.
- h_{AC} : Thickness of the AC layer/sublayer, in.
- n : Number of axle load applications.
- T : Mix or pavement temperature, measured in degrees Fahrenheit (°F).
- k_z : Depth confinement factor.
- k_{1r}, k_{2r}, k_{3r} : Global laboratory-derived coefficients for dense-graded neat AC mixtures (values: $k_{1r} = -3.35412$, $k_{2r} = 0.4791$, $k_{3r} = 1.5606$).
- $\beta_{1r}, \beta_{2r}, \beta_{3r}$: Local or mixture-specific field calibration constants; for the purposes of global calibration, all constants are set to 1.0.
- D : Depth below the surface, in.
- $\Delta_{P(Soil)}$: Permanent or plastic deformation in the soil layer or sublayer (inches).
- $:$: Intercept determined from laboratory repeated load permanent deformation tests (in/in).

- ε_r : Resilient strain imposed in laboratory tests to obtain material properties ε_o , β , and ρ (in/in).
- ε_v : Average vertical resilient (elastic) strain in the layer or sublayer, calculated by the structural response model (in/in).
- h_{soil} : Thickness of the unbound soil layer or sublayer (inches).
- k_{s1} : Global model coefficient dependent on material type; $k_{s1}=0.965$ for aggregate base granular materials, 0.965 for coarse-grained soils, 0.635 for sandy soils, and 0.675 for fine-grained soils.
- β_{s1} : Local calibration constant for rutting in unbound layers; for global calibration, this constant is set to 1.0 for all unbound materials.
- W_c : Water content, %. M_r : Resilient modulus of the unbound layer or sublayer, psi.
- $a_{1,9}$: Regression constants; $a_1 = 0.15$ and $a_9 = 20.0$
- $b_{1,9}$: Regression constants; $b_1 = 0.0$ and $b_9 = 0.0$.

The damage accumulation due to cracking or fatigue in the pavement layers is being modeled through the tensile strain that the traffic loads cause. The MEPDG uses an equation to predict the initiation of the fatigue cracking as illustrated in Eq. 10 to Eq. 14.

$$N_f = 0.00432 \cdot k'_1 C \left(\frac{1}{\varepsilon_t} \right)^{3.9492} \left(\frac{1}{E} \right)^\alpha \quad \text{Eq. 10}$$

$$C = 10^{4.84 \left(\frac{V_b}{V_a + V_b} - 0.69 \right)} \quad \text{Eq. 11}$$

$$k'_1 = \frac{1}{0.000398 + \frac{0.003602}{1 + e^{11.02 - 3.49h_{ac}}}} \quad \text{Eq. 12}$$

$$DI = \sum \left(\frac{n}{N_f} \right) \quad \text{Eq. 13}$$

$$FC_{Bottom} = \left(\frac{1}{60} \right) \left\{ \frac{C_4}{1 + e^{[C_1 C_1^* + C_2 C_2^* \log(DI_{Bottom} * 100)]}} \right\} \quad \text{Eq. 14}$$

Where:

- N_f : Number of load repetitions to fatigue failure.
- ε_t : Tensile strain at the bottom of the HMA layer (in/in).
- E : Bitumen elastic modulus (psi).

- k'_1, C, α : Calibration constants, α is the Factor that has been calibrated in this study (from 1.281 to 1.42).

The MEPDG curves were calibrated to match Amador-Jiménez & Mrawira (2009) method for Rutting.

3.2.5 Pavement Management System (PMS) Development

To effectively manage pavement assets, a robust PMS was meticulously developed. This system incorporated trigger criteria associated with various treatment types, designed to address specific pavement distresses such as rutting and cracking. Through a rigorous process, trigger values were established based on recognized industry standards, including Alberta Transportation's Guidelines for Assessing Pavement Preservation Treatments and Strategies, which provide detailed treatment applicability and cost frameworks, while the Federal Highway Administration's pavement preservation manuals offer standardized thresholds for selecting and timing actions (Alberta Infrastructure and Transportation, 2006; FHWA, 2010), which provide standardized thresholds for pavement condition classification. These federally mandated performance measures, combined with proven practices from state transportation agencies, ensure that the trigger values align with nationally recognized pavement management protocols (Table 3-8), guiding the identification of appropriate actions for each treatment type (Table 3-9). To optimize the allocation of assets and maximize a 30-year life of the pavements within budget limitations, a novel method was employed. With the commercial solution capabilities of the Open Solver add-in and Excel used as the user interface, an optimization function was applied. The function was used to find the most effective treatment strategies and timings, utilizing the assets efficiently. The core of the optimization process was the application of a master condition index to each year. That Overall Condition (OC), calculated through a formula that weighted rutting and cracking, was used to lead the optimization process, as shown in Eq. 15.

$$OC = [(2 \times 10 \times \text{Rutting}) + \text{Cracking}] \times 0.17 \times 2 \quad \text{Eq. 15}$$

Where rutting received a weighting of twice that of cracking, and a multiplication by a factor of ten was applied to place the rutting at the same order of magnitude as cracking. The 2 and 0.17 in the equation represent the number of lanes and the conversion of the road length from 0.1 mile, as it was used in the dataset, to km. The reasoning used here came from the distinctive climatic conditions of the State of Alaska, where rutting is considered a vital deficiency of the pavements because of its increased importance in cold environments. With these things brought into the PMS, a full and holistic framework was created, allowing informed decisions to be made on the allocation of assets and effective maintenance of the pavement assets.

Table 3-8 : Distresses grouping

Rutting (inches)		Cracking (Area %)
0		0
Excellent (E)		
0.25		5

Good (G)		
0.5		10
Intermediate (I)		
1		20
Bad (B)		
>1		100

Table 3-9 : Pavement Action Plan

Rutting	Cracking	Action	Cost (USD Per Lane-KM)
E	E	Do Nothing	\$0
E	G	Crack Sealing	\$3,000
E	I	Mill & Overlay	\$60,000
E	B	Reconstruction	\$50,000
G	E	Micro-surfacing	\$25,000
G	G	Micro-surfacing	\$25,000
G	I	Mill & Overlay	\$60,000
G	B	Reconstruction	\$500,000
I	E	Mill & Overlay	\$60,000
I	G	Mill & Overlay	\$60,000
I	I	Mill & Overlay	\$60,000
I	B	Reconstruction	\$500,000
B	E	Reconstruction	\$500,000
B	G	Reconstruction	\$500,000
B	I	Reconstruction	\$500,000
B	B	Reconstruction	\$500,000

*Note: E = Excellent, G = Good, I = Intermediate and B = Bad

*Source: Source: Adapted from Alberta Transportation's Guidelines for Assessing Pavement Preservation Treatments and Strategies (Alberta Infrastructure and Transportation, 2006), FHWA Pavement Preservation manuals (FHWA, 2010). Values are synthesized for consistency.

3.2.6 Optimization and Resource Allocation

The development of a PMS is a pivotal aspect of this research. The PMS is designed to manage pavement assets efficiently, incorporating trigger criteria for various maintenance treatments based on observed distress such as rutting and cracking. Trigger values specify the conditions under which different treatments should be applied. An optimization framework for a network is the goal of this research, and it minimizes, as a main objective, the network condition score for each year. The condition index is computed using the aforementioned formula (Eq. 15). The PMSs were designed by applying an optimization algorithm with an objective function that aimed at reducing the overall pavement condition. The primary limitation is the maintenance budget for the network, which is distributed annually, and the total spending must not exceed the money allocated for each year. The decision variables are expressed in the form of two binary numbers, where 0 means no action, and 1 indicates that a maintenance intervention is applied according to the pre-established policy. Hence, this set-up allows the model to choose the most appropriate combination of road treatments along the whole network, which is able to balance the improvement of the condition with budget limits whilst keeping the mathematical feasibility and the real use by road agency authorities. This function is designed to determine the most effective treatment strategies and timing over a 30-year planning horizon, ensuring optimal resource allocation while adhering to budgetary constraints. Figure 3-4 & Figure 3-5 showcase the tool decision support developed by Amador (unpublished) and used in this research.

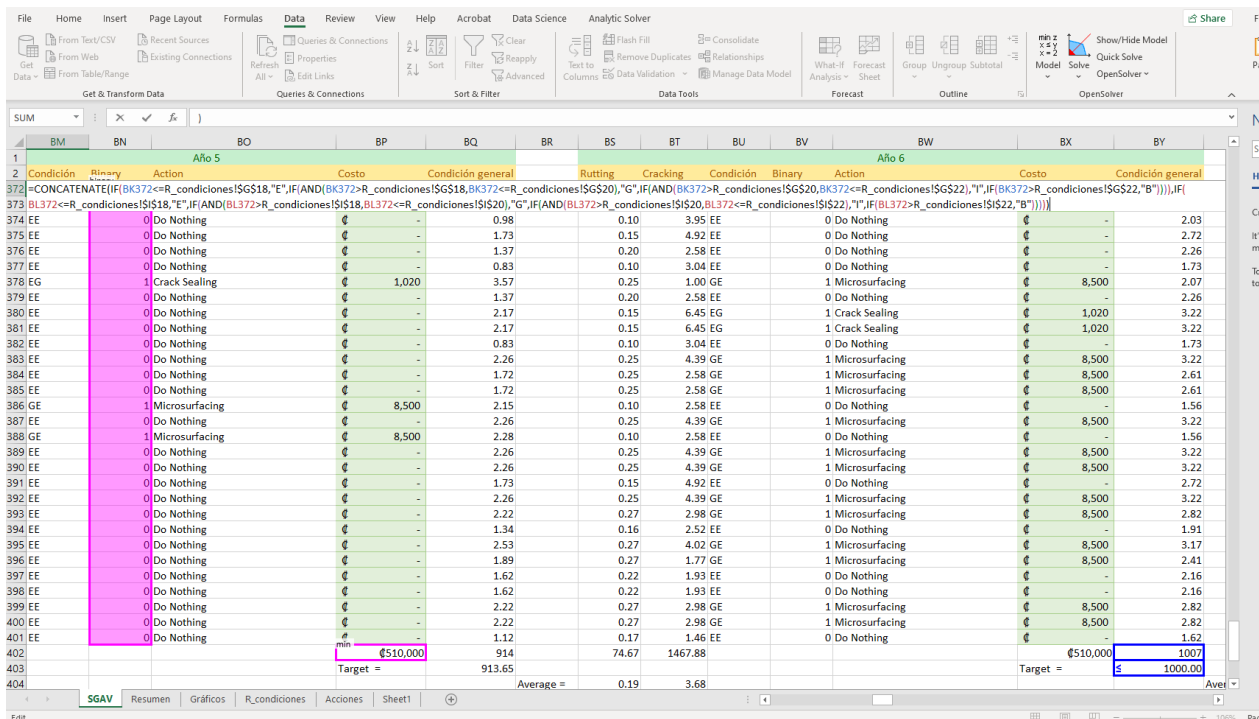


Figure 3-4: PMS Optimization Technique as used for multiple years

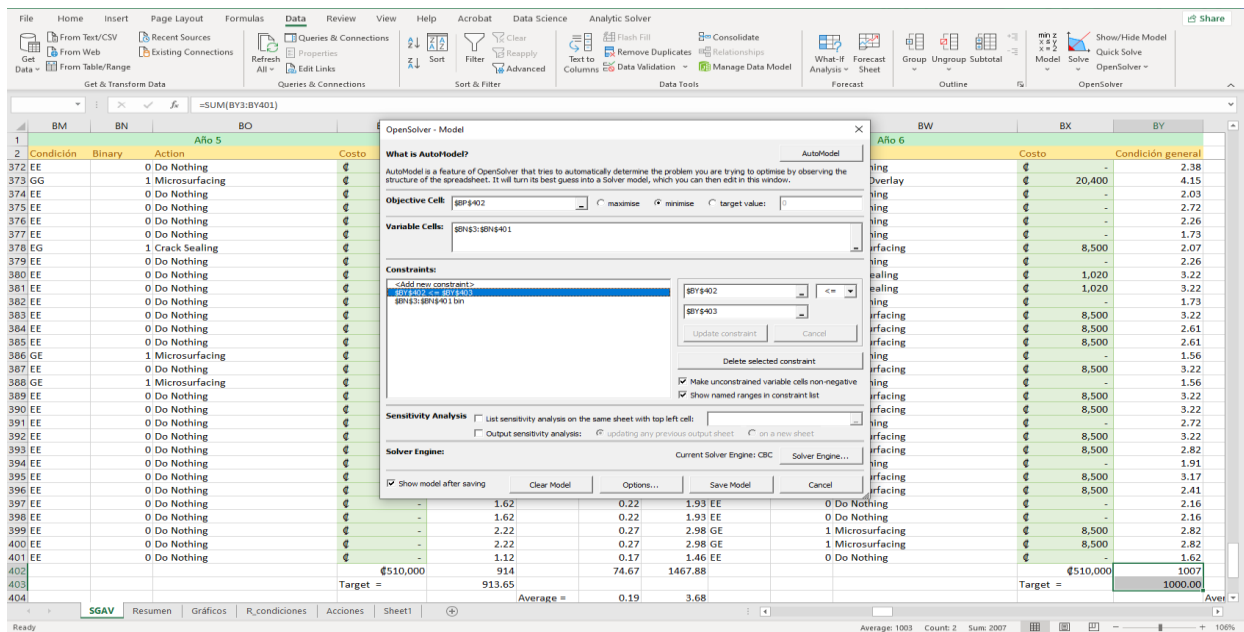


Figure 3-5: Optimization Function and Constraints “Open Solver”

3.3 Proposed Approach for the Second Objective

The proposed methodology for the second objective focuses on evaluating the integration of PMS into the MEPDG framework, with a specific emphasis on the challenges presented by limited pavement data and poor overall pavement conditions in the resource-constrained environment of Uganda. The objective of this study is to thoroughly assess an MEPDG-PMS combined framework as a possible solution for more accurate pavement design, better prediction of pavement performance, and maintenance strategy planning, particularly in areas with limited data like Uganda. In this regard, the study will apply the data and insights from PMS to show how such synergistic integration can aid in enhancing the reliability and applicability of the MEPDG process for making more informed decisions in the optimization of pavement management practices in Uganda. These findings from the study will certainly offer meaningful guidance to transportation agencies of developing countries with similar challenges in terms of the availability of pavement data and overall condition of pavement regarding ensuring effective allocation of scarce resources and thereby improving the performance of the road infrastructure.

The methodological approach of this study is depicted in Figure 3-6. Comprehensive data, including pavement distresses, average annual daily traffic (AADT), and pavement length, among other relevant parameters, is first collected. In cases where the pavement structure information is missing, the AASHTO 1993 design guide is utilized to determine the necessary layer thicknesses. The pavement structure is then analyzed using KENPAVE software to obtain the required strain values, which are incorporated into the MEPDG models. The rutting and cracking distresses associated with various levels of the IRI are calculated and subsequently calibrated and compared with the MEPDG predictions, enabling the development of deterioration models and the conduct

of calibration and validation procedures. Finally, a PMS is constructed using optimization techniques to identify the best treatment strategies and timing for the pavement's lifecycle, leveraging the insights gained from the integrated PMS-MEPDG framework.

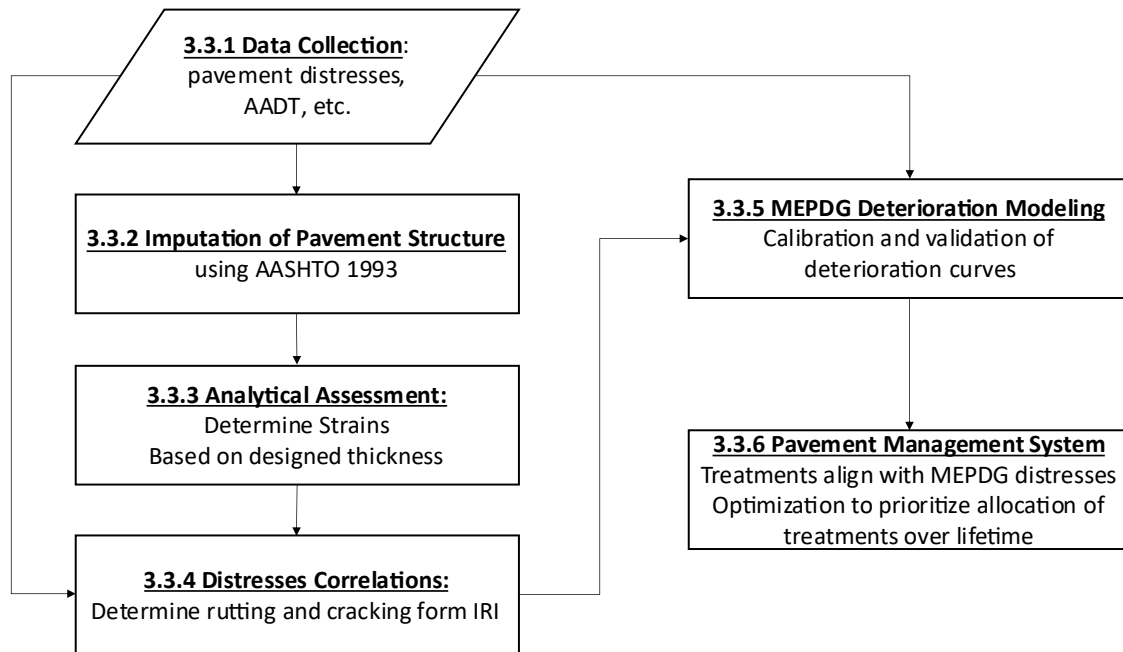


Figure 3-6: Methodology for the Second Objective

3.3.1 Data Collection

This study utilizes the Uganda Pavement dataset, which encompasses data on a road network spanning approximately 3000 kilometers (about 1864.11 mi). The dataset contains key attributes for each road segment, such as road number, section length, Average Annual Daily Traffic (AADT), Structural Number (SN), roughness, rutting, total lane crack percentage, and pavement age ranging from 1 to 25 years. These attributes are recorded for 2009 only, and no other year is represented in this dataset. This is quite common in many early years of agencies using a pavement management system. Figure 3-7 Illustrates the road network for Uganda as exported from ArcGIS.

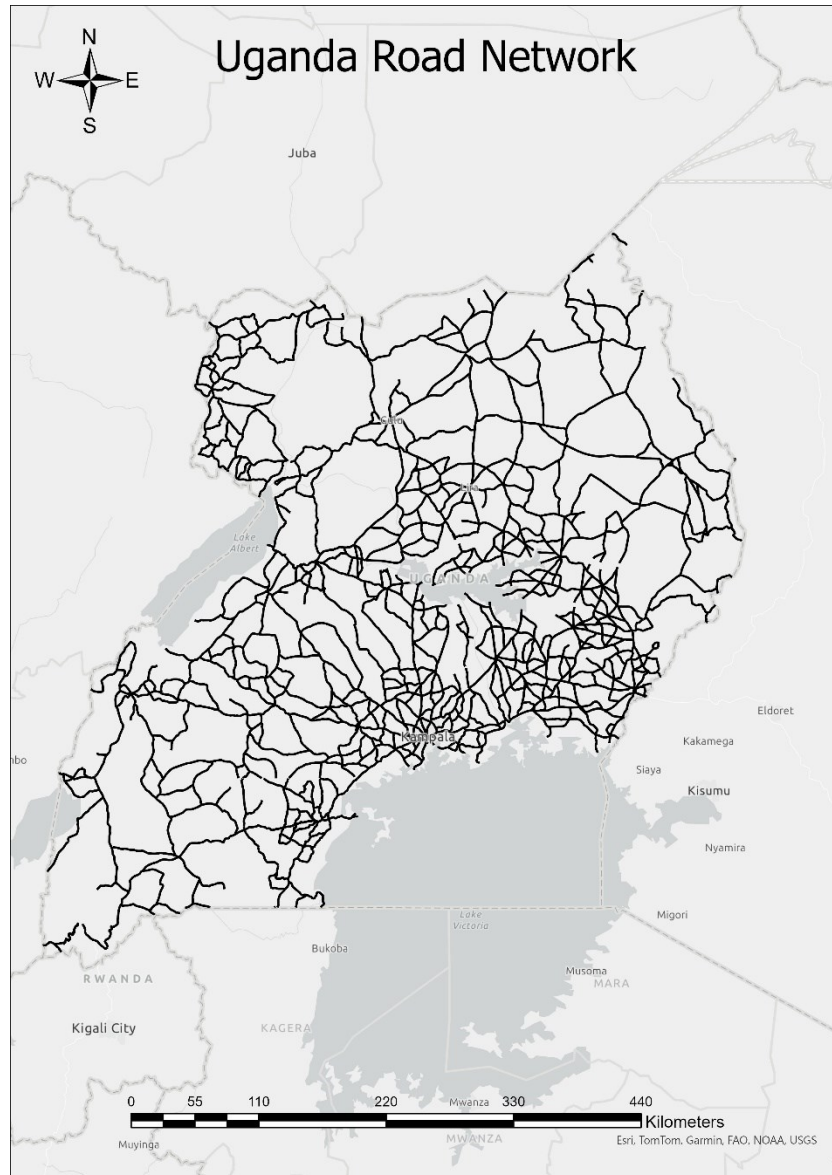


Figure 3-7: Uganda Road Network Map

3.3.2 Imputation of Pavement Structure

Following data collection, the study uses the AASHTO 93 empirical method to design a pavement structure based on different traffic conditions of Uganda. The overall road network of Uganda has been divided into four traffic categories: low-volume roads, moderate-volume roads, high-volume roads, and very high-volume roads, considering various classes of vehicular traffic.

During the design process, some assumptions are made regarding Lane Distribution Factor (LDF) and Directional Splits (DS). These assumptions are based on practices known and followed within

the road construction industry of Uganda, and according to guidelines given by the Uganda National Roads Authority (UNRA) or other relevant regional governing authorities.

Unlike the study for Alaska, the analysis of pavement performance in Uganda presented unique challenges due to inconsistencies in the available dataset, particularly regarding cracking records. While data on rutting and roughness (measured as the International Roughness Index, IRI) are provided alongside the age of each pavement section, the absence of reliable cracking data necessitated innovative approaches to model deterioration accurately. Given the availability of rutting data and the age of the pavement sections, a rutting deterioration curve was successfully developed without relying on the MEPDG rutting model. Instead, the MEPDG-IRI model was utilized to predict the progression of roughness over time. This model was subsequently calibrated to align with the measured IRI values from the Ugandan dataset, ensuring its relevance and accuracy within the local context.

To validate the robustness of the calibrated models, a two-step verification process was undertaken. First, the relationship between rutting and the calibrated IRI values was examined to ensure the precision of the rutting deterioration model. This step confirmed that the predicted rutting trends were consistent with observed roughness levels, reinforcing the reliability of the approach. Second, an indirect relationship between IRI and cracking was established by interpreting cracking percentages based on corresponding IRI values. For instance, it was determined that when the IRI reaches 6 m/km—a threshold indicating the end of the pavement's service life—it correlates with approximately 20% cracking. This methodology not only addressed the lack of direct cracking data but also provided a practical means to estimate cracking severity using roughness as a proxy.

Eq. 16 was used to predict the International Roughness Index (IRI) for flexible pavements over their lifetime. In order to enhance the accuracy of the predictions, coefficients C1, C2, and C4 were calibrated. This calibration process aimed to minimize the discrepancies between the predicted IRI values - generated using MEDPG - and the observed IRI values obtained from the original dataset. By aligning the model's outputs with real-world observations, this approach ensures that the predictive capability of Eq. 16 is robust and reliable when applied to the Ugandan case study.

Table 3-10 shows the calibration factors as been recommended by MEPDG and their values after calibration for Uganda case.

Table 3-10: IRI Calibration

Coefficient	MEPDG	Uganda
C ₁	40.0	40.0
C ₂	0.400	0.40
C ₄	0.015	0.09

For the purpose of calculating the site factor (Eq. 17), there is a need for data characterizing the subgrade soil and the precipitation regime. Such data was unavailable and therefore assumed in order to proceed, these assumptions have been made based on the real values of Uganda (Hasan & Sayed, 2017; Stampone et al., 2011). Table 3-11 below shows the parameters and their assumed values.

Table 3-11: List of Assumptions

Variable	Assumption
Soil Type	Silty clay
Plasticity Index (PI)	14.700
Freezing Index (FI)	0
Precipitation in inches	47.126
Percentage of subgrade soil passing sieve P ₀₂	48 %
Percentage of subgrade soil passing sieve P ₂₀₀	100 %

A comparison was developed between the average observed roughness levels of each integer year of age of the pavement sections, and the predicted values from the calibrated MEPDG - IRI model for Uganda. The comparison served to visually verify the accuracy of the calibrated MEPDG – IRI model (after calibration) over the pavement lifetime. Figure 3-8 shows such comparison for the calibrated MEPDG - IRI model and how it predicts closely the observed IRI for most of the years.

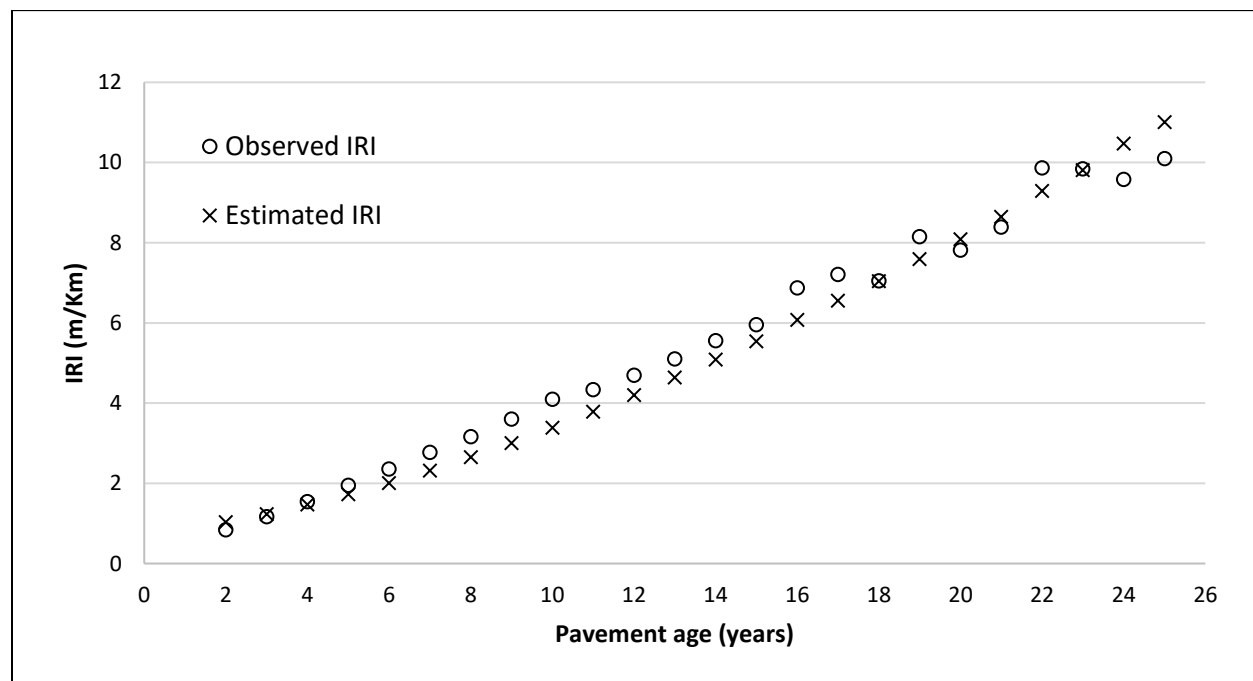


Figure 3-8: Comparison of calibrated predicted MEPDG versus Observed IRI

3.3.3 Analytical Assessment

The study follows the pavement thickness design for Uganda's road infrastructure using the AASHTO 93 methodology by employing KENPAVE Software in carrying out an elaborate structural analysis. This helps in linking the empirical AASHTO 93 method to the MEPDG mechanistic-empirical model.

The computed pavement thicknesses from AASHTO 93 for each traffic class are then used as an input in KENPAVE, a software package based on multi-layer elastic theory to analyze the response of the pavement system to a suite of loading scenarios representative of traffic flow in Uganda.

KENPAVE proceeds with the calculations of critical stresses and strains at critical locations in the pavement structure. In more detail, the study identifies:

- Horizontal tensile strain at the bottom of the asphalt layer (for fatigue cracking prediction)
- Vertical compressive strain at the top of the subgrade (for rutting prediction)

These two critical responses are extracted from the KENPAVE analysis and prepared for use in the MEPDG performance prediction equations. These equations will help forecast the long-term performance of the pavement designs under Uganda's specific conditions, including:

- Local climate data (temperature, precipitation, etc.)
- Uganda's traffic patterns and vehicle types
- Available materials and their properties

By using KENPAVE as an intermediate step, the research combines the simplicity of the AASHTO 93 approach with the comprehensive analysis tools required by MEPDG predictions. This approach allows for a detailed assessment of the future performance of designed pavements under the specific Uganda conditions in terms of cracking and rutting, hence enabling better decisions on pavement management and maintenance strategies.

3.3.4 Distresses Correlations

3.3.4.1 IRI Prediction

In the absence of multi-year data, this study aims to develop deterioration curves for rutting, cracking, and IRI across pavement age. To achieve this, MEPDG IRI equation was used. Specifically, Eq. 16 below is used to predict IRI for flexible pavements over their lifetime:

$$IRI = IRI_o + C_1(RD) + C_2(FC_{Total}) + C_3(TC) + C_4(SF) \quad \text{Eq. 16}$$

Where:

IRI: International Roughness Index

IRI_o: Initial International Roughness Index (at the beginning of the analysis)

RD: Rut Depth

FC_{Total} : Total Fatigue Cracking

TC : Transverse Cracking

SF : Site Factor

The coefficients C1, C2, and C4 are calibrated to eliminate the difference between the predicted values (using the MEPDG) and the observed values for IRI originally found within the dataset. The Site Factor (SF) is calculated using Eq. 17 below:

$$SF = Age^{1.5} [\ln((Precip + 1)(FI + 1)P_{02}) + \ln((Precip + 1)(PI + 1)P_{200})] \quad \text{Eq. 17}$$

Where:

Age : The age of the pavement.

$Precip$: Precipitation, total amount of rainfall.

PI : Plasticity Index.

FI : Freezing Index.

P_{02} : Percentage passing through 0.02 mm sieve.

P_{200} : percentage passing through the 0.075-mm sieve.

To calculate the site factor, data characterizing the subgrade soil and precipitation regime is required. As such data was unavailable, assumptions were made based on real values for Uganda obtained from available sources.

3.3.4.2 Rutting Analysis

To verify the theory that rutting significantly influences IRI values, a logarithmic best-fit correlation was performed between the mean observed rutting levels for each integer year of age versus observed IRI. This allowed the establishment of a statistical correlation between IRI and rutting. The resulting regression model used to obtain a model capable of estimating rutting values, which allowed the incorporation of pavement age directly into the rutting calculation process.

3.3.5 MEPDG Deterioration Modeling

To ensure the accuracy and reliability of the roughness, rutting and cracking models, several comparisons and validations were conducted. First, the average observed roughness levels of each integer year of pavement age with the predicted values from the calibrated MEPDG - IRI model for Uganda was compared. This comparison serves to visually verify the accuracy of the calibrated model over the pavement lifetime.

For rutting, after deriving values for each year through the established correlation between rutting and IRI, a comparison to assess the agreement between calculated and measured rutting values has been conducted. This allows the validation of the effectiveness of IRI-Rutting relationship in estimating rutting across varying pavement ages.

In the case of cracking, following the acquisition of cracking percentage values through the applied expert-based correlation, a deterioration curve to illustrate the progression of cracking over pavement ages was constructed. The reasonableness of this curve was assessed against traditional criteria, such as the Federal Highway Administration Report, that Limited criteria of 20% cracking before reconstruction (FHWA, 2018).

3.3.6 Pavement Management Systems

The integration of data analysis, visualization, and interpretation constitutes a vital part of the PMSs strategy of the road network. Following the same optimization framework as in the Alaska case study, the PMS used one objective function aimed to minimize the network condition deterioration, subjected to annual budget allocations that acted as constraints and employed binary decision variables where 0 stands for no intervention in the pavement section, and 1 denotes the application of a maintenance treatment along with the specified policies. The use of this common method allows for the strategic maintenance activities' priority while achieving the maximum performance benefits of the network-wide at the level of available financial resources.

These models have been applied to back-calculate results and subsequently evaluate model performance under conditions prevailing in Uganda. The current evaluation focuses on verifying congruence between theoretical and measured values of the major indicators of distress, i.e., IRI, rutting, and cracking. Comparative evaluation has been done to establish the ability of the models to accurately forecast particular patterns of distress under climatic, traffic, and construction conditions prevailing in Uganda.

Specific focus was brought to the rationality of the resulting deterioration curves; this has actually proved them to hold close to real-life pavement behavior in Uganda. Such evaluation is necessary to validate the models and make them applicable in practice.

In response to the need to maximize the benefits accrued to the road network over a 30-year period, with minimum budget constraints given the limited resources accruing to developing countries such as Uganda, an innovative optimization approach was adopted. This was implemented through the commercial functionality of the Open Solver add-in that has been embedded in Excel as the user interface. The combination provided for the realization of an optimization function that was used to define the most cost-effective timing and treatment options. The optimization considered several factors such as the condition of the pavement, urgency of repairs, and availability of funds; this way, the efficiency of scarce resources was ensured.

The principal objective underpinning the optimization framework was the annual formulation of a comprehensive condition index, serving as a synthesized metric for network-level pavement assessment. This condition index acted as a composite index whereby weighting different distresses yield the overall whole of a pavement's condition. The index was computed according to the approach explained in Eq. 15, where rutting was given maximum weight due to its immense importance on road safety, especially under the frequently wet conditions of Uganda. The very

presence of rutting creates a hazard where hydroplaning and loss of control of the vehicle become paramount, hence a priority for intervention. A weighting factor of ten was thus attached to the rutting measurements in millimeters so that it represents the same order of magnitude as with the percent cracks. Cracking is of less immediate danger than rutting; however, it is still important to the degradation of the pavement because the cracks serve as an entry for water into the structure, which accelerates the degradation of the pavement over time.

The choice of giving priority to rutting and cracking in this manner was predicated on the climatic and economic setting prevailing in Uganda. In a tropical environment where heavy rains prevail, these two distresses greatly affect road performance and maintenance costs. Thus, the PMS, by focusing attention on the critical parameters in question, can prioritize where interventions will count the most towards the road network's longevity and minimizing long-term costs. By including these elements into the PMS framework, a full-blown decision-making instrument for the efficient use of scarce resources has been created. This PMS assists in the maintenance and conservation of the vital road network assets in Uganda and thus serves a strategic purpose in its investments, earmarking urgent needs while balancing long-term sustainability. Ultimately, this will augment road safety, enhance transportation efficiency, and support socio-economic development in the region. Table 3-12 presents the trigger criteria established for rutting and cracking, while Table 3-13 outlines the pavement action plan adopted in this study.

Table 3-12: Rutting and Cracking Trigger values

Rutting (mm)		Cracking (Area %)
0		0
Excellent (E)		
3		5
Good (G)		
6		10
Intermediate (I)		
12		20
Bad (B)		
>12		100

Table 3-13: Pavement Action Plan

Rutting	Cracking	Action	Cost (USD Per Lane-KM)
E	E	Do Nothing	\$0
E	G	Crack Sealing	\$3,000
E	I	Mill & Overlay	\$60,000
E	B	Reconstruction	\$50,000
G	E	Micro-surfacing	\$25,000

G	G	Micro-surfacing	\$25,000
G	I	Mill & Overlay	\$60,000
G	B	Reconstruction	\$500,000
I	E	Mill & Overlay	\$60,000
I	G	Mill & Overlay	\$60,000
I	I	Mill & Overlay	\$60,000
I	B	Reconstruction	\$500,000
B	E	Reconstruction	\$500,000
B	G	Reconstruction	\$500,000
B	I	Reconstruction	\$500,000
B	B	Reconstruction	\$500,000

3.4 Proposed approach for the third objective

The methodology embraced in this study is divided into eight major steps illustrated in Figure 3-9, each carefully crafted to methodically examine pavement data, simulate road behavior, and compare the effectiveness of different treatments. The holistic methodology guarantees a comprehensive and solid grasp of the behavior of the roads under varying traffic conditions and affords actionable results to drive pavement management and rehabilitation decisions based on direct and indirect damage indicators. The process starts with raw data collection and organization, continues through superior analysis and simulation methods, and reaches its conclusion in the assessment of treatment efficacy through statistical and probabilistic means. Below is a substantive discussion of each step, noting the tools, methodological techniques, and justifications of the methodologies used. The systematic process not only guarantees precision and reliability of results but also affords a lucid roadmap to future studies in road engineering and management.

In contrast to the approach presented in Section 3.3, the approach of this section further develops a method to measure the effectiveness of treatments (section 3.3.7) and employs it to measure the effectiveness of PMSs built upon the MEPDG as presented before.

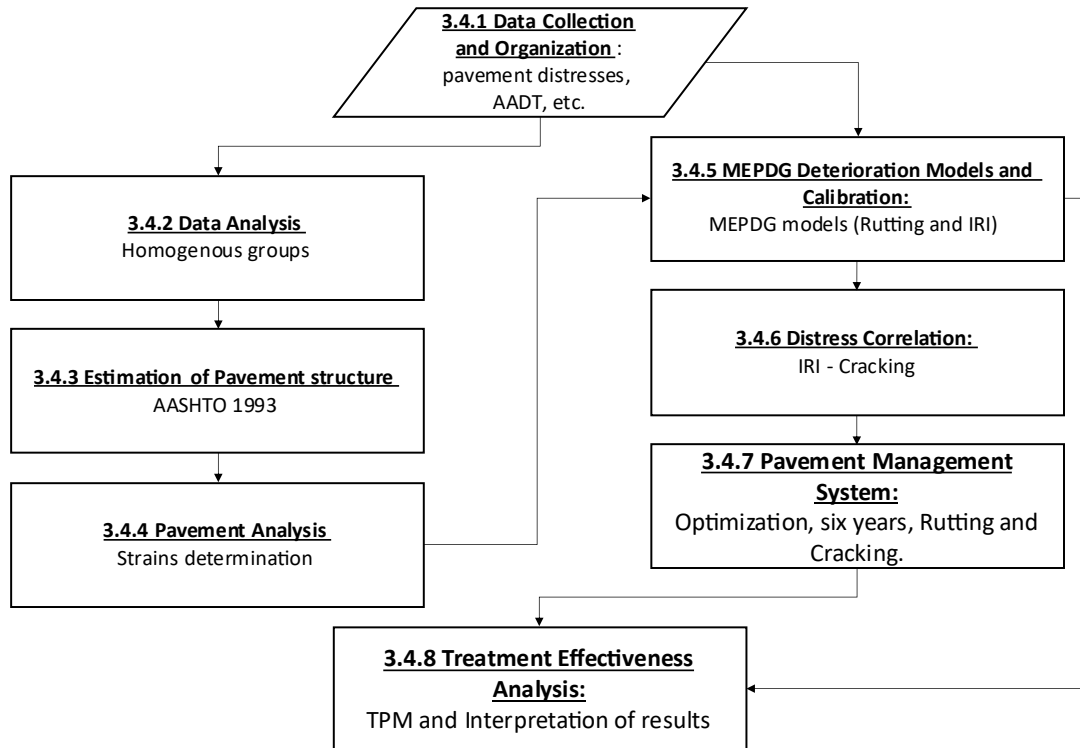


Figure 3-9: Methodology for the third Objective

3.4.1 Data Collection and Organization

The initial step in methodology entailed collection and organization of pavement data into annual files, with ESALs. Each annual file supplied detailed information concerning road sections, including identifiers like road number, road code, lane code, and geocoordinates. These identifiers were essential to accurately identify each section within the network of roads that are shown in Figure 3-10. The files also included the major pavement condition indicators, that is, the IRI and Rutting values, which are vital to evaluate the performance of the pavements.

Pavement data from the official webpage of Alberta's Transportation Ministry was framed into six annual files from 2018 to 2023, with a separate file including ESALs. Each annual file supplied detailed information concerning road sections, usually 50 meters in length, including identifiers like road number, road code, lane code, and geocoordinates (Government of Alberta, n.d.). These identifiers were essential to accurately identify each section within the network of roads. The files also included the major pavement condition indicators, that is, the IRI and Rutting values, which are vital to evaluate the performance of the pavements.

For ease of analysis, the six annual files and the ESALs file were combined into a single, consolidated dataset. Because of the large nature and complexity of the data, Excel was not adequate to achieve this, and Python was used to combine the files. The process of combining depended on eight identifiers to accurately match data from various files per road section. The process was done again to combine the ESAL data with the consolidated dataset to make sure that

traffic load information was incorporated into every road section. Through a systematic process of organization, the analysis that followed drew from a solid build-up of a comprehensive and integrated dataset combining both the pavement condition measures and traffic load information. Figure 3-10 demonstrates the huge amount of data that the Alberta Pavement Dataset acquires.

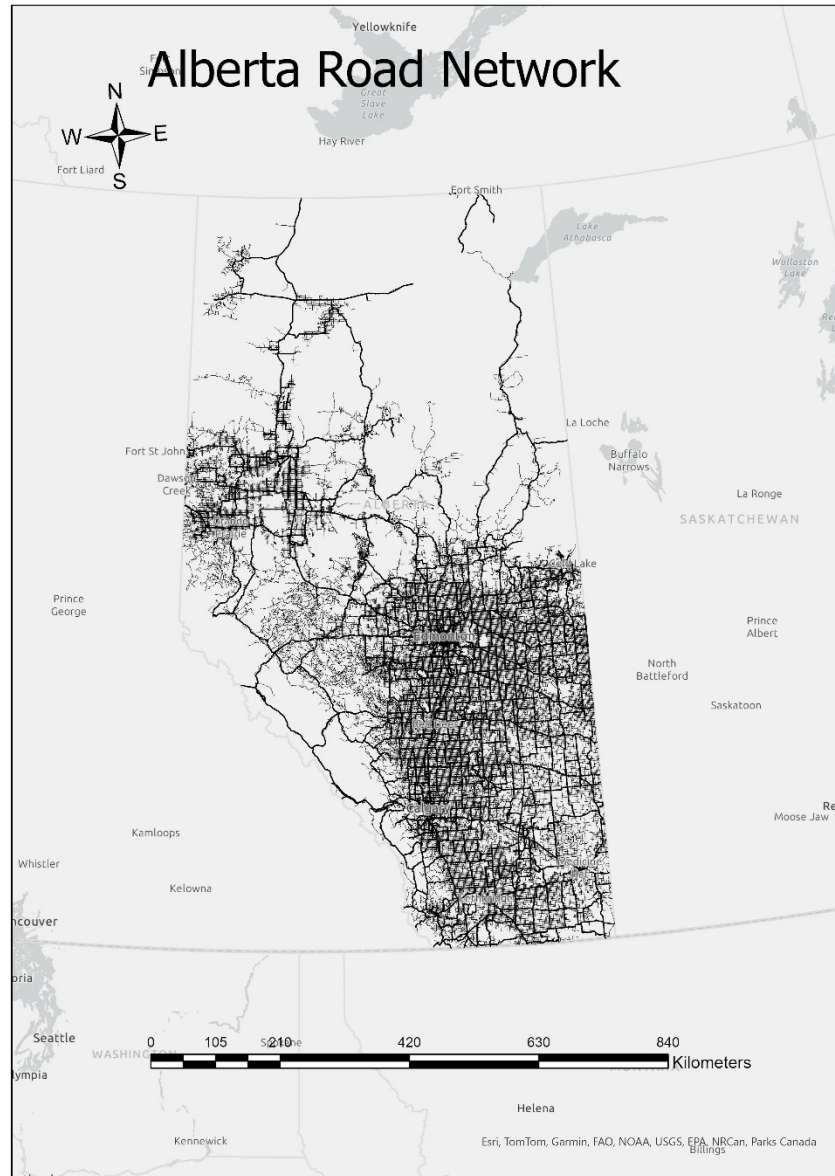


Figure 3-10: Alberta Road Network

3.4.2 Data Analysis

After consolidating the data, it was classified by ESALs values from low to high. Percentiles of 25th, 50th, and 75th of the ESALs were computed to divide the road network into four uniform categories of traffic intensity: Low, Moderate, High, and Very High. The classification facilitated a better evaluation of the performance of roads under varying traffic levels.

3.4.3 Imputation of pavement structure

After consolidating the data, it was classified by ESAL values from low to high. Percentiles of the 25th, 50th, and 75th of the ESAL were computed to divide the road network into four uniform categories of traffic intensity: Low, Moderate, High, and Very High. The classification facilitated a better evaluation of the performance of roads under varying traffic levels.

Following the approach explained in Section 3.3, the data collected for Alberta province in Canada was organized into six annual data files containing the rutting condition and the ESALs combined into a single dataset. The data was assigned into four uniform categories of traffic intensity: Low, Moderate, High, and Very High. The pavement structure was input as explained in Section 3.3.3, utilizing the AASHTO 1993 method. The KENPAVE software was used to simulate the behavior of a pavement subjected to traffic loading to obtain the cycles of stress and strain experienced by each of the pavement structures.

3.4.4 Pavement Analysis

Those pavement designs were also simulated through the KENPAVE program, a computer program used to simulate the behavior of a pavement subjected to traffic loading. The program used the calculated thicknesses and other parameters to simulate the cycles of stress and strain experienced by each of the pavement designs. The calculations shed light on how each of the pavement designs will behave against anticipated traffic loads and are a crucial input parameter to MEPDG modelling to create a deterioration curve.

3.4.5 MEPDG Deterioration Models and Calibration

To forecast the durability of pavements over time, MEPDG models were used to establish the deterioration curves of Rutting and IRI. Each of the four traffic intensity categories - Low, Moderate, High, and Very High - had separate curves, allowing a more sophisticated investigation into how conditions of a pavement deteriorate over time based on the amount of traffic. Through these models, insights into how damage to a pavement is anticipated to develop were gleaned, which assisted in directing maintenance and rehabilitation plans.

To validate the reliability and accuracy of the MEPDG-based deterioration curves, they were also calibrated against actual data by the method of Amador-Jiménez & Mrawira (2009). The calibration process entailed developing a best-fit regression for actual deterioration curves from two data points spanning 25 years of a pavement's life. These actual curves were compared to the MEPDG predictions to refine and fine-tune the models to accurately represent actual pavement performance. The process was vital to fine-tuning the precision of the predictions so that the deterioration curves conveyed the actual behavior of pavements under various levels of traffic activity. The incorporation of calibration into the modeling process not only boosted the strength of the analysis but also ensured the resultant predictions could confidently support decision-making within the field of pavement management.

3.4.6 Distresses Correlation

Since direct cracking measurements within the Alberta pavement dataset were not available, another method was used to approximate cracking values through correlation with the IRI. The reason for doing so was to maintain continuity of performance evaluation, especially under the scenario of a long-duration analysis of pavements, where cracking is a vital parameter in evaluating structural and surface conditions.

It is assumed that IRI measures of pavement roughness are representative of cracking severity, including distress. Expert judgment was used to establish plausible mappings between representative IRI levels and associated cracking percentages. For example, a value of 6 per km, a value typifying severe levels of deterioration that are candidates for reconstruction, was paired with a predicted level of cracking of 20%. Equivalent mappings were created between other IRI levels, allowing cracking values to be imputed across the dataset.

Although this procedure does not substitute for measurement, it is a logical and systematic way of estimating cracking when data are not available. The procedure allows for uniformity in the assessment of a roadway's condition and facilitates the application of performance models and decision-making tools that call for cracking as one of the inputs. Overall, the process of imputation is a realistic option in data-limited environments that complements engineering judgment and standard pavement condition thresholds.

3.4.7 Pavement Management System

After the development of the deterioration curves by the above-mentioned process, the performance correlation analysis was made in order to estimate cracking values that correspond to the actual IRI values from the original dataset. Further, an optimization procedure was conducted with the aim of generating PMS scenarios with a time span of six years. The choice of six years for the analysis horizon is linked to the length of the pavement performance dataset for the Alberta province, thus allowing a more in-depth and meaningful comparison between the traditional PMS approaches, which mainly rely on indirect indicators like IRI for making investment decisions, and the new method that utilizes direct structural damage indicators such as rutting and cracking. This time frame facilitates the assessment of the maintenance strategies under consideration for their long-term viability as well as the assurance that the obtained optimization outcomes are grounded in performance data validated by empirical evidence from the Alberta transportation network.

3.4.8 Treatment Effectiveness Analysis

The culmination of the methodology entailed assessing the efficacy of the treatments by formulating and analyzing Transition Probability Matrices (TPMs). TPM is a method of quantifying the probabilities of pavement conditions changing over time, offering crucial information regarding the treatment strategies' long-term effects.

Two sets of TPMs were created to support this appraisal. The first set was based on actual rutting measurements from the original dataset, with treatment decisions based largely on thresholds from

the IRI. It represents the standard IRI-based treatment process employed within the treatment decision-making of the dataset. The second set of TPMs was formulated based on rutting values that were calibrated through the MEPDG. These were incorporated into PMSs framework where the direct damage indicators of rutting and cracking are prioritized foremost, serving as the criteria on which to choose the right treatment.

By comparing TPMs resulting from these two methods, differences in treatment efficacy and changes in pavement conditions when moving from an IRI-based method to one based on direct distress indicators can be evaluated. The prominence of integrating mechanistic-empirical calibration into practices of managing pavements is thus reflected by the foregoing. It not only improves the reliability of prognoses of long-term performance but also ensures that maintenance and rehabilitation measures are closer to the structural requirements of pavements. The transformation eventually reflects the potential of making better decisions and achieving sustainable pavements. The procedure is outlined below in a systematic way:

3.4.8.1 Matrix Structure Definition

Transition Probability Matrices (TPMs) were carefully constructed to present a holistic and intuitive form of modeling of the transition of pavement conditions after different interventions. The "before treatment" states are represented by the matrix rows, which show the original conditions of the pavement before intervention, and the "after treatment" states are represented by the columns, which reflect the conditions of the pavement after a particular treatment has been applied. The systematic organization makes it possible to see explicitly and in detail how the conditions of the pavements develop through time based on maintenance and rehabilitation activities.

Structure, Interpretation, and Visual Representation of the TPM:

TPM is organized in such a way that the rows represent the pavement condition, in terms of rutting, prior to treatment, and the columns represent the pavement condition following the treatment. Each cell in the matrix describes the number of sections transitioning between various rutting values over a time interval (one year). This organization provides an overall picture of the response of the pavement sections to maintenance treatments and allows the effectiveness of treatments to be studied exhaustively. The main parts of the matrix are shown in Figure 3-11 can be described as follows:

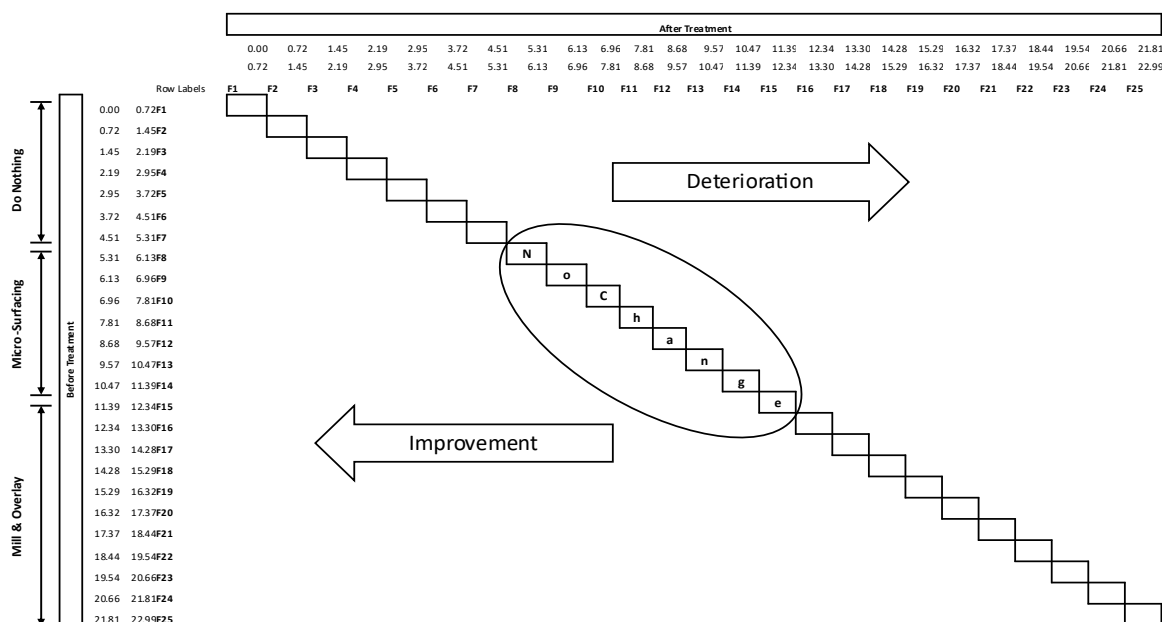


Figure 3-11: Transition Probability Matrix (TPM) Mechanism

Every cell in the matrix measures the likelihood or occurrence of a transition from a particular state, "pre-treatment" to a specific "post-treatment" state. For instance, as shown on Figure 3-11, a transition measured over a period of 25 years creates a 25 x 25 matrix, with the following particularities:

- **Main Diagonal:** illustrates segments where no change in pavement condition happened. These entries imply that the treatment given either maintained the existing condition or no treatment was applied, resulting in rutting values being held in the same state.
- **Left of the Diagonal:** This part of the matrix represents the improvements in pavement condition. Segments falling within this part have experienced a reduction in rutting depth, indicating that the applied treatment effectively restored or enhanced the road's quality. For example, if a segment with an original rutting depth between 6.96 and 7.81 mm (F10) moves to a lower rutting depth (e.g., 6.5 mm or F9), it implies an improvement caused by the treatment.
- **Right of the Diagonal:** This part of the matrix reflects deterioration in the condition of the pavement. Segments found in this zone exhibit an increase in rutting depth, indicating that either no corrective actions were taken or that the interventions employed were insufficient to prevent further deterioration. For instance, if a segment has a rutting depth between 6.13 and 6.96 mm (F9) and later on shows a higher rutting depth (e.g., 7.5 mm or F10), it means that the condition worsened over time.

This visual representation aligns with the TPM data, providing a clear framework for understanding how different treatments influence pavement condition transitions over time. For instance, a concentration of entries to the left of the diagonal indicates widespread improvements, while entries to the right highlight areas of concern where deterioration has occurred despite maintenance efforts.

The TPM serves as a powerful tool for evaluating the effectiveness of pavement treatments and guiding decision-making in road maintenance. By systematically analyzing transition probabilities, the TPM not only quantifies the benefits of optimized maintenance strategies but also identifies inefficiencies in traditional approaches. The insights gained from the TPM enable agencies to adopt proactive, data-driven maintenance practices that maximize resource allocation, extend the service life of road assets, and ensure sustainable and cost-effective infrastructure management.

This design of the TPM not only makes it possible to find effective treatments but also points to where the current strategy falls short. For example, if there are a disproportionate number of transitions along the vertical center of the matrix (where "prior to treatment" and "post treatment" states are the same), it means that the treatment used was not effective or adequate to recover from the damage. Blank areas within the matrix also serve to identify situations where there was no treatment that applied or where there were not enough instances of a particular transition to show, which identifies areas of potential weaknesses within the maintenance plan.

By integrating the TPMs in this way, the methodology is a highly effective means of comparing and analyzing the results of various treatment methods under diverse conditions of pavements. Both highlighting the differences between Alberta's policy of making investments based on indirect damage metrics such as IRI and the new PMSs that makes direct damage metrics like Rutting and Cracking a priority, as well as emphasizing the value of prioritizing maintenance according to structural requirements, are facilitated by a systematic strategy. Quantification and visualization of these shifts within a probabilistic context allow transportation agencies to make informed decisions based on data, ensuring that repair funding is spent on treatments that correct structural weaknesses, not just enhance ride quality. By making shifts to direct damage metrics, the methodology allows the development of improved pavement management measures that are better suited to meet both structural and performance requirements. Ultimately, the method promotes the creation of cost-saving, sustainable, and structurally sound road maintenance practices that serve transportation agencies and road users equally.

3.4.8.2 Boundary Definition

Boundaries for the damage indicator (i.e., rutting intervals) were established based on the average damage values across all homogeneous traffic groups, ensuring a unified and generalized classification framework for the entire dataset. The boundaries were carefully defined to encompass 25 distinct condition states, ranging from minimal to severe rutting, the values used in the case study presented in Section 4.3 are used to illustrate boundaries and shown Table 3-14:

Table 3-14: TPM Rutting Boundaries

Rutting (mm)			Category
From	To		
0.00	0.72		F1
0.72	1.45		F2
1.45	2.19		F3
2.19	2.95		F4
2.95	3.72		F5
3.72	4.51		F6
4.51	5.31		F7
5.31	6.13		F8
6.13	6.96		F9
6.96	7.81		F10
7.81	8.68		F11
8.68	9.57		F12
9.57	10.47		F13
10.47	11.39		F14
11.39	12.34		F15
12.34	13.30		F16
13.30	14.28		F17
14.28	15.29		F18
15.29	16.32		F19
16.32	17.37		F20
17.37	18.44		F21
18.44	19.54		F22
19.54	20.66		F23
20.66	21.81		F24
21.81	22.99		F25

These boundaries were critical in systematically categorizing the data into discrete condition states, providing a consistent and structured approach for analysis across the entire road network. For example:

- F1 (0.00–0.72 mm): Represents sections with minimal rutting, indicating good structural integrity and minimal apparent age.
- F25 (21.81–22.99 mm): Represents sections with severe rutting, reflecting advanced structural deterioration.

This method not only facilitated the accurate representation of pavement deterioration patterns but also enabled a more comprehensive understanding of the progression of structural damage over time, independent of variations in traffic conditions. By averaging the boundaries across all homogeneous groups, the analysis ensured a holistic perspective, supporting the development of robust and broadly applicable insights into pavement performance and treatment effectiveness.

3.4.8.3 Unique Identifiers

Each interval was also given a distinctive code, from F1 to F25, to facilitate classification and analysis. The codes represented unique ranges of rutting values that served to precisely categorize and accurately evaluate pavement conditions.

3.4.8.4 Data Sorting and Classification

To identify sequentially consecutive years where interventions (treatments) have been implemented, consecutive year pair data (e.g., 2018–2019, 2019–2020) was classified and sorted based on a systematic method. The method entailed comparing consecutive year Rutting values to identify "before treatment" and "after treatment" conditions. The analysis specifically targeted identifying occurrences where Rutting values in the first year were greater than in the next year, signifying that a treatment to enhance the conditions of the pavements was applied.

The process of classification was created to make the process of identifying treated sections accurate and consistent. By separating the subject Rutting values relating to before and after treatment, the procedure created a standard method of analyzing the effects of interventions on the performance of pavements. The method not only simplified the structuring of intricate data but also created a solid platform to build Transition Probability Matrices (TPMs). These TPMs were critical to quantitatively analyze how the pavement conditions changed over time under the influence of different treatments to understand how effective they were.

By means of this systematic classification, the research ensured that the analysis encompassed all applicable data in a clear and understandable way. The resultant dataset served as a basis for the subsequent analyses, including the classification of pavement conditions into pre-defined states and the analysis of the treatment results by traffic intensity classes. The methodical rigor served to immensely increase the strength of the results, thereby enabling informed decision-making in pavement management and maintenance plans.

3.4.8.5 Yearly Pair Analysis

This process was then repeated for each pair of consecutive years (2018–2019, 2019–2020, 2020–2021, etc.), with each set of corresponding data points incorporated into the analysis.

3.4.8.6 Data Consolidation

For the overall dataset, the before-treatment and after-treatment values of each year pair were combined into a single dataset. This was done independently with both the actual pavement data from Alberta's Ministry of Transportation and the PMSs data that was created using calibrated damage values through direct damage indicators. The data were ordered from lowest to highest damage (i.e., rutting) values by before-treatment values, making the datasets uniform and analyzable. The dataset then comprised two columns at this point in time, one of before-treatment values and one of after-treatment values. The systematic method brought clarity to comparing the actual data with the PMSs data, making treatment effectiveness assessment over the overall road network a better-informed process.

3.4.8.7 Group Classification

Rutting values were grouped into pre-defined condition states (e.g., F1 to F25) from the set boundaries and unique identifiers. The process of grouping ensured each Rutting value was consistently allocated to its respective state group, allowing a systematic index to support subsequent analysis. The resultant categorized data served as the basis to create the Transition Probability Matrices (TPMs), allowing accurate and systematic representation of shifts of pavement conditions and treatment efficacy.

3.4.8.8 Final Data Structure

Four core variables formed the basis of the final dataset, which was carefully designed to provide a comparative evaluation of both the field-collected performance measurements and the results produced by the PMSs simulations. The first variable named "Before Treatment," describes the rutting depths that were recorded just before the maintenance intervention was implemented. It is very important that this original measure is used in defining the starting point of the condition of each pavement section, and also it allows the changes in performance that have been made to be measured against it.

The second variable, "After Treatment," captures the rutting depths measured immediately after the maintenance treatment was applied. Thus, by comparing the post-treatment values with their respective pre-treatment baselines, the first point of contact between each maintenance method and its relative effectiveness can be numerically evaluated in both the real and the simulated datasets. Going beyond mere deformation metrics, the third variable - "Group (Before)" - changes the continuous pre-treatment rutting depths into condition state categories (e.g., F1, F2, F3) based on threshold ranges that are defined very strictly. Besides serving as a means to interpret condition based on common ground found even in the most different pavement sections, this classification also ensures that the performance criteria used are the same for each dataset.

The fourth variable - "Group (After)" - identifies the same class given to the post-treatment rutting measurements by utilizing this categorical schema. Monitoring the "Group (Before)" and "Group (After)" changes for each pavement segment can thus show by precise numbers the treatment-induced improvements or deteriorations in condition state. The use of this consistent, four-variable framework for both the original and PMS-derived datasets results in methodological consistency during the analytical process, comparability that has been enhanced, and robustness of conclusions about calibration accuracy and optimization effectiveness of the PMS framework have been strengthened.

3.4.8.9 Matrix Completion and Interpretation

The count data were used to fill the TPMs, directly illustrating transitions across pavement condition states. Interpretation of motions was enabled by quantifying the number of "before treatment" to "after treatment" states.

3.4.9 Comparative Analysis of Treatment Effectiveness: Alberta's Original Data vs. Optimized-PMSs

Traditional representations of pavement condition, such as average metrics or summary statistics, often fail to capture the dynamic nature of annual maintenance programs. This limitation underscores the need for more advanced analytical tools, such as Transition Probability Matrices (TPMs), to provide a tangible representation of deterioration patterns and the impact of maintenance interventions. This section presents a comparative analysis of treatment effectiveness between the actual maintenance policy implemented by Alberta's Ministry of Transportation (original data) and the optimized-PMSs developed in this study. The comparison leverages TPMs to evaluate how each approach influences pavement conditions over time, offering insights into their respective strengths and limitations.

4 Data Analysis, Results, and Discussion

This chapter presents and discusses the findings derived from the systematic investigation conducted to address the three primary objectives of this study. These objectives were pursued through the application of three distinct methodologies, each carefully designed and outlined in the previous chapters to ensure a comprehensive exploration of the research questions. The first objective, which sought to examine the feasibility, effectiveness, and likely benefits of MEPDG integration in PMS in increasing pavement design accuracy, performance prediction, and maintenance optimal strategies due to the particular climatic and environmental conditions, was addressed using [Methodology 1]. The second objective, focused on the incorporation of Pavement Management Systems into the Mechanistic-Empirical Pavement Design Guide framework, ensuring due consideration to all peculiar challenges arising from limited or no pavement data, was tackled through [Methodology 2]. Finally, the third objective, aimed at estimating the effectiveness of pavement interventions through MEPDG indicators and performance curves for rutting, was examined via [Methodology 3].

4.1 Case Study One (Alaska)

4.1.1 MEPDG Calibration of Deterioration Model

To comprehensively assess pavement deterioration, two different approaches were used. First, Amador-Jiménez & Mrawira (2009) approach was applied to build deterioration curves from two consecutive years. This method provided insights into the rate of deterioration within the pavement over its lifecycle, with particular focus on rutting and cracking. Second, the MEPDG models were utilized to predict pavement deterioration over its lifespan, predicting future pavement performance for each traffic intensity group.

Following the development of deterioration curves for rutting and cracking using the MEPDG models, a comprehensive calibration process was undertaken. This step was essential to ensure that the predictive accuracy of the MEPDG models was adequately refined and aligned with the observed field performance data. The calibration process involved adjusting key model parameters to minimize discrepancies between the predicted and actual pavement performance metrics, thereby enhancing the reliability and applicability of the models. By iteratively fine-tuning these parameters, aiming to achieve a higher degree of precision in the predictions, ensuring that the models could effectively capture the complex mechanisms underlying pavement deterioration. This rigorous calibration not only validated the robustness of the MEPDG framework but also reinforced its suitability for practical engineering applications.

The MEPDG curves were calibrated to align with the method proposed by Amador-Jiménez & Mrawira (2009) for modeling rutting, as illustrated in Figure 4-1. The same calibration procedure was applied to cracking, and both models demonstrated comparable results, as shown in Figure 4-1 which illustrates the rutting progression over time for a representative subset of the road network with low traffic intensities. It demonstrates the layer-specific potential of rutting as

predicted by the MEPDG and is shown for the hot mix asphalt (HMA), base, and subbase layers by the circle, triangle, and X markers, respectively. While the cumulative rut which is across all layers is shown by the dashed line with rhombus markers. Comparing these predictions is the rut, which is the progression by the Amador-Jiménez & Mrawira (2009) approximation method, which represents the overall rut without further division by structural layer. All MEPDG curves were locally calibrated against field observations. The calibrated MEPDG predictions are very close to the Amador results during the first ten years of service, as evident, after which, these two methods separate. This separation can be mainly explained by two reasons. One is the limited nature of the Amador method, which does not consider layer-specific deformation processes, and the other is the possibility that, after the tenth year, new distress data will be used to update the MEPDG calibration. Therefore, the difference that can be seen beyond the ten-year point is both methodologically cognizable and envisaged within the ongoing calibration framework. Figure 4-2 illustrates the cracking percentage progression over time for the same traffic intensity group as an example. It compares the MEPDG calibrated cracking percentage with Amador method. However, the calibration for the cracking percentage is showing a better result as the values from both methods are close for the entire life of the pavement. This consistent calibration process highlights the robustness and reliability of the MEPDG framework in accurately predicting pavement performance across different distress types.

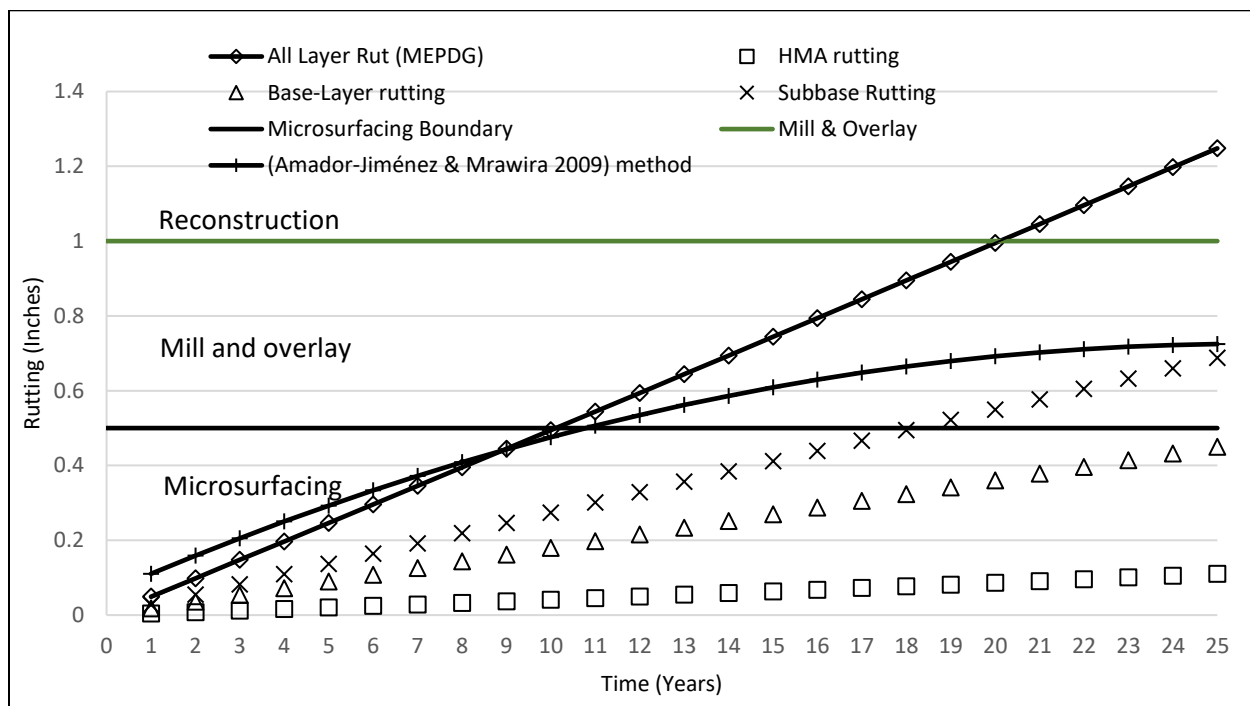


Figure 4-1 : Rutting Damage Progression Over time for Low ESALs traffic group

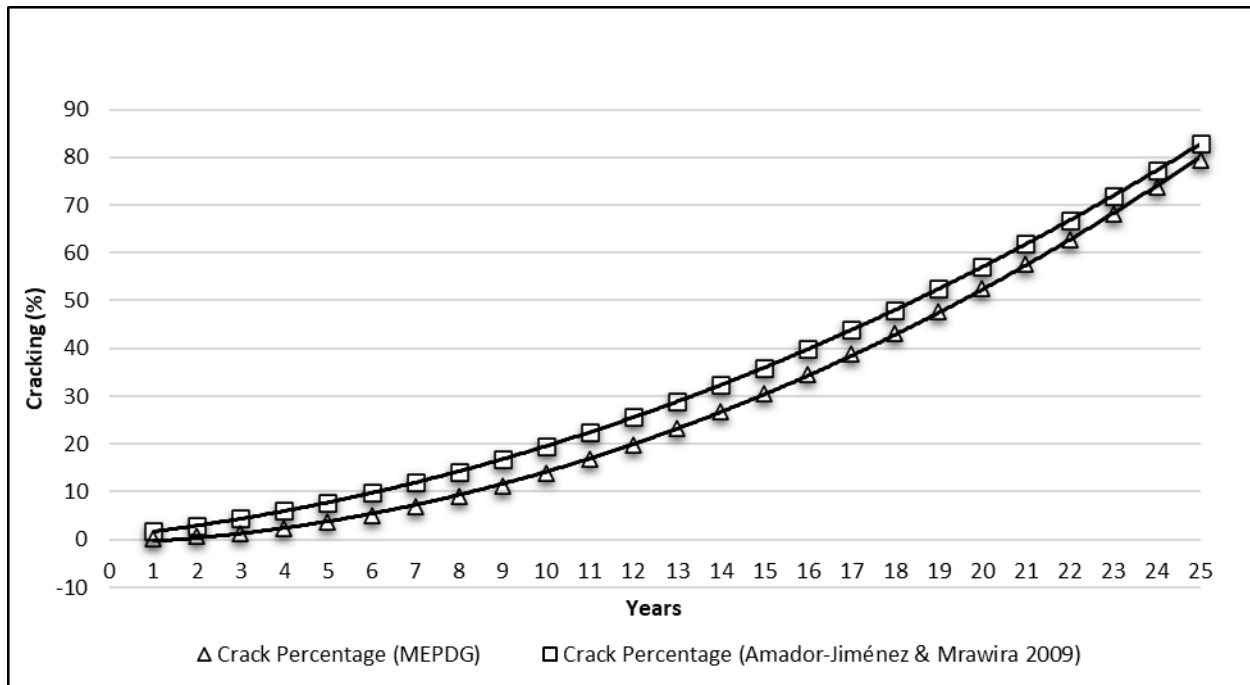


Figure 4-2 : Cracking Percentage Progression Over time for Low ESALs traffic group

The developed MEPDG rutting model demonstrates a very strong predictive capability for pavements subjected to rutting, evidenced by an R-square value of 0.9385

To further validate the model's performance, several error metrics were analyzed, providing additional insights into its predictive accuracy. The Mean Absolute Error (MAE) was found to be 0.1646 inches. Similarly, the Root Mean Squared Error (RMSE), which penalizes larger deviations more heavily than the MAE, was calculated to be 0.2272 inches. This relatively low RMSE value further confirms the model's precision and reliability in predicting rutting progression over time. Collectively, these error metrics reinforce the conclusion that the MEPDG rutting model is capable of producing accurate and dependable predictions, making it a valuable tool for pavement management and design.

Despite the model's good performance, it is important to acknowledge certain limitations that may influence its predictive accuracy. One key factor is the quality and comprehensiveness of the data used for model development. Pavement performance is influenced by a multitude of variables, including material properties, construction practices, traffic loading, and environmental conditions. Variability in the composition of pavement materials, such as differences in aggregate gradation, binder content, and mix design, can introduce uncertainties that are challenging to account for fully within the model. Additionally, environmental factors, such as temperature fluctuations, precipitation patterns, and freeze-thaw cycles, play a critical role in pavement deterioration but may not always be captured with sufficient granularity in the available datasets.

Another limitation lies in the inherent complexity of modeling real-world pavement systems, which often exhibit nonlinear behaviors and interactions that are difficult to replicate precisely in

a predictive framework. For instance, localized anomalies, such as subgrade instability or drainage issues, may disproportionately affect rutting performance but are not always reflected in the broader dataset. Furthermore, the long-term effects of climate change, which could alter precipitation regimes and temperature profiles, pose an additional challenge to the model's applicability over extended time horizons.

In light of these considerations, while the developed MEPDG rutting model represents a significant advancement in predictive modeling for pavement performance, it is essential to approach its application with a degree of caution. Continuous efforts should be made to refine the model by incorporating higher-quality data, accounting for regional variations, and integrating emerging technologies such as machine learning and remote sensing to enhance data collection and analysis capabilities. By addressing these limitations, future iterations of the model can further improve its accuracy and broaden its applicability across diverse geographic and climatic contexts. Ultimately, the successful integration of such advanced predictive tools into Pavement Management Systems (PMS) holds the potential to revolutionize decision-making processes, enabling more efficient resource allocation and sustainable infrastructure management. Metrics for the rutting and cracking fitness models are presented in Table 4-1, all ratios showed good fitness.

Table 4-1: Rutting model performance metrics

Metric	Value	
	Rutting	Cracking
Mean Absolute Error (MAE)	16.46%	2.1250 %
Mean Squared Error (MSE)	5.16%	21.2501 %
Root Mean Squared Error	22.72%	4.6098 %
R-Squared	0.9386	0.9979

The MEPDG-calibrated models exhibit excellent predictive capabilities, with the cracking model being able to explain 99.79% of the variance in the data ($R^2 = 0.9979$), while along with it the rutting model reached should the R^2 of 0.9386. These very good numbers present a great success if compared to other studies in the field that deal with different areas of research. To be more specific, local calibration studies for engineering prediction of road works in the range of 0.75-0.90 are mostly encountered for different types of cracking-related problems (Diana et al., 2024; Liu et al., 2022), and for rutting situations, the R^2 numbers usually fall between 0.70 and 0.85 (Fernando & Coelho, 2016; K. D. Hall et al., 2006). The extremely high R^2 values registered clearly reveal the bright performance of the models and the successful tuning to local conditions.

For instance, the rutting model reports errors that can be measured by MAE of 16.46% and RMSE of 22.72% and these levels of precision are in agreement with other similar MEPDG calibration studies. The researchers in Arkansas have found error metrics similar to those reported here for rutting prediction, where they have also demonstrated the effectiveness of their local calibration by shifting the standard error of estimate from 8.68 to 2.17 mm (K. D. Hall et al., 2006). There are studies from other regions in which MAE values for rutting models fall between 10% and 25% are

reported, and the differences among these come from the utilized datasets (Fernando & Coelho, 2016; Liu et al., 2022). The cracking model presents better performance, as it has a MAE of 2.13% and RMSE of 4.61%, which are much lower than in most of the published papers where cracking model errors have been reported in the range of 15-30% (Diana et al., 2024; Liu et al., 2022).

The fact that both high R^2 and low error metrics are observed simultaneously for both models can be taken as a sign for the consistency and reliability of the models' inference. The rutting model's error measures are somewhat worse than those for the cracking model, but this difference is within the usual pattern of MEPDG studies, where rutting is dealt with as the most complicated case due mainly to the extensive range of interactions between the physical properties of materials, ambient conditions, and traffic loads that consequently widen the variance of the rutting process. The accuracy of both models is either within or above what has been reported in the literature for the successful implementation of the MEPDG.

Considering the inherent variability in pavement cracking data, which is influenced by factors such as material properties, environmental conditions, and traffic loading, the performance of the model is particularly impressive. The combination of an exceptionally high R-squared value and relatively low error metrics highlights the model's effectiveness in accurately predicting the progression of cracking over time. Such strong performance not only validates the model's utility but also reinforces its potential as a valuable tool for pavement management and decision-making.

Despite these promising results, it is important to acknowledge certain limitations that may affect the model's predictive accuracy. Factors such as inconsistencies in data collection methods, variations in pavement material composition, and localized environmental influences can introduce uncertainties that may not be fully captured by the model. Additionally, the long-term effects of climate change and evolving traffic patterns pose challenges to the model's applicability over extended time horizons. Addressing these limitations through improved data quality, advanced modeling techniques, and continuous calibration will further enhance the model's reliability and broaden its applicability across diverse geographic and climatic contexts.

4.1.2 Evaluation of Key Pavement Performance Indicators and Financial Implications:

This section focuses on the evaluation of key performance metrics that collectively provide a comprehensive understanding of the pavement network's condition and the associated financial implications. The analysis centers on four critical aspects: Pavement Overall Condition, which offers a broad assessment of the network's functional and structural integrity; Average Network Rutting, which quantifies deformation-related distress and its impact on ride quality and safety; Network Cracking Percentage, which measures the extent of surface cracking as an indicator of pavement deterioration; and Annual Expenditure, which reflects the financial resources required to maintain and rehabilitate the network effectively.

Each of these metrics has been examined using rigorous analytical techniques, ensuring a detailed and accurate representation of their current status and trends over time. The results presented in this section are discussed in relation to their significance for pavement management, offering insights into how these factors interact and influence decision-making processes. By addressing these dimensions, this analysis aims to highlight areas of strength and concern within the network, while also identifying opportunities for optimizing resource allocation and improving long-term performance. This discussion sets the stage for evidence-based recommendations to enhance the sustainability and efficiency of pavement maintenance strategies.

4.1.2.1 Pavement Overall Condition

This study examines the overall condition of pavements across a road network that is generally in good condition and emphasizes sustained investment in maintenance to preserve this condition. The network is managed using PMSs that integrate key performance indicators - specifically rutting and cracking data - into its decision-making framework. Figure 4-3 illustrates the changes in pavement condition over a 30-year period, with the y-axis representing the overall condition index calculated as a weighted combination of rutting and cracking metrics adjusted by segment length. It is important to note that in this context, higher condition values signify greater pavement distress and thus worse performance, while lower values indicate better condition.

The observed trend in the graph reveals periodic fluctuations, yet an overall pattern of improvement is evident, particularly in the way the peaks (worst conditions) tend to decrease slightly over time. This suggests that the PMS is effectively mitigating pavement deterioration through timely and targeted maintenance interventions. The repeating cyclical nature of the curve also highlights the possible influence of regular maintenance schedules, where treatment is applied after certain condition thresholds are reached, leading to periodic improvements followed by gradual deterioration.

However, these fluctuations also underscore the complexity of managing a large road network, where factors such as the severity of initial pavement distress, the precision and timing of maintenance actions, and external influences like traffic load and environmental conditions all play a role. In some periods, a delayed response or inadequate treatment may contribute to a spike in condition values, indicating a temporary decline in pavement quality.

To enhance the effectiveness of the PMS, further research is recommended. This should include detailed, section-level monitoring to capture localized variations in performance, a thorough evaluation of the types and timing of maintenance interventions, and a cost-benefit analysis to ensure optimal resource allocation. Incorporating predictive modeling and long-term performance tracking will also help refine intervention strategies, thereby supporting the long-term sustainability and reliability of the road network.

Overall, the graph supports the conclusion that a well-structured PMS, grounded in detailed distress performance data such as rutting and cracking, can contribute significantly to preserving pavement condition over time, even in the face of recurring wear and environmental stressors.

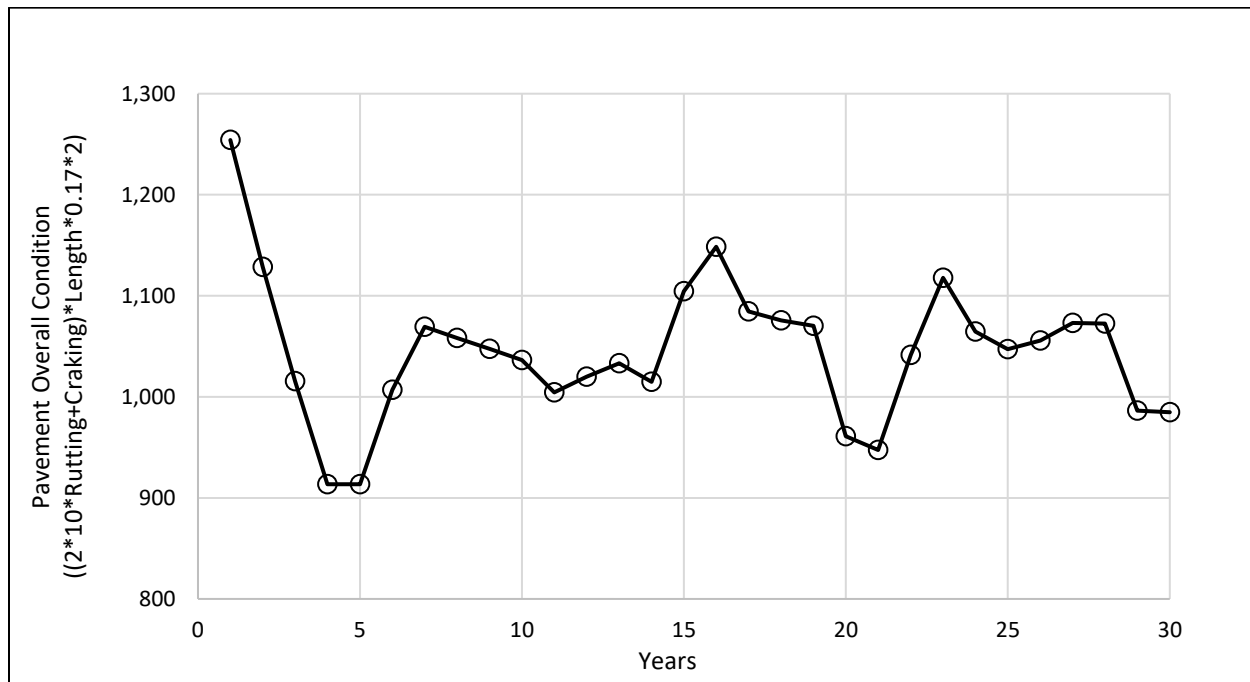


Figure 4-3 : Pavement Overall condition over time considering maintenance

4.1.2.2 Average Network Rutting

Figure 4-4 illustrates the trend in average rut depth across the pavement network over a 30-year period. The x-axis represents time in years, while the y-axis displays the average rutting in inches, a key indicator of surface deformation due to repeated traffic loads. This graph serves as an important metric for evaluating the effectiveness of the implemented PMSs.

At the beginning of the timeline, rutting values are relatively high - above 0.23 inches - indicating the presence of significant surface distress. However, a sharp decline occurs within the first few years, suggesting a successful early intervention phase. This initial improvement reflects the PMS's ability to promptly detect and prioritize sections with critical rutting issues, allowing for effective deployment of maintenance treatments.

Following this initial drop, the average network rutting levels fluctuate in a cyclical pattern but remain quite good, with values generally oscillating between 0.16 and 0.22 inches. These oscillations likely correspond to routine maintenance cycles and treatment triggers within the PMS. Periods of increasing rutting are followed by noticeable reductions, which implies that maintenance activities—either preventive or corrective—are being carried out when needed to maintain performance thresholds.

The recurrence of these peaks and valleys over the years indicates that while rutting continues to develop over time, it is being managed proactively rather than reactively. In particular, the consistent return to lower rut depth levels following spikes highlights the sustained effectiveness of the PMS. This pattern aligns with best practices in pavement management, where well-timed interventions can slow the rate of deterioration and extend pavement service life.

It's also worth noting that rutting never returns to the higher initial levels after the first intervention period, which reinforces the idea that the PMS has established a long-term maintenance regime capable of stabilizing network performance. Continued monitoring and data-driven adjustments will be essential to further refine this system, potentially allowing for even earlier detection of distress trends and more cost-effective maintenance scheduling.

In summary, the average rutting trend over three decades supports the conclusion that the PMS in place is successfully managing rut progression, optimizing pavement performance, and preserving overall ride quality throughout the network.

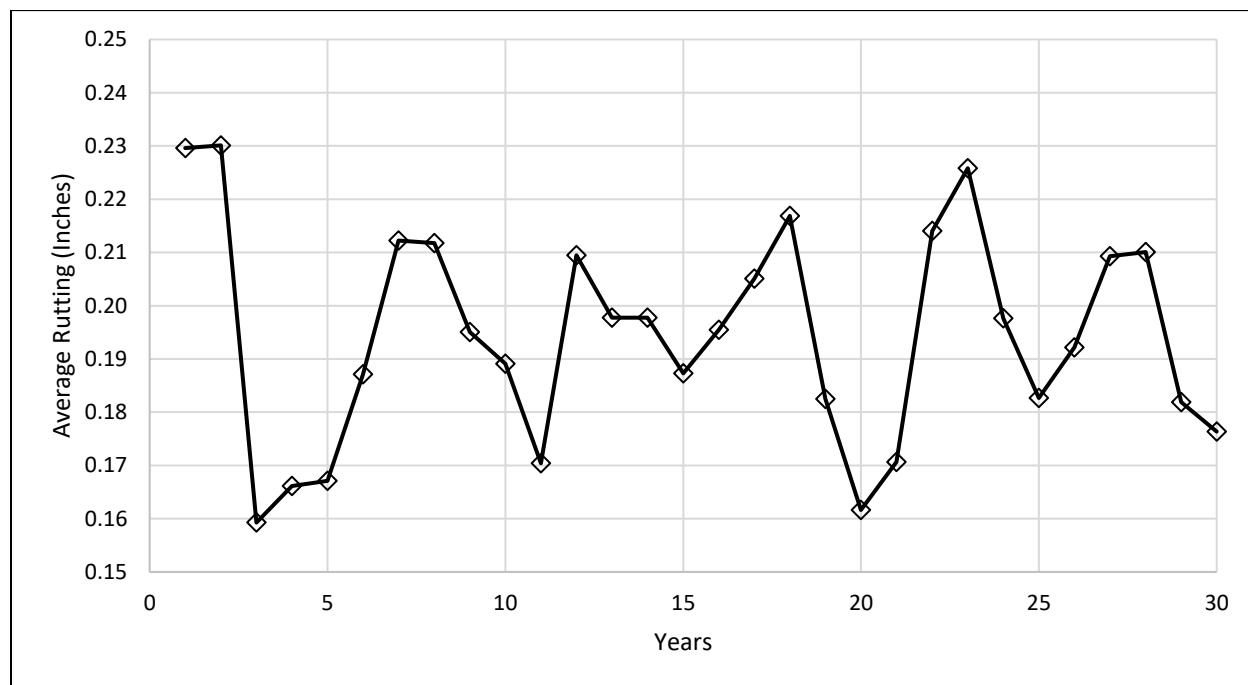


Figure 4-4 : Average Network Rutting Over Time After Maintenance

4.1.2.3 Network Cracking Percentage

Figure 4-5 presents a line graph that illustrates the progression of pavement cracking in the network over time (x-axis) and evaluates the efficiency of the applied PMSs. The graph provides valuable insights into how the PMS has influenced the severity of cracking (y-axis) across the years.

In the early stages of the timeline (approximately the first five years), the graph shows a significant decline in the severity of pavement cracking. This initial drop is a clear indicator of the success of the PMS in effectively prioritizing and addressing critical maintenance requirements. During this period, the system likely identified high-priority areas with severe cracking and implemented timely interventions such as crack sealing or other repair measures. These proactive actions helped to mitigate further damage and stabilize the overall condition of the pavement network.

Following this initial decline, the graph reveals a period of stabilization or a gradual decline in cracking levels, which spans from around year 5 to year 25. This phase suggests that the maintenance activities assigned by the PMS - such as routine inspections, targeted crack sealing, and possibly preventive treatments - are effectively preventing new cracks from forming and existing cracks from worsening. The consistency in these trends aligns well with established principles of pavement management, which emphasize the importance of early intervention through measures like crack sealing and repair. By addressing fractures at an early stage, these interventions can halt the propagation of cracks, thereby enhancing the performance and extending the lifespan of the pavement.

It is worth noting that the graph also exhibits some fluctuations in cracking severity throughout the timeline. For instance, there are periods where the cracking percentage increases slightly before stabilizing again. These fluctuations could be attributed to various factors, such as changes in traffic loads, environmental conditions, or the introduction of new sections of pavement that may have different material properties or construction standards. However, despite these minor variations, the overall trend remains positive, indicating that the PMS is successfully managing the network's condition over the long term.

The final segment of the graph, from approximately year 25 onward, shows a slight downward trend in cracking severity, suggesting that the maintenance efforts are not only effective but also sustainable. This consistent pattern reinforces the idea that the PMS is operating efficiently and adapting to the evolving needs of the pavement network. By continuously monitoring and addressing cracking issues, the system ensures that the infrastructure remains in good condition, reducing the likelihood of costly repairs or premature replacement.

In summary, Figure 4-5 demonstrates the effectiveness of the PMSs in controlling and mitigating pavement cracking over time. The initial decline in cracking severity highlights the success of early interventions, while the subsequent stabilization and gradual improvements underscore the system's ability to maintain optimal pavement conditions. This graph serves as a compelling example of how proactive and data-driven maintenance strategies based on direct damage indicators can significantly enhance the durability and performance of road networks, ultimately leading to cost savings and improved safety for users.

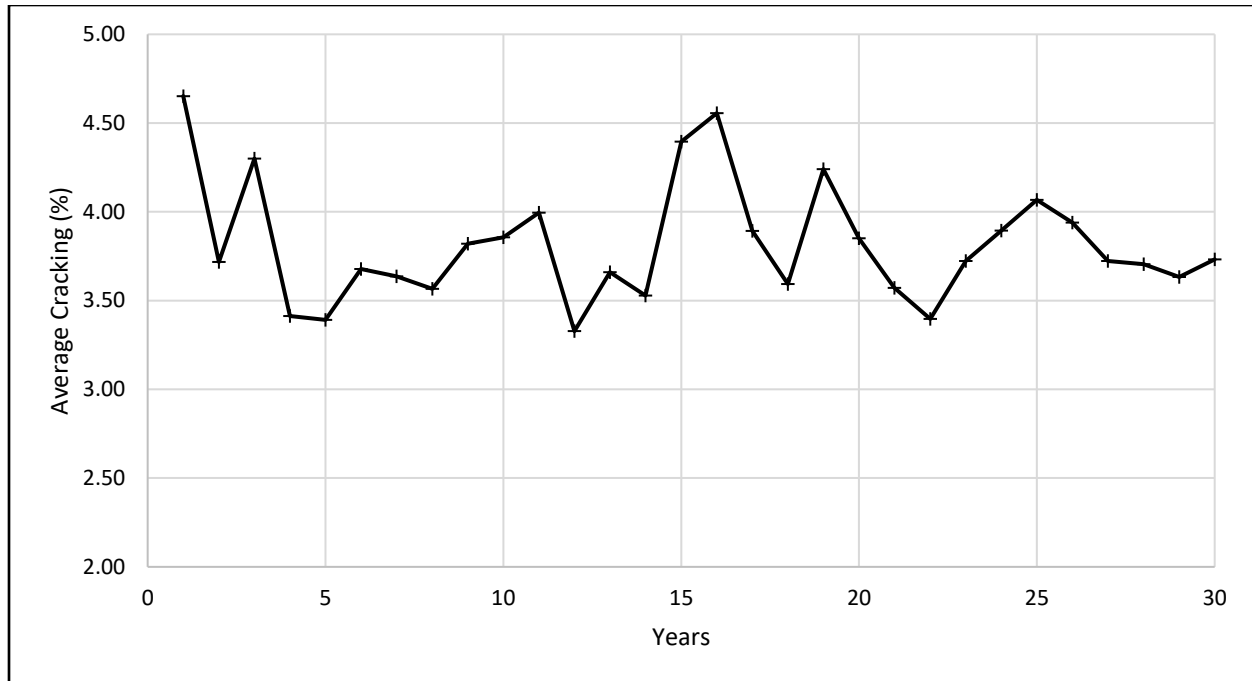


Figure 4-5 : Network Cracking Percentage Over Time After Maintenance

4.1.2.4 Annual Expenditure

The graph in Figure 4-6 provides a clear depiction of the progression of annual expenditures for pavement maintenance works over time, with the x-axis representing the years and the y-axis showing the total cost in USD. This visualization offers valuable insights into how the PMSs has influenced spending patterns and the overall efficiency of maintenance efforts.

In the early years (approximately the first five years), the graph reveals a significant increase in annual expenditures. This spike in spending can be attributed to the necessity of addressing a substantial backlog of maintenance needs and undertaking more costly rehabilitation projects for pavement sections that were in poor condition. During this period, the network likely required extensive repairs, including structural improvements or complete reconstruction of deteriorated areas. These high-cost interventions were essential to restore the pavement to a functional state and prevent further degradation.

Transitioning pavement management strategies from reactive, backlog-driven rehabilitation to a more proactive, condition-triggered approach aligns with both international literature and real-world expenditure trends in Alaska and other regions. By prioritizing preventive maintenance - such as timely crack sealing, thin overlays, and chip seals - agencies stabilize annual outlays and defer costly, major interventions, ultimately decreasing long-term life-cycle costs (Department of Transportation and Public Facilities, 2024). This approach is reinforced by life-cycle cost analysis, which demonstrates the economic value of early, lower-cost treatments compared to delayed, heavy rehabilitation measures. Dedicated annual budgets for preventive actions, sometimes as modest as USD 1,000,000 for sizable deteriorating networks, provide realistic, academically

defensible scenarios for evaluating policy and optimization choices. Such conditions require agencies to triage repairs toward segments exhibiting real structural distress, as accurate prioritization ensures limited funds are spent where failure risks are greatest, following best practices documented in North American surveys and case studies (Cuelho et al., 2006). This pattern is consistent in both wealthy and developing contexts, where constrained envelopes necessitate rigorous asset management and ongoing refinement of performance monitoring and treatment selection (Cuelho et al., 2006; Department of Transportation and Public Facilities, 2024).

As the PMS is deployed and preventative maintenance measures are implemented, there is a noticeable shift in spending trends. Following the initial surge in costs, the graph shows a progressive reduction in annual expenses in subsequent years. This decline indicates a transition from reactive, high-cost rehabilitation projects to a more proactive and sustainable maintenance approach. By prioritizing preventative measures such as routine inspections, crack sealing, surface treatments, and other low-cost interventions, the PMS effectively mitigates the need for expensive repairs later on. This strategic shift not only reduces immediate financial burdens but also enhances the long-term durability and performance of the pavement network.

The leveling out of expenses in the later years (from approximately year 10 onward) suggests that the PMS has established an efficient and consistent maintenance schedule. The relatively stable expenditure pattern implies that the system is successfully managing the network's condition through regular, cost-effective interventions. This consistency in spending reflects a well-balanced approach to maintenance, where resources are allocated strategically to preserve the pavement in a satisfactory state without incurring unnecessary costs.

It is worth noting that while the overall trend shows a reduction in annual expenditures, there are some fluctuations in spending throughout the timeline. For instance, certain years exhibit minor spikes in costs, which could be due to unforeseen events such as extreme weather conditions, traffic-related damages, or the introduction of new technologies requiring additional investment. However, these fluctuations are generally contained within a manageable range, indicating that the PMS is adaptable and capable of responding to unexpected challenges without derailing the overall cost-efficient strategy.

The graph also highlights the economic and environmental advantages of adopting a preventative maintenance approach. By addressing issues early and avoiding major rehabilitation projects, the PMS minimizes the use of resources and reduces the carbon footprint associated with large-scale construction activities. This approach not only saves money in the long run but also aligns with sustainability goals by promoting a more environmentally friendly infrastructure management strategy. Alternatively, road agencies can estimate the average annual cost from the 30 years analysis and re-run an optimization with the objective of optimizing levels of service subject to a fixed annual budget (increase only by inflation) in order to avoid the cycling nature of the annual maintenance expenditures. Such estimation is very common and left outside this research.

In conclusion, Figure 4-6 effectively illustrates the impact of the PMSs on annual maintenance expenditures. The initial increase in spending during the early years underscores the importance of addressing existing deficiencies, while the subsequent reduction and stabilization of costs demonstrate the effectiveness of preventative maintenance strategies. This transition towards a more sustainable and economically advantageous approach ensures that the pavement network remains in good condition, ultimately benefiting both public safety and fiscal responsibility.

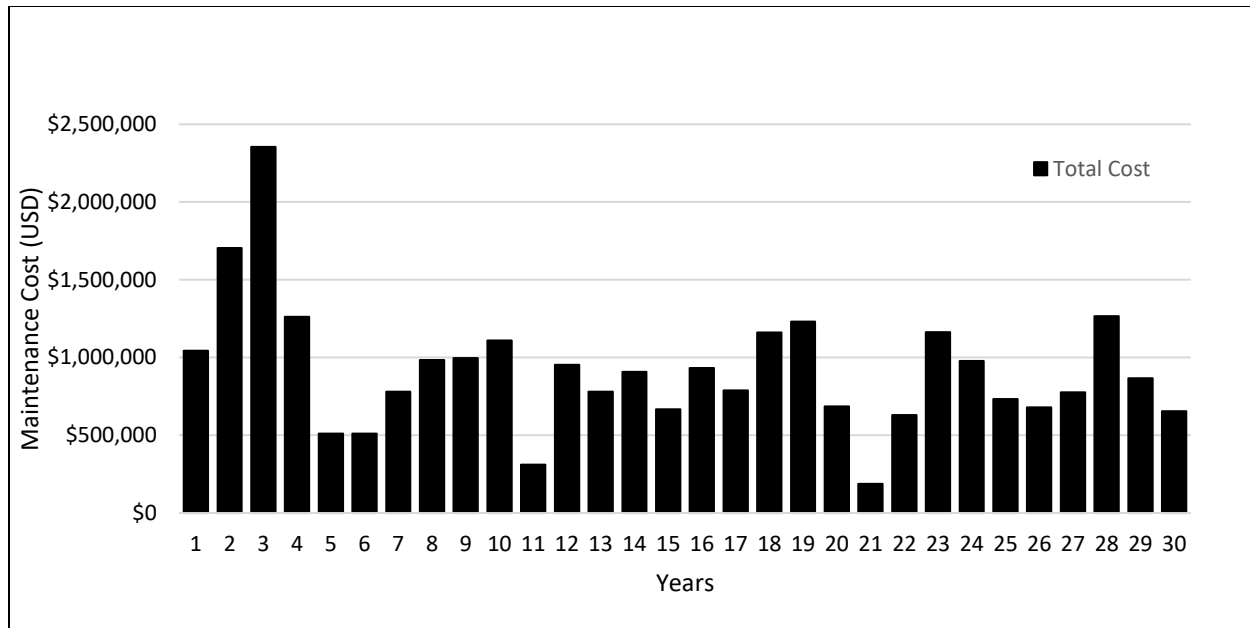


Figure 4-6 : Annual Expenditure over the pavement lifetime

4.1.3 Results discussion

The optimized PMS that was integrated with calibrated MEPDG rutting and cracking models had a clear lead over traditional IRI-based methods. By visually showing how structural distresses were being directly targeted, the system not only preserved the pavement health at a very good level but also managed to decrease the magnitude of rutting and cracking over the 30-year analysis period (Figure 4-4 and Figure 4-5). These findings highlight the accuracy of mechanistic-empirical interventions in cold regions, where the processes of freezing and thawing as well as very low temperatures, are the main causes of deterioration.

The study has managed to go beyond the problem of insufficient distress data for the long term, which is usually a major obstacle for MEPDG application, by using the Amador-Jiménez & Mrawira (2009) calibration method for only two temporal points. This method has allowed the establishment of suitable relationships between pavement distress and the apparent age associated with the level of deterioration, thus enabling a reliable prediction of performance and manifesting the possibility of using advanced PMSs in less data-rich environments.

The financial evaluation (Figure 4-6) has also shown that the optimized PMS is economically feasible and can be comfortably accommodated within Alaska's budget. An initial and pre-planned

investment in the first stages of rehabilitation treatments was followed by lower and more stable annual expenditures, thus showing how early and complete interventions can lead to savings and a network condition that is maintained over time. This spending pattern with a balanced allocation of resources confirms the ability of the optimization algorithm in combining maintenance activities that are in line with both performance targets and funding restrictions.

The Alaska case study offers convincing examples that properly measured, damage-indicator-based PMSs may be able to increase the lifespan of the pavement, make the use of the available resources more efficient, and adjust to the peculiarities of the cold climate infrastructure. Such a framework can serve as a roadmap for the agencies in the transportation sector, aiming to achieve not only technical accuracy but also economic efficiencies in their pavement management routines.

In summary, the incorporation process of MEPDG models into PMSs, through the use of deterioration curves calibrated for rutting and cracking, based on actual performance data, confirmed strong predictive ability and thus validated their use in pursuit of maintenance decisions, even with data limitations and environmental-induced variation. Over the thirty years of operation, under the integrated PMS, pavement conditions were maintained, payment being made in keeping with the control of rutting and cracking progression, and stabilization of expenditure in maintenance. This evidence highlights the applicability of the integration of mechanistic-empirical methods into the PMS framework for enhanced predictive ability, resource allocation, and thereby long-term sustainability of infrastructure under changing operational circumstances.

4.2 Case Study Two (Uganda)

4.2.1 Distresses Correlations

4.2.1.1 Relationship between rutting and roughness

The observed mean rutting levels for every integer year of pavement age were graphed against the corresponding observed IRI values to investigate the interaction between the IRI and rutting. This was intended to test the hypothesis that rutting significantly determines IRI values, and thus their magnitude. The main objective was to learn how rutting influences total roughness with age by investigating the interaction over pavement ages.

As Figure 4-7 shows, the analysis which followed showed that there was a strong correlation between IRI and rutting. Over 25 years, the graph shows average IRI (in m per km) against average rut depth (in millimeters). The points show evidence of the hypothesis that rutting is a significant factor in road roughness measurement by giving a trend in which higher values of IRI correspond to deeper rutting.

A good illustration of this correlation is provided in Figure 4-7. The correlation between IRI and rutting is represented by Eq. 18 in the figure. The two parameters are found to be positively correlated as indicated by the coefficient of determination (R^2) of 0.8655.

$$y = 2.8362 \ln x + 4.9671$$

Eq. 18

Where:

y : Cracking percentage.

x : IRI in (m/km)

A model for estimating rutting values from IRI measurements is derived based on this established correlation. As it enables engineers and researchers to use pavement age explicitly within the calculation process of rutting, such a model is especially useful. Instead of just depending on the individual measurements of rutting, which can be time-consuming and expensive to collect, the progression of rutting over time may be forecast by employing the rutting-IRI relationship.

Figure 4-7 demonstrates several observations. Firstly, the depths of rutting are comparatively superficial for smaller values of IRI (i.e., below approximately 4 m/km), in other words, the road surface is well kept with less deformation. Rut depths increase though, with rises in the values of IRI, displaying advanced pavement deterioration. Considering higher values of roughness normally represent sophisticated degrees of wearing and tearing off, such as rutting, the pattern goes as should be expected.

Moreover, turning to the natural logarithm for the model is suggesting a log correlation, which means, limiting of rutting on surface irregularities index (IRI) enlarges as pavement wear amplifies, rather than being a direct one. This result marries well with the general theme of the performance modeling in pavement engineering, where the nonlinear (logarithmic or exponential) variants dominate the simple linear ones in terms of fitting quality. As an instance, the Long-Term Pavement Performance (LTPP) program of the FHWA revealed that the easiest way of representing IRI development was through an exponential IRI–age model, while the logarithmic rut depth–age model provided a better fit for rut depth progression (Perera & Kohn, 2001). Along the same lines, recent empirical, machine-learning studies also indicate that the IRI–distress relationships are non-linear by nature; interpretable ML models and surrogate modeling approaches corroborate that rutting leads to IRI increase in complex, non-linear ways (Kwon et al., 2024; H. Li et al., 2024).

On the other hand, linear regression is very limited in its capability to reveal most of the variation in the data - for instance, Al-Mansour & Shokri (2022) reported only one R^2 value of 0.36 for the prediction of IRI by distress density - pointing to the necessity of nonlinear models. Some research works even employ standard logarithmic forms between rut depth and IRI in an attempt to be successful when linear fits give unsatisfactory results (Mubarak, 2016). Moreover, deep rut field observations indicate that locations with deeper rut are always characterized by high values of IRI, which means that there is a positive but non-linear relationship between the two parameters (Luo et al., 2022). Such discovery points out that little increments in rutting at already very high IRI levels can cause very large jumps in roughness, so, prying rutting open during the pioneering stage of pavement service life is imperative for long service life facilitation.

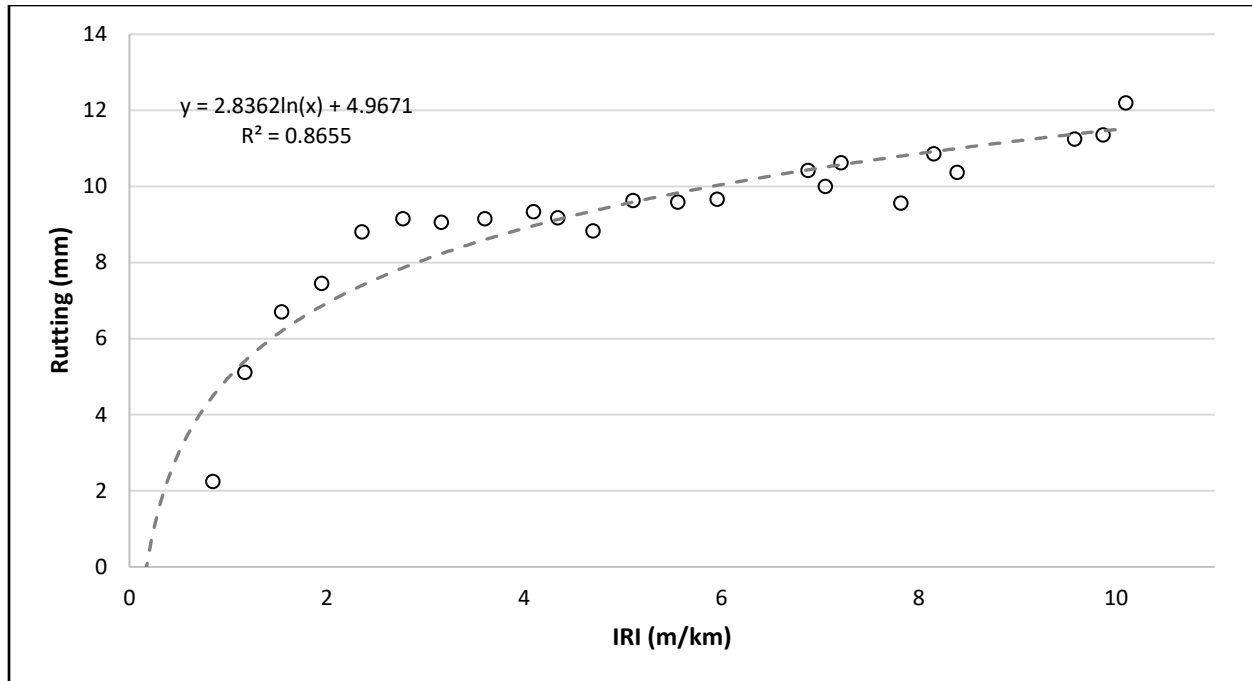


Figure 4-7: Relation between rutting and roughness (Observed)

Once the rutting values of each year were computed through the correlation established between rutting and the International Roughness Index (IRI), a general comparison was made to analyze the conformance between computed (estimated) rutting values and observed rutting values. This was done for the verification of the accuracy and reliability of the established IRI-rutting relationship for the overall lifespan of the pavement.

Figure 4-8 Below is a graphical illustration of the time trend of estimated and measured rutting values for a range of 0 to 25 years of pavement age. The figure illustrates clearly the relationship between the rutting values estimated directly from the correlation between IRI and rutting, and actual measured values of rutting at different pavement ages.

The results particularly demonstrate the high correlation between the predicted and measured rutting values. As can be seen from Figure 4-8 The predicted rutting values (marked by crosses) tightly follow the trend of the measured rutting values (marked by squares) along the entire range of pavement age. This high agreement indicates that the developed model accurately captures the relationship between IRI and rutting, allowing for accurate prediction of rutting progression over time.

The relationship between the two sets of values is especially interesting, with the indication that the IRI-rutting relationship can provide a reliable method of estimating rutting depths where no direct rutting measurements are available. This approach is useful when direct rutting measurements are either tricky or expensive to get, in that it holds out the very real possibility of determining pavement condition using easily accessed IRI data.

Besides, the graph indicates that the correlation between the estimated and actual rutting values is high even when the road is aging. Such consistency attests to the model's capability of considering the typical trends of pavement deterioration, i.e., the increasing rutting depth over time in a progressive manner. The slight discrepancies noted between the estimated and actual values are within an acceptable range of error, further attesting to the validity of the model predictions.

Therefore, the examination in Figure 4-8 underscores the performance of the IRI-rutting correlation in effectively predicting rutting values for various pavement ages. Not only does this finding verify the stability of the developed model, but it also indicates the model's potential usefulness in real-world pavement management scenarios. By using this correlation, both engineers and researchers can make well-informed decisions regarding maintenance strategies, rehabilitation requirements, and general pavement performance, all of which further enhance the sustainability and cost-effectiveness of infrastructure management routines.

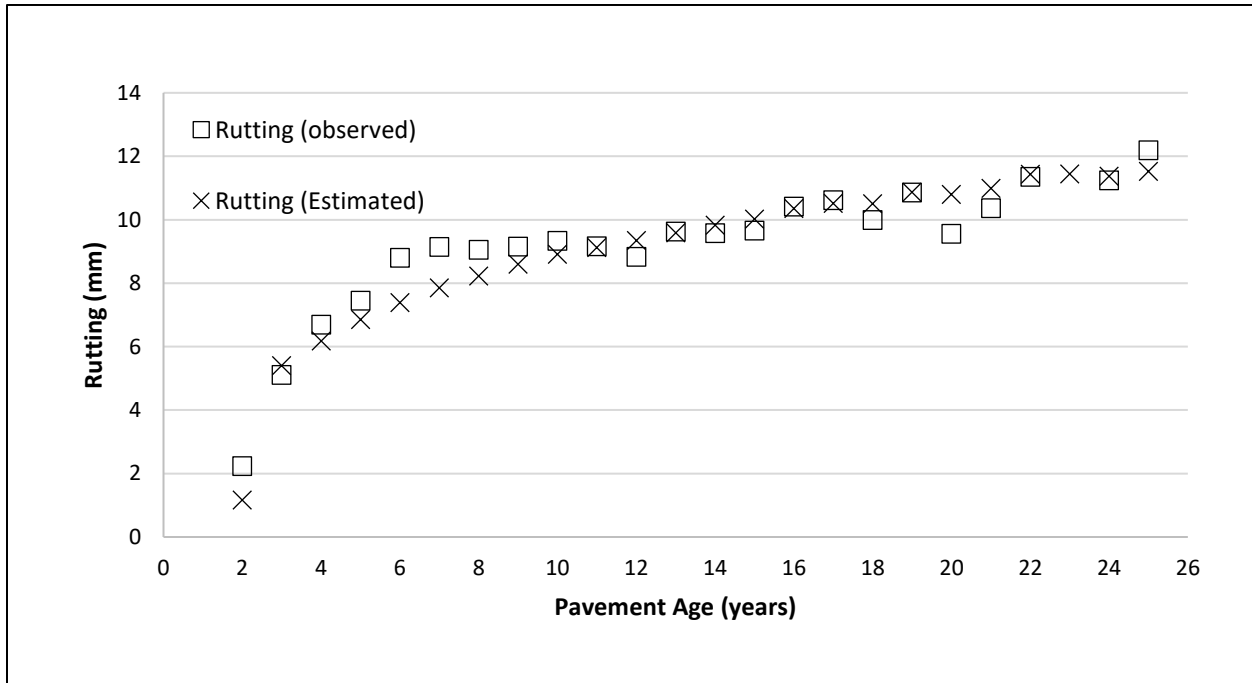


Figure 4-8: Estimated Vs. Observed Average rutting over Pavement Age

4.2.1.2 Relationship between cracking and roughness

The Uganda dataset presented significant challenges in terms of reliability when it came to cracking data. Many road segments had recorded zero values for cracking, despite exhibiting substantial roughness levels (as indicated by high IRI values). This inconsistency raised concerns, as the presence of significant roughness often suggests that water infiltration through cracks could be affecting the granular layers beneath the pavement. Given this unreliability in the cracking data, it became necessary to establish an alternative approach to estimate cracking percentages.

To address this issue, a correlation was developed between cracking values and the International Roughness Index (IRI). This approach involved creating a relationship based on expert criteria, aiming to approximate how cracking contributes to overall road roughness. Recognizable IRI levels commonly associated with reconstruction were selected as reference points, and corresponding cracking percentages were assigned accordingly. For instance, an IRI value of 6 m/km—a threshold typically linked to the need for reconstruction—was associated with a cracking percentage of 20%. This method allowed us to derive a set of cracking values that aligned with observed roughness trends, even in the absence of direct cracking measurements.

Table 4-2 below summarizes the IRI values alongside their associated cracking percentages, as derived from this correlation. The table illustrates a progressive increase in cracking percentages as IRI values rise, reflecting the expected relationship between roughness and cracking severity. For example, at an IRI of 0 m/km, the cracking percentage is 0%, indicating a perfectly smooth surface with no visible cracking. As the IRI increases to 1 m/km, the cracking percentage rises to 4%, and this trend continues until an IRI of 6 m/km, where the cracking percentage reaches 20%. This structured approach ensures that the estimated cracking values are both logical and consistent with established industry standards.

Table 4-2: IRI values and their associated Cracking Percentages

IRI (m/km)	Cracking (%)
0	0
1	4
2	8
3	10
4	12
5	16
6	20

With these derived percentages of cracking, a deterioration curve was developed to show the time progression of cracking over the life of the pavement. This curve, shown in Figure 4-9, graphically illustrates the cracking evolution with time in the aging of pavement. Eq. 19 states the quadratic relationship between the age of pavement in years and the estimated average cracking percentages. A coefficient of determination or R² of 0.9983 is indicative of a very good fit between model and data, thus giving further weight to supporting the accuracy of the correlation.

$$CP = 0.0514(Age)^2 + 0.1668(Age) + 4.2719 \quad \text{Eq. 19}$$

Where:

CP: Cracking Percentage.

Age: Pavement age in years.

There was a definite upward trend in the cracking percentages with the increasing age of the pavement, as illustrated in Figure 4-9. The beginning of the lifecycle of the pavement (about 2-4 years), however, has a rather low percentage of cracking, which indicates good durability of the

pavement structure at the early ages. Yet with time, deterioration accelerates, and after a lifespan of about 10 years, cracking seems to take an exponential shape. By 16 years, cracking would be approaching 20%, which is again in agreement with the FHWA (2018) limiting criteria for reconstruction when cracking exceeds 20% in this respect.

The corroboration of predictions from the model with accepted, well-known benchmarks of the industry restores confidence in this deterioration curve. It confirms that the estimated cracking values seem appropriate and reasonable to correlate with real-life expectations. Moreover, the fact that the relationship is quadratic accentuates the fact that cracks accelerate with age, which would imply that prompt maintenance methods will defer to the extent possible infrastructural deterioration before it becomes serious by employing the analysis techniques herein.

In summary, having established in this process a correlation between IRI and cracking and therefore generated a deterioration curve, gives a firmer basis to estimating the advance of cracking over the age of pavement. Even with the shortcomings in the original dataset, the approach provided fairly sound results in line with expert criteria and industry specifications. Such findings should not only clarify the understanding of pavement behavior, but are also instrumental in drawing guidelines for developing sound maintenance and rehabilitation strategies in Uganda.

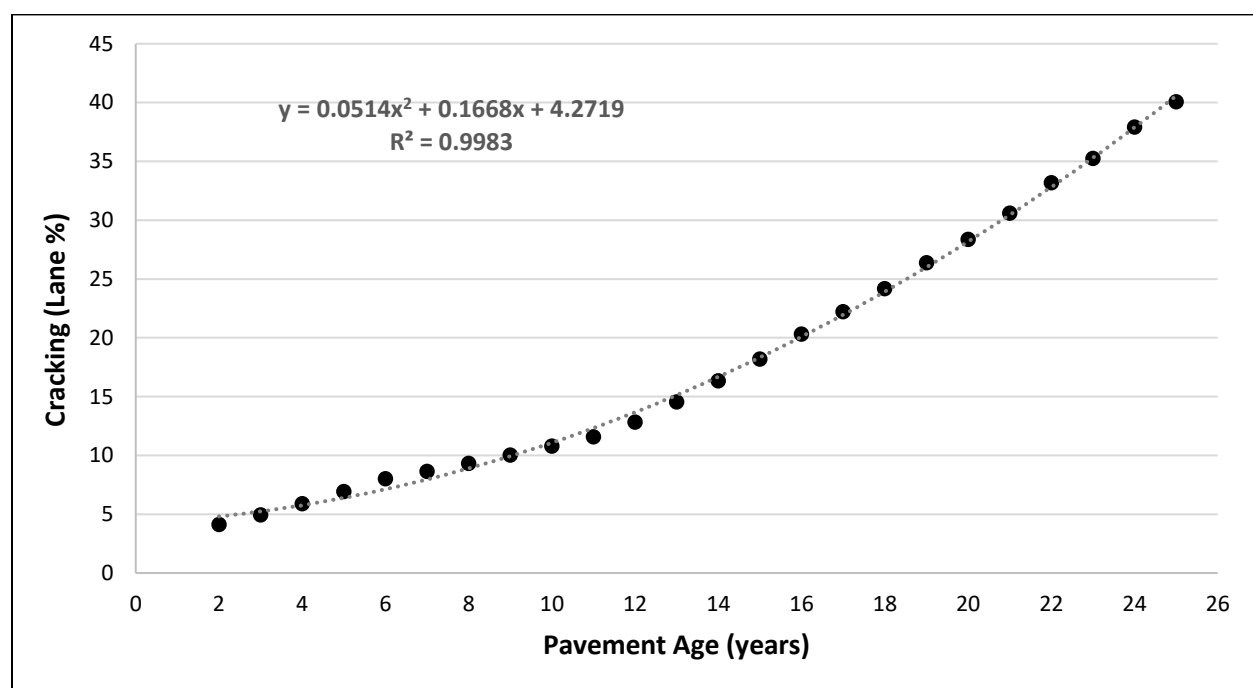


Figure 4-9: Estimated Average Cracking Percentage based on its effect on IRI

4.2.1.3 Cracking Analysis

Due to inconsistencies in the cracking data within the Uganda dataset, where many road segments showed zero cracking despite significant roughness values, a correlation to align cracking values directly with IRI values has been established, as shown in Figure 4-10. The figure illustrates a

comparison between measured and estimated pavement cracking percentages across a 25-year timespan. The graph presents two distinct datasets: actual measured cracking values shown as black squares, and estimated cracking values derived from IRI (International Roughness Index) represented by X markers connected by a line. The measured data exhibit considerable variability and inconsistency, with readings scattered between 0-20% cracking, lacking a clear pattern of progression. In contrast, the estimated cracking follows a more predictable growth pattern, as demonstrated by Eq. 20, with a remarkably high R^2 value of 0.9905, indicating excellent model fit. This approach involves imputation of values based on expert criteria, aiming to approximate the relationship between IRI and cracking. Specifically, recognizable IRI levels (e.g., 6 m/km) commonly associated with reconstruction are selected, and corresponding cracking percentages (e.g., 20%) are matched accordingly.

$$CP = 0.03(IRI)^2 + 0.8265(IRI) \quad \text{Eq. 20}$$

This cracking progression from imputation, the significant difference from the measured values, the original Uganda dataset with incomplete and inconsistent cracking records that caused the data to be zero-valued most of the time, is the main reason for the difference. These zero-values led to the estimated cracking curve being a representation of the smoothed, mechanistic-empirical relationship rather than the nature of the under-reported cracking data. The method, however, has some limitations. Being the most significant that the reconstructed cracking percentages can hardly be regarded as accurate due to the scarce number of direct cracking observations in the primary dataset. Nevertheless, these estimated values are based on the global trends of cracking that have been widely observed and on the IRI thresholds that have been validated by experts, thus a reliable approximation of the real pavement deterioration can be made in the absence of complete field measurements.

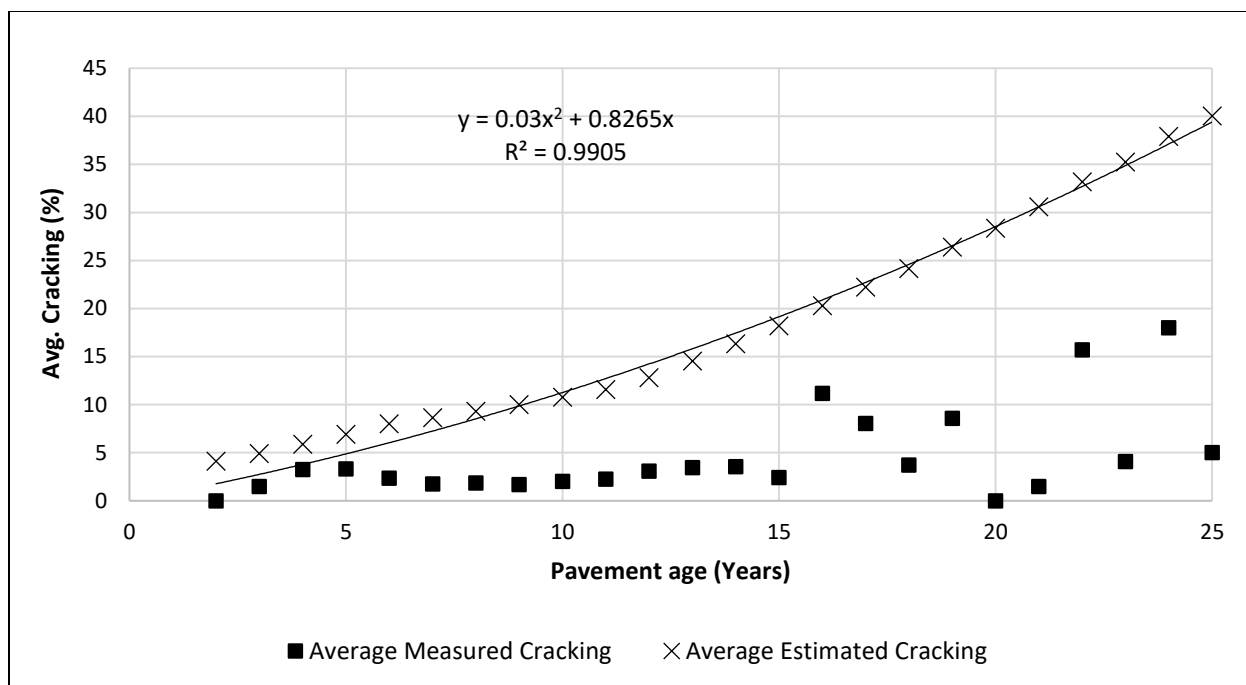


Figure 4-10: Average Estimated (Imputed from IRI) vs. Measured Cracking (%)

4.2.2 Evaluation of Key Pavement Performance Indicators

This study examines the condition of a road network over a 30-year period, with a particular focus on rut depth as a critical indicator of pavement performance. The analysis is visualized in Figure 4-11, which plots Network Rut Depth (in millimeters) on the y-axis against Years on the x-axis. This graph provides valuable insights into how the network's condition has evolved over time and the effectiveness of the maintenance strategies employed.

The initial segment of the graph reveals a dramatic improvement in pavement condition during the first five years. Specifically, the network rut depth declines sharply from approximately 3100 mm to around 350 mm—a reduction of nearly 90%. This steep decline strongly suggests that intensive rehabilitation or reconstruction efforts were undertaken early in the analysis period. Such significant improvements are typically indicative of major interventions aimed at restoring the structural integrity of the pavement and addressing severe distress like deep rutting.

Following this initial phase of substantial improvement, the graph transitions into a more cyclical pattern. Over the subsequent years, the rut depth exhibits a series of gradual increases and decreases, generally fluctuating within a range of approximately 500 mm to 1000 mm. This oscillating trend highlights the dynamic nature of pavement management, where deterioration occurs naturally over time but is periodically addressed through maintenance actions. The consistent presence of these cycles suggests that PMSs are actively monitoring the network's condition and implementing timely interventions to manage rut depth effectively.

The cyclic nature of the graph implies a reactive maintenance strategy, wherein treatments are applied when rut depths reach certain thresholds. For example, the periodic peaks observed around years 8, 15, and 23 - where rut depth temporarily rises before sharp declines - are clear indicators of successful maintenance or rehabilitation efforts. These interventions appear to be effective in reducing rut depth and restoring pavement performance, as evidenced by the subsequent declines in rut depth after each peak.

However, the recurring cyclical pattern also raises important considerations about the current PMS. While the system successfully manages rut depth through reactive measures, the consistent recurrence of higher rut levels suggests that there may be room for improvement in terms of proactive strategies. By adopting more preventive approaches, such as routine inspections, targeted surface treatments, or pre-emptive repairs, it might be possible to mitigate the severity of rutting before it reaches critical thresholds. This could lead to more stable and predictable performance over the long term, potentially reducing the need for costly and disruptive rehabilitation projects.

Figure 4-11 provides a comprehensive overview of the network's rut depth trends over 30 years. It underscores the success of early, intensive rehabilitation efforts and the effectiveness of a PMS in managing rut depth through timely interventions. However, the recurring cyclical pattern also highlights opportunities for enhancing the system by incorporating more proactive strategies to further optimize pavement performance and extend the lifespan of the road network. This analysis not only sheds light on the current state of the network but also offers valuable insights for future maintenance planning and resource allocation.

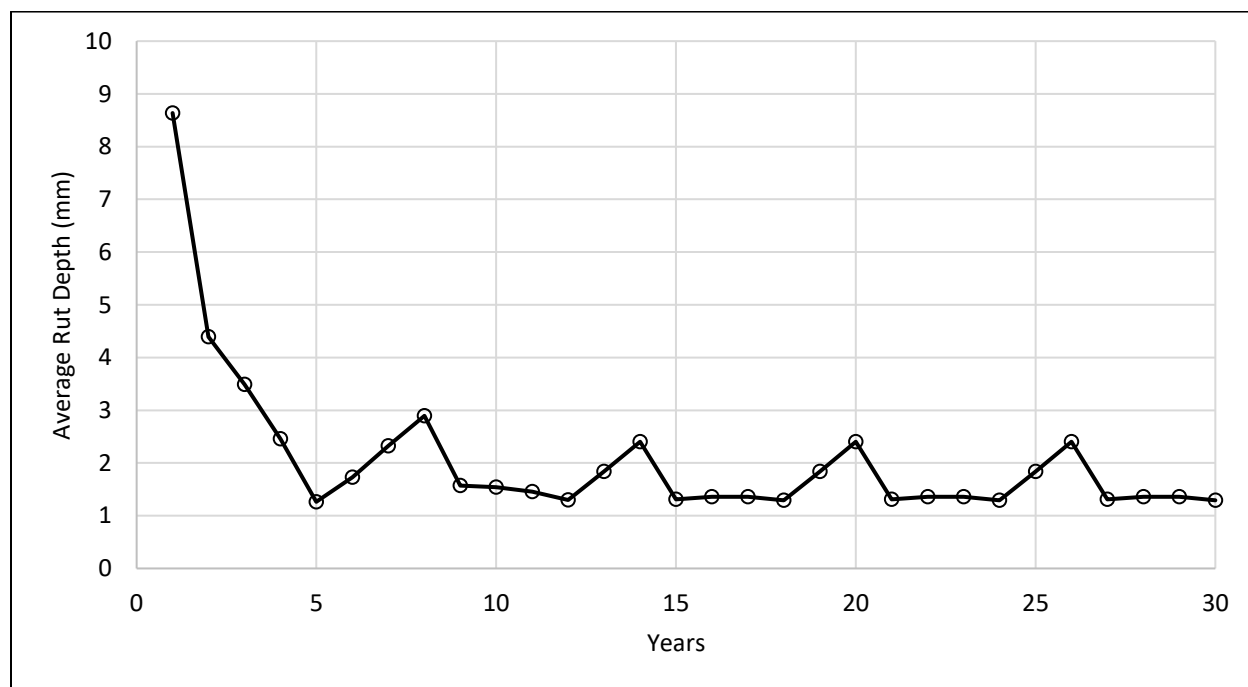


Figure 4-11 Mean Rutting progression for the entire road network

Figure 4-12 illustrates the evolution of Network Cracking Percentage over 30 years, providing valuable insights into the effectiveness of the implemented PMSs and the overall condition of the road network.

The changing through time network cracking percentage unveils the presence of three phases having very different characteristics during the temporal extent under analysis. The stage of the first rehabilitation (years 0-5) comes first, in which the network cracking percentage dramatically falls from around 3,700% to 750%, thus, basically, ascribing the interventions to the whole or to a major part of the network, respectively. The steep downfall gives considerably clear indications of the initial period of the study being an era of substantial capital investment in infrastructure restoration.

The event of stabilization occurs at year 5. The figure of the inflection point is such that the network cracking percentage reaches the lowest value, namely, about 750%. This is the point at which the effectiveness of the first rehabilitation measures and the criteria for the evaluation of the subsequent interventions, both turning into the maintenance baseline, are fixed.

The cyclic maintenance phase (years 5-30) is then presented, which shows the phenomenon of fluctuation where the network cracking percentage varies from the lowest value of about 1,000% to the highest value of about 1,600%. The peaks in temporal maxima at years 8, 15, and 23, along with the sudden drops after them, provide strong arguments for the existence of threshold-triggered maintenance activities within the pavement management framework. This type of cycle is typical for the maintenance strategy that is mainly based on reactivity, where only at a particular condition level, the corrective interventions are allowed to be carried out, thus keeping the network performance at a certain level of acceptability.

The cyclical nature of the graph during the maintenance phase implies that the current PMS effectively manages cracking, preventing it from reaching the initial severe levels. However, the recurring pattern also suggests potential opportunities for optimization, possibly through more proactive maintenance strategies.

It is noteworthy that the cracking percentages exceed 100%, which is atypical for individual pavement sections. This anomaly suggests that the data likely represent cumulative cracking across the entire network, possibly including multiple types of cracking (e.g., longitudinal, transverse, and alligator cracking) or reflecting a particular calculation method used in this study.

The overall trend demonstrates the PMS's efficacy in maintaining network cracking at significantly lower levels compared to the initial condition. However, the persistent oscillations indicate that there may be room for further refinement of the maintenance strategy to achieve more consistent pavement performance over time.

A significant distinction between the two diagrams – Alaska case Figure 4-5 and Uganda case Figure 4-12 - is the more pronounced variation in the Alaska pavement network, shown in the first graph, compared to the better continuity of the Uganda data series. The higher range of change in

Alaska can be mainly traced back to the better-than-average overall condition of its pavement infrastructure, which in turn permits higher amplitudes and variability of cracking performance over time.

This analysis provides valuable insights for pavement managers and researchers, highlighting the importance of initial rehabilitation efforts and the need for ongoing, optimized maintenance strategies to manage network-level cracking effectively. Further research could focus on the cost-effectiveness of the current intervention cycles, the potential for more frequent, less intensive treatments, and the relationship between cracking and other pavement distresses to enhance the overall performance of the road network.

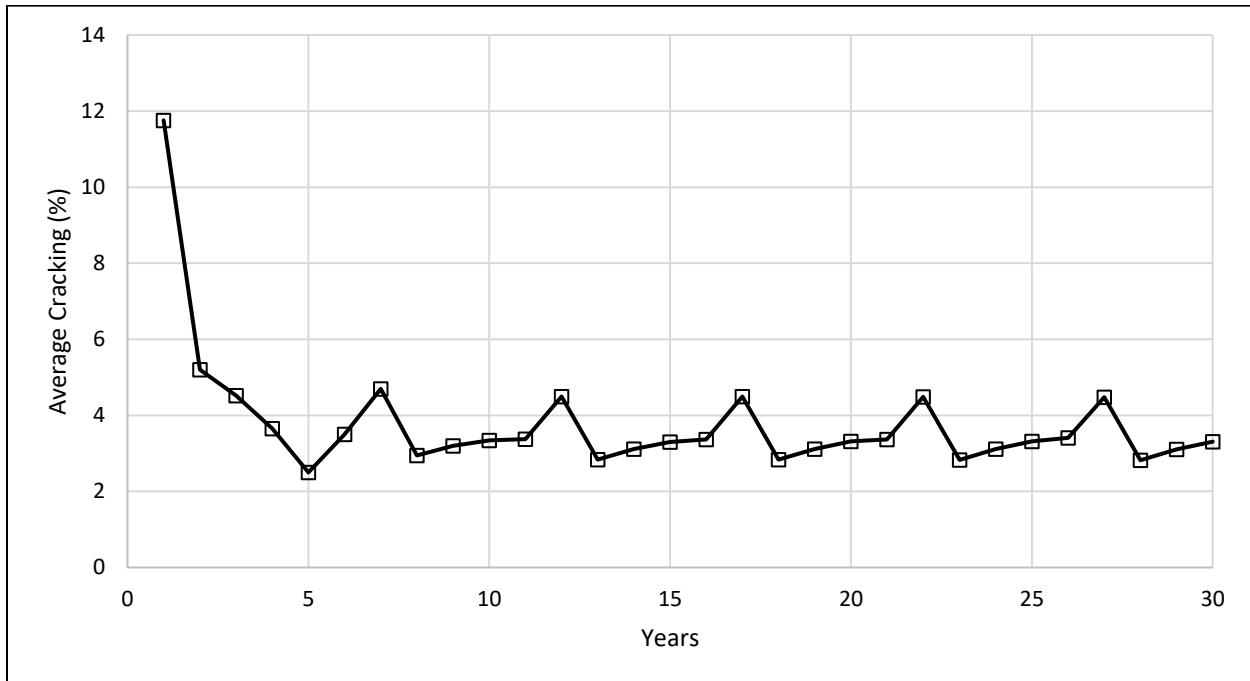


Figure 4-12: Mean Cracking progression for the entire road network

Figure 4-13 depicts the temporal evolution of road condition over a 30-year period, utilizing a composite index that amalgamates both rutting and cracking metrics. This index is calculated using the formula previously mentioned and discussed in Eq. 15, which assigns a significantly higher weight to rutting due to its critical impact on road safety, particularly in Uganda's predominantly wet climate.

The pavement's condition index starts off the longitudinal profile at nearly 740,000, indicating a perfect or close to new road condition. The rapid deterioration stage is then observed within the first five years, where the condition index halves, showing the accelerated degradation phase, which is usually going to be typical of new or rehabilitated pavements. Following this, the index of conditions seems to vary between approximately 200,000 and 400,000. These variations correspond to periods in which the pavement condition has both improved and deteriorated over time.

These subtle variations may be attributed to improvements in the pavement condition resulting from maintenance or rehabilitation activities conducted during the observation period. The last peak is lower than the first ones in the graph, which means that the pavement has become progressively older and more Deteriorated. The data illustrates that the pavement is going through cycles of degradation followed by improvement, which is probably a result of scheduled maintenance or interventions based on the funding available. Eventually, the condition index settles at about 200,000, the lowest point in the 30 years period, which is a very big fall from the cleanest state at the beginning of the timeframe.

This longitudinal pattern is very much in line with the common pavement lifecycle models where at first a high-level condition is rapidly deteriorating, then a number of improvement phases driven by rehabilitation and finally, a gradual decline to a terminal state of reduced condition.

The weighting scheme employed in the condition index calculation heavily emphasizes rutting over cracking. This methodological choice is justified by the prevalence of wet conditions in Uganda and the concomitant safety implications of rutting under such circumstances. Consequently, variations in rutting measurements are expected to exert a disproportionate influence on the overall condition score relative to changes in cracking.

This longitudinal analysis provides valuable insights into the lifecycle performance of road infrastructure, highlighting the need for regular maintenance interventions and the challenges of maintaining optimal road conditions over extended periods in challenging environmental contexts.

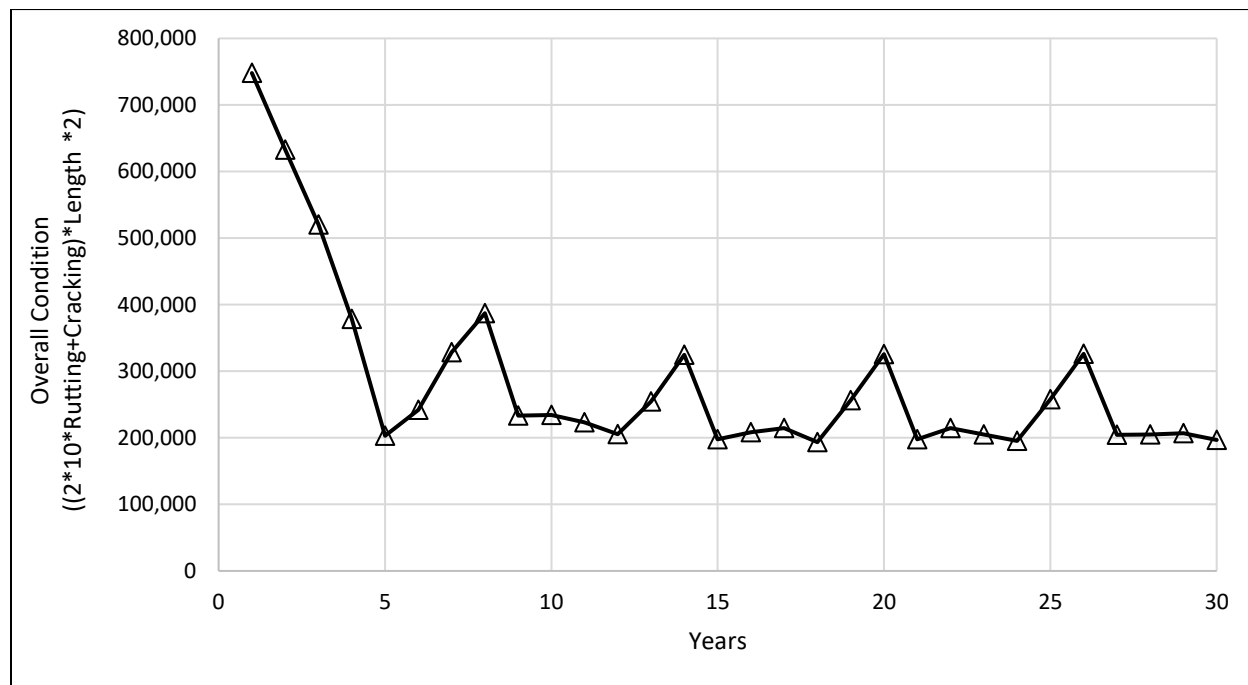


Figure 4-13: Pavement Overall condition over time considering maintenance

Figure 4-14 illustrates the annual expenditure for pavement maintenance in Uganda over a 30-year period. The chart reveals a complex and fluctuating pattern of spending that offers insights into the country's approach to road infrastructure management.

In the initial years, there is a noticeable upward trend in expenditure, with costs rising steadily from around \$50 million to peak at nearly \$80 million by year 4. This initial surge in spending is an indicative of a concerted effort to address a backlog of maintenance needs or to undertake significant rehabilitation projects on severely deteriorated road sections. Such front-loading of expenses is often seen when countries embark on major infrastructure improvement initiatives.

Following this initial peak, the expenditure pattern becomes more erratic, with significant year-to-year variations. There are several years where spending remains high, around the \$70-75 million mark (years 8, 15, 20, and 26), interspersed with periods of much lower expenditure, sometimes dropping below \$20 million (years 13, 19, and 25). This oscillating pattern reflects a cyclical approach to maintenance, where years of heavy investment are followed by periods of reduced spending as the benefits of the previous works are realized.

Interestingly, the chart does not show a clear trend towards consistently lower expenditures over time, which might have been expected if a highly effective preventative maintenance system had been implemented. Instead, the recurring spikes in spending suggest that Uganda is dealing with ongoing challenges in maintaining its road network, due to factors such as harsh weather conditions, heavy usage, or limited resources for consistent preventative maintenance.

The latter part of the 30-year period shows a slight moderation in the extremes of spending, with costs generally ranging between \$30-70 million annually. This could indicate a move towards a more balanced approach to pavement maintenance, reflecting improved management practices or a better understanding of the long-term needs of the road network.

Another option is for transportation agencies to determine the annual average maintenance expense, which is derived from the 30 years of analysis period and use this figure to restart the optimization process. In this updated case, the goal would be to increase the service levels as much as possible while ensuring that a fixed annual budget, which is only adjusted for inflation, is respected. Implementing such a steady-budget approach is an old and proven practice in pavement management since it largely reduces the year-to-year variations in maintenance spending and makes it easier to plan financially in the long-term. The use of this method is common in most agencies albeit not in the current study, however, the latter had not included such an estimation nor had it done budget-constrained optimization as it was beyond the research scope. Overall, this expenditure pattern reflects the complex realities of managing road infrastructure in a developing country like Uganda. It suggests a reactive approach to maintenance needs, with periodic large investments rather than a smooth, proactive maintenance strategy. The data highlights the ongoing challenges in achieving a sustainable and cost-effective PMSs in the face of likely resource constraints and infrastructure demands.

According to OFFICE OF THE CLERK TO PARLIAMENT (2024) Road Fund documentation, the approved annual maintenance allocation for the Financial Year (FY) of 2024/25 is UGX 401.952 billion - roughly USD \$100-110 million, depending on the exchange rate, which is higher than the maximum annual spends shown in the optimized-PMS Figure 4-14 and far above the ~USD \$34 million annual average. This disparity supports the study's scope, emphasizing direct damage indicators (Rutting and Cracking) over indirect indices like IRI/PCI, because with a realistic, higher national maintenance envelope, prioritization based on structural condition is more defensible and aligned with Uganda pavement maintenance funding levels.

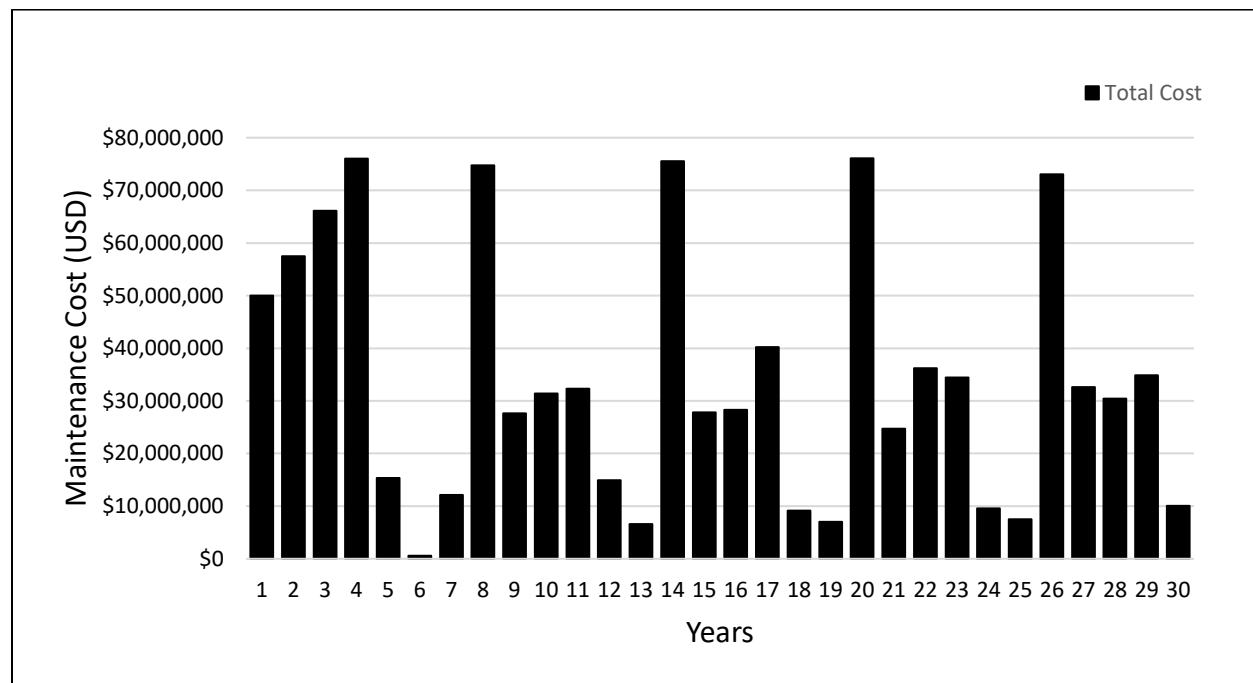


Figure 4-14: Annual Expenditure over the pavement's lifetime

4.2.3 Results discussion

The optimized PMS improved the network condition in a very clear way, as it managed to keep the rutting and cracking at very low levels throughout the whole 30-year horizon. In comparison with the Alaska case study, where more significant fluctuations in the performance metrics can be noticed, the Uganda network has less variability, and the heights of the peaks of both rut depth and cracking are lower (Figure 4-11 and Figure 4-12). The reason for this fluctuation in the performance of the Alaska network is that the pavement condition was initially very good, thus only very small absolute changes appear as visible cycles within the "excellent" condition range in the figures, rather than severe distress.

One main difference between the two datasets is that the Uganda dataset has missing cracking measurements, which made it difficult to model the performance. In order to complete the cracking series, predicted values were used based on the correlation between the IRI and cracking, although it might bring some uncertainty into the series of cracks. The optimization formula (Eq. 15) helped

to reduce this uncertainty by weighting rutting twice as much as cracking and thus giving the decision of the intervention mainly to that distress which was most reliably measured. This weighting plan was not the factor that made the profile of the condition a smoother one, but rather it was meant to offset the effect of any over- or under-prediction of the estimated cracking values on the condition profile.

As the missing cracking data hindered full visibility into network distress, the optimized PMS still managed to keep the rut depths from exceedingly approximately 3mm and the cracking percentages from going over 5 percent for almost the entire analysis period - these are the levels significantly lower than those that were observed in the initial rehabilitation phase (years 0–5) or in the Alaska case. This result points to the benefit of using weighted multi-distress objectives: if a performance measure is estimated, the system is still capable of focusing on the more critical distress (rutting) and thus it can achieve the wide network benefits.

Thinking about the future, the sole method of totally ridding of estimating when developing cracking predictions is to gather a dataset that is complete with both rut and cracking measurements for every time. Having such a thorough dataset, the PMS would be able to adjust its maintenance thresholds more precisely and hence, make a better overall network performance. Even so, the present optimized scheme has already illustrated a substantial advance, being able to maintain pavement quality over time with less and more targeted actions than a strategy that is only reactive.

In summary, Uganda's pavement performance model was suitably adapted amidst significant data limitations, primarily the lack of credible cracking records. Calibration of IRI-based deterioration models and establishment of strong relationships between IRI, rutting, and estimated cracking enabled a sound framework to model pavement aging. These relationships enabled the development of predictive models that compared fairly well with available data, forming the basis of accurate forecasting of pavement conditions. Based on these results, a tailored Pavement Management System was put in place, such as condition indices, trigger threshold levels according to distress, and cost-optimization models suitable for Uganda's climate and resource limitations. Cyclical maintenance practice and funding volatility were long-term studies that highlighted both the responsiveness of the system and the need for increased proactive measures. Together, these results enhance the evidence base for data-scarce pavement maintenance planning.

4.3 Case Study Three (Alberta)

4.3.1 Calibration of the Deterioration Model

Rutting was calibrated following the approach mention in section 3.3.5. The resulting calibration sample for the moderate traffic intensity roads is shown on Figure 4-15. The close match between the All-Layer-Rutting (MEPDG) and “Amador-Jiménez & Mrawira (2009)” method demonstrates the efficiency of the calibration and justifying the reliance on these predictions in PMS to optimize the maintenance policy. Figure 4-15 also illustrated the breakdown of rutting for the subgrade,

subbase and HMA pavement structure layers. As expected, the HMA carries most of the rutting being the layer that absorbs most of the stresses from the traffic load, followed by the subbase.

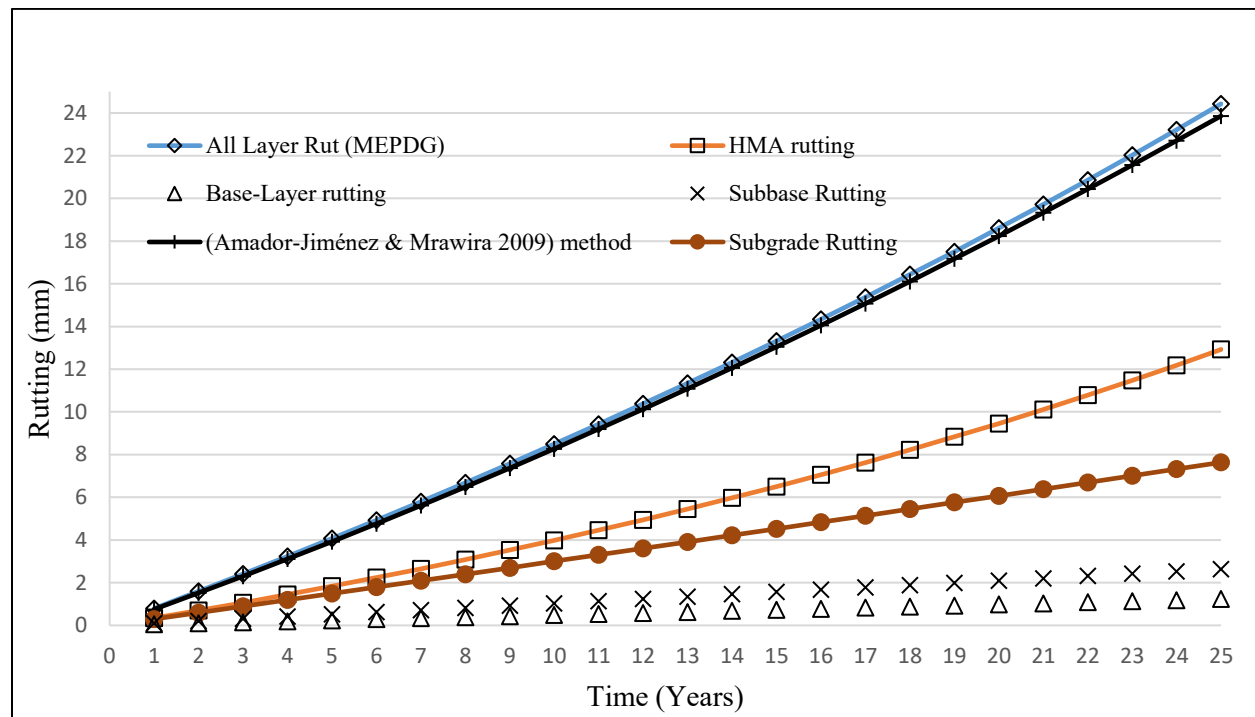


Figure 4-15: Rutting Calibration (Moderate ESALs)

4.3.2 Representation of Pavement Conditions using the TPM

Figure 4-16 to Figure 4-25 illustrate the traditional representation of pavement average condition for the actual maintenance policy, alongside the pavement management output from the PMS optimization. While both approaches aim to improve pavement performance, the TPM mechanism reveals significant differences in their effectiveness. Specifically:

- The actual maintenance policy shows gradual deterioration over time, with limited improvements in overall pavement condition.
- In contrast, the PMS demonstrates a marked improvement in average pavement condition, reflecting its ability to optimize resource allocation and prioritize cost-effective treatments.

The superiority of the PMS becomes evident when analyzed through TPMs, which highlight the nuanced transitions between pavement states that traditional methods fail to capture.

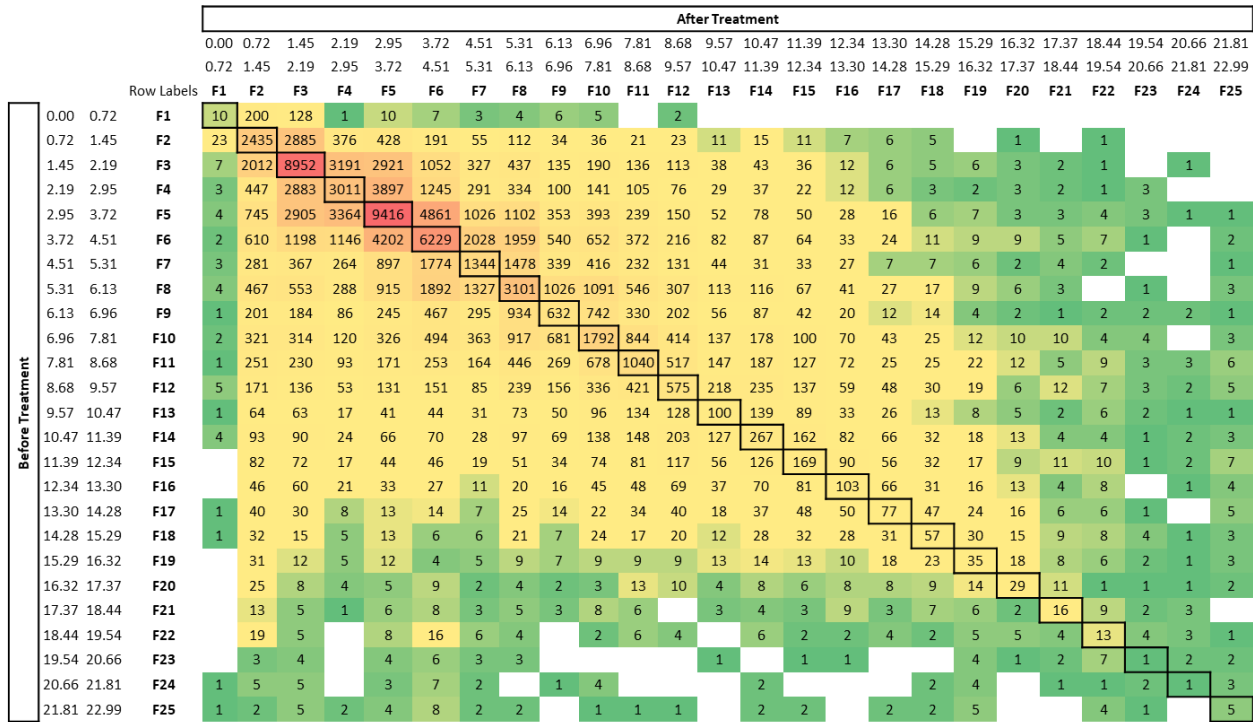


Figure 4-16: TPM 2018-2019 (Actual Policy)

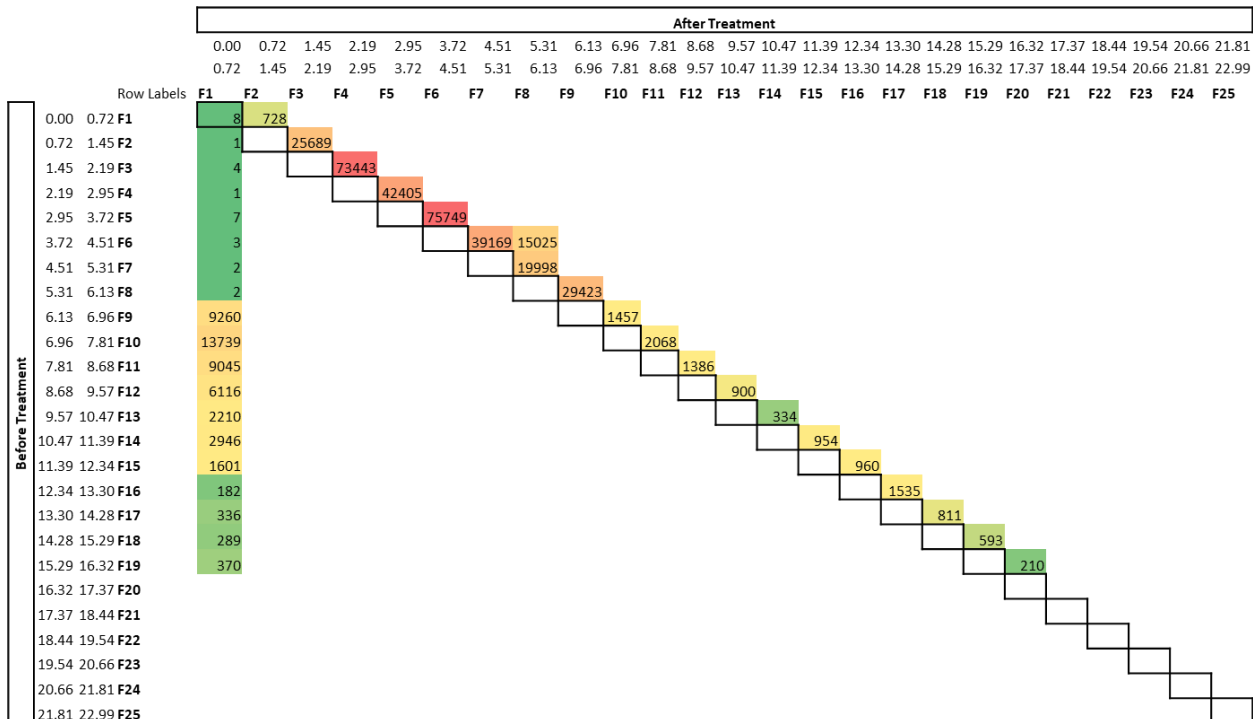


Figure 4-17: TPM 2018-2019 (optimized-PMS)

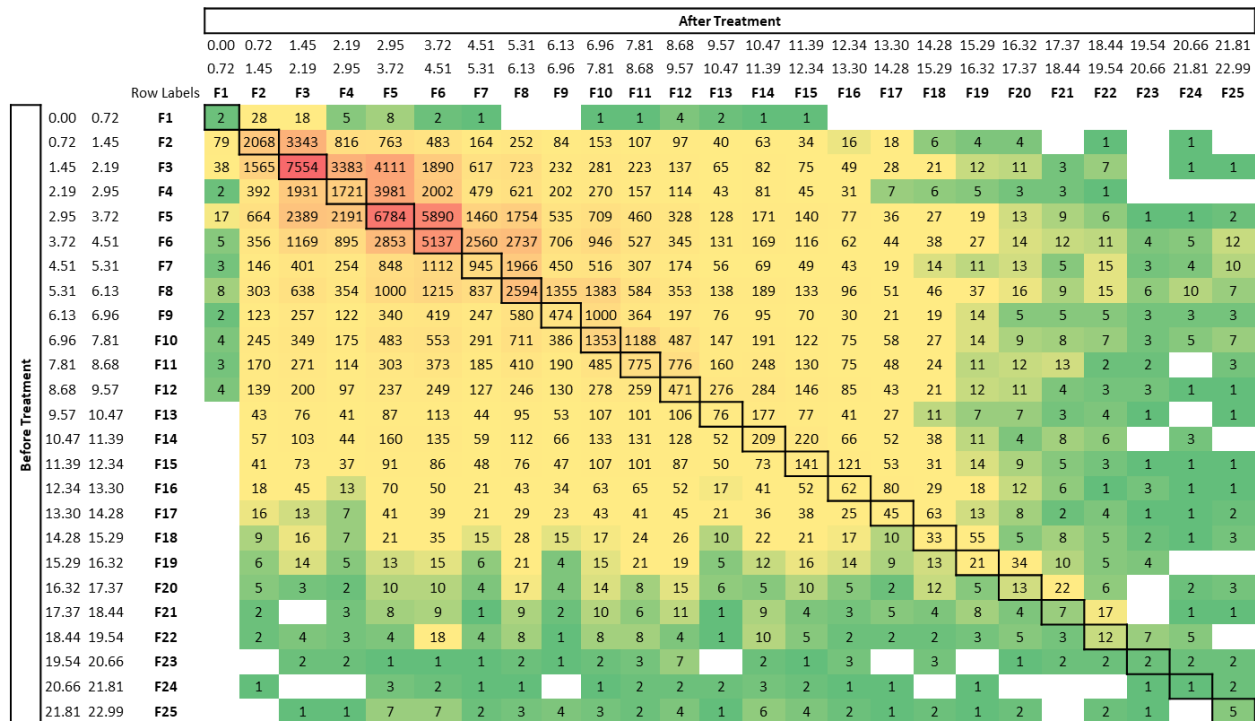


Figure 4-18: TPM 2019-2020 (Actual Policy)

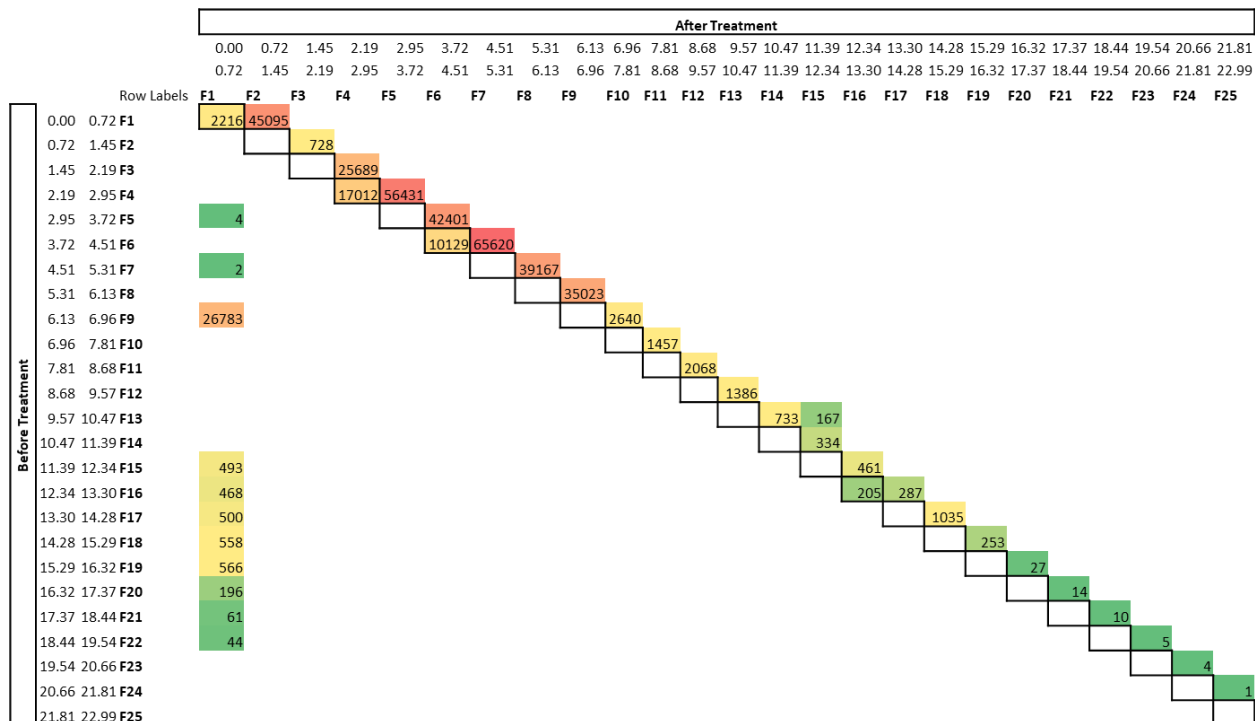


Figure 4-19: TPM 2019-2020 (optimized-PMS)

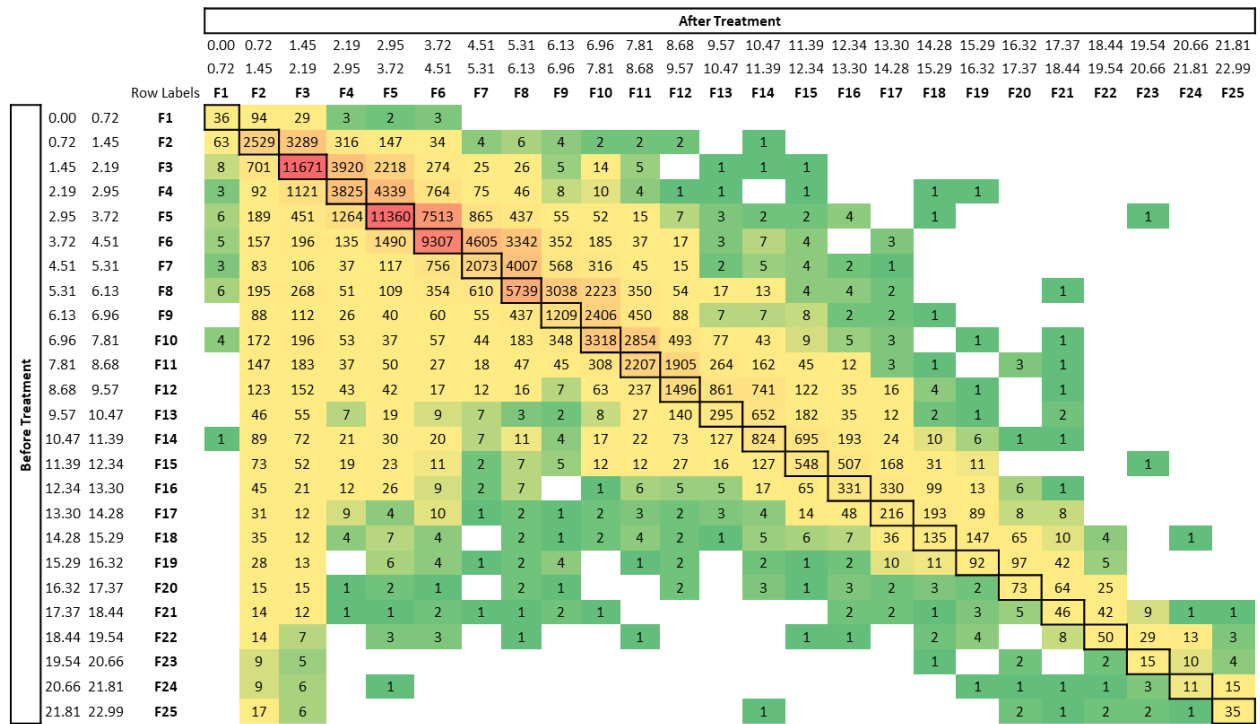


Figure 4-20: TPM 2020-2021 (Actual Policy)

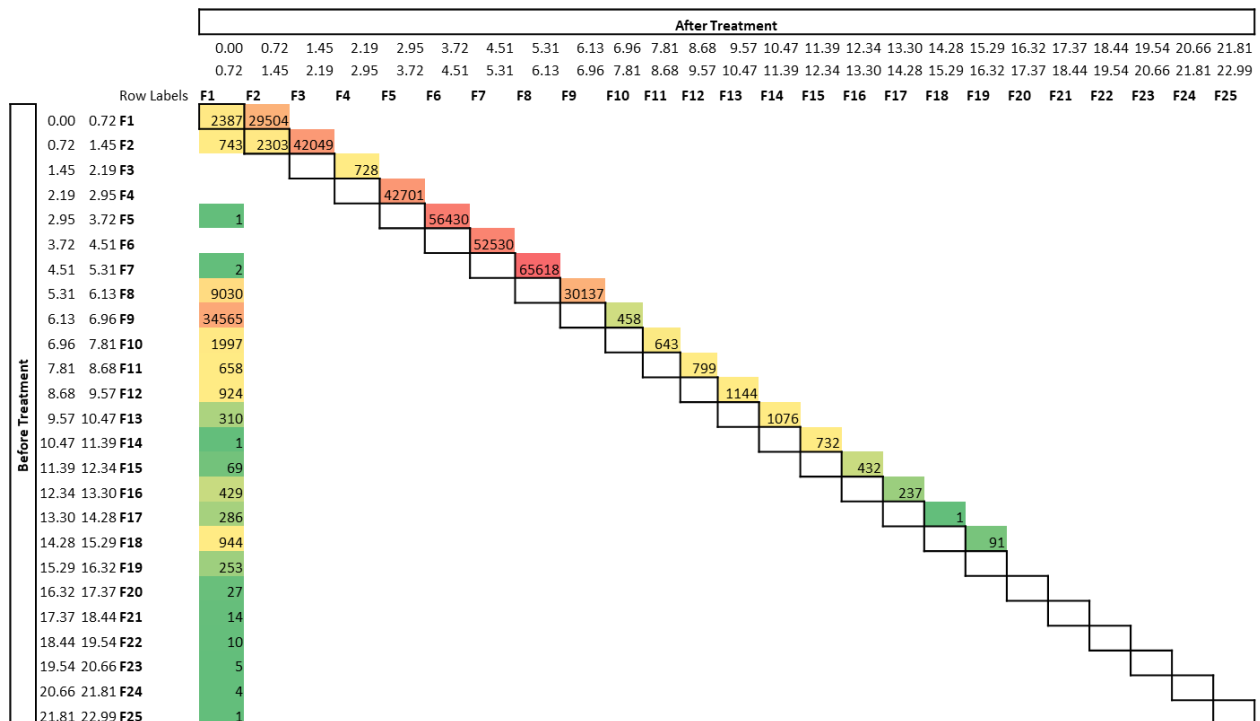


Figure 4-21: TPM 2020-2021 (optimized-PMS)

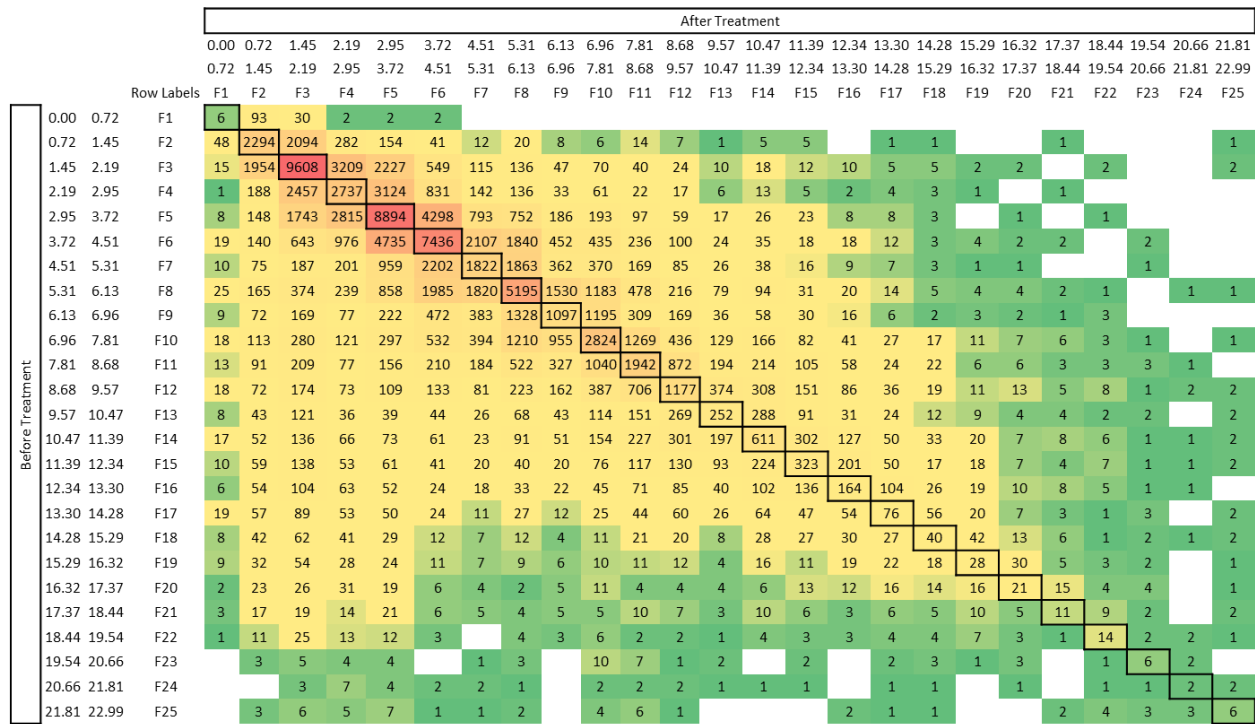


Figure 4-22: TPM 2021-2022 (Actual Policy)

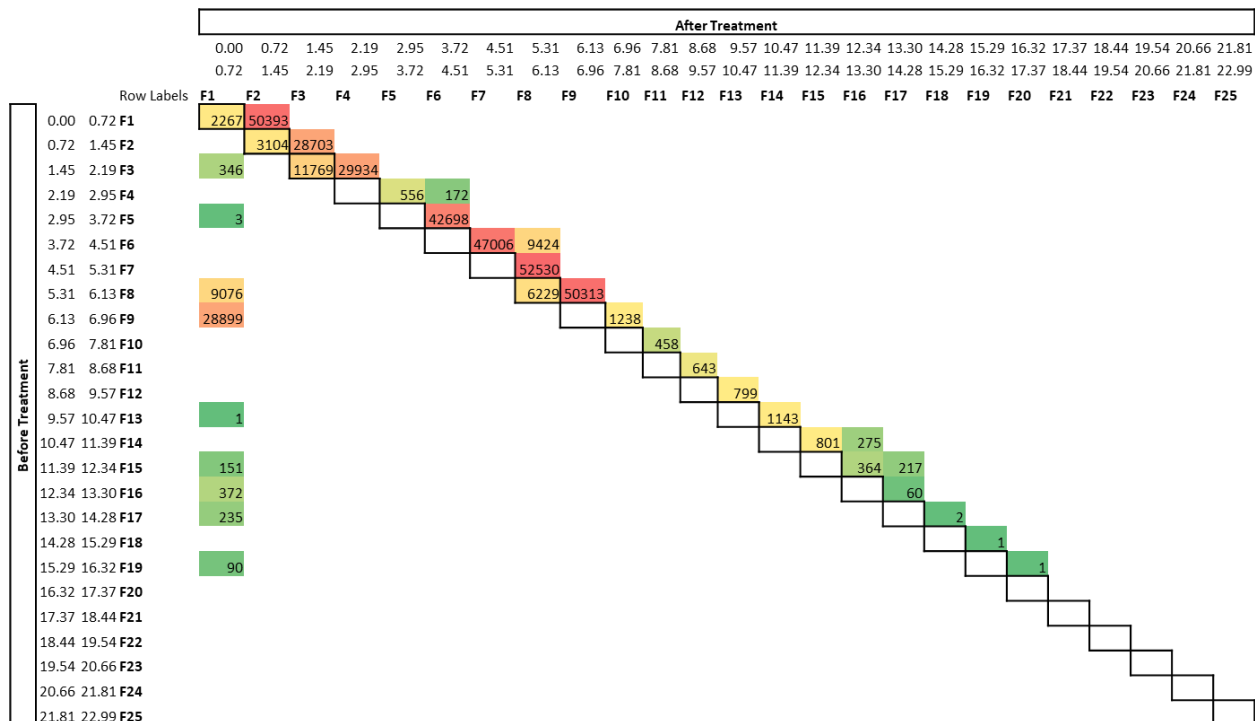


Figure 4-23: TPM 2021-2022 (optimized-PMS)

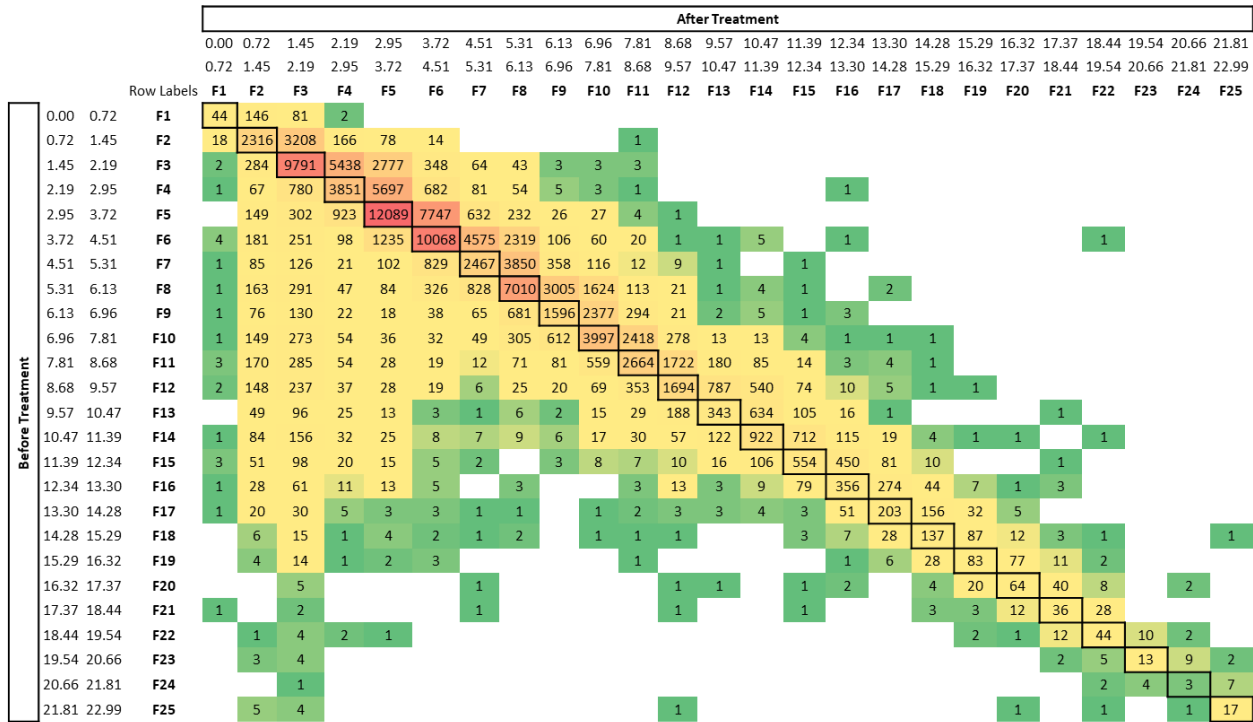


Figure 4-24: TPM 2022-2023 (Actual Policy)

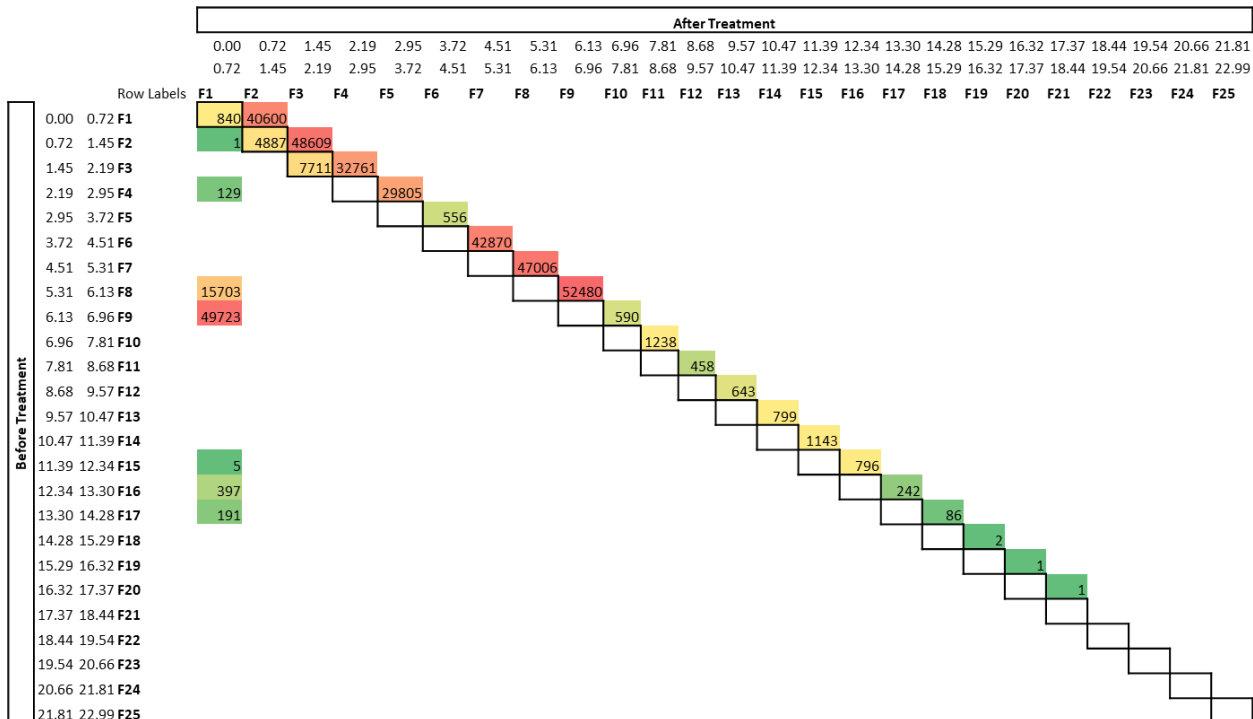


Figure 4-25: TPM 2022-2023 (optimized-PMS)

Transition Probability Matrices (TPMs) analyzed and provided in Figure 4-16 to Figure 4-25 describe the time changes in the conditions of the roads, particularly rutting, between the period

2018 to 2023. The matrices compare the real policy of the agency to the optimized PMS policies calculated for the same budget constraints. Large differences emerge regarding the effectiveness of the two methodologies. The policy of the agency has recorded deterioration spreading across the majority of the period 2018-2019, as the TPMs have all shifted to the right. Numerous stretches started to reflect an increase in the rutting depth, while some advanced to higher severity grades. On the contrary, PMS-optimized decisions registered better control over the deterioration of the roads over the period, especially in the years 2020-2021 and 2022-2023. On the PMS budget, barely no roads reflected bad conditions (rutting > 20 mm); therefore, it can be claimed that the PMS method prevents additional deterioration and decreases the frequency of intervention.

The inefficiency of the current policy mainly stems from the fact that it cannot maintain roads to near-new conditions. After treatment, some parts of the road continued to be in medium to poor conditions, making them likely candidates for larger-scale and costly rehabilitation in the future. As of 2023, some parts of the roads had rutting basin depths exceeding 20mm with the current policy, which would depend on total rehabilitation. The results confirm the shortfalls of reactive maintenance solutions to proactively curb factors causing further deterioration.

On the contrary, the PMS adopts a focused, cost-effective approach to maintenance through preventative treatments. As an instance, in 2018-2019, the pavement in question was treated with micro-surfacing to reduce rutting (7-12mm) and stop further degradation. Targeted treatments like mill-and-overlay were carried out in 2019-2020 to avoid major degradation in the vital stretches. Effective scheduling of treatments played a significant role in ensuring acceptable road conditions while minimizing ongoing costs.

PMS continued its economic approach of micro-surfacing for large-scale remediation of medium rutting during 2020-2021 and beyond. This treatment plan worked well to tackle immediate problems and restrict the growth of rutting to further worse conditions. By 2023, the regular execution of the plan made sure the majority of the road stretches were in a better state, with only a minor percentage crossing the 12mm rutting mark. This last situation favorably depicts the PMS's achievement of the targeted road condition while maintaining the same budgetary appropriation.

4.3.2.1 Transition Probability Matrices (TPMs): Actual Data vs. PMS

The Alberta Transportation Maintenance Policy (TPM) data from the initial groundwork conveys a number of important insights mainly referring to a routine maintenance strategy. Among all changes, it points to a general and large-scale deterioration spreading over the whole network, which becomes especially widely used during the last periods (2020–2023). Such a tendency indicates that most of the routes have been going downhill during their lifespan notwithstanding the regular maintenance activities. On the other hand, the study also indicates that the present interventions are hardly efficient because of the segments next to the principal diagonal implying activities like micro-surfacing and thin overlays, which have not resulted in the recovery of pavements to “as-new” conditions. Besides, the continuous presence of segments with rutting levels more than 20 mm, even in 2023, is one of the evidences pointing to the incompleteness of

the removal process of the poorly maintained pavements from the service. These findings mainly emphasize the shortcomings of the current maintenance policy method especially the matter of the secondary indicators like the International Roughness Index (IRI) being used instead of primary damage indicators such as rutting, which are of key importance to make prediction more accurate and PMS implementation effective.

On the other hand, the PMSs represent a more informed and systematized approach to pavement maintenance. Analysis of the PMS matrix game shows that the segments are more tightly clustered toward the principal diagonal which, in turn, suggests better stability of pavement conditions over the network and thus the successful control of broadly distributed deterioration. Highlighting preventive maintenance, the PMS specifies treatments on those parts with moderate rutting (7–12 mm) as the riding condition that, on one hand, leads to a prolonged period of safe usage and, on the other, substantially reduces the amount of the restoration work needed. The system also attests to a diminution of the number of heavily deteriorated segments (e.g., rutting >20 mm), thus proving its ability to keep pavements in high quality and to increase the part of the network in good condition. Furthermore, the PMS tools allow for a rational use of resources, which is done mainly by a careful application of expensive methods like milling and overlay in a small number of cases only and a total reconstruction being reserved for the cases, which are without alternatives. Such optimizing of resources is the tool which makes it possible to exploit the available budget in the best way for maintaining the situation in general favorable.

4.3.2.2 Key Insights from the Comparison

The spread of segments in actual data shows that segments that have deteriorated are scattered to the right of the principal diagonal, which means that the conventional maintenance policy allowed pavement degradation to be widespread over time. The widespread degradation of pavement indicates that there must be inefficiencies within the existing maintenance strategy, as many segments have progressively changed their states to poorer ones. On the other hand, the matrix of the PMSs demonstrates that a much closer clustering of segments along the diagonal, reflecting the success of the optimized maintenance strategy in restraining deterioration and reducing the rate at which pavement segments degraded into poor condition.

Actually, concerning the impact of treatments, the data shows a great number of segments that are close to the principal diagonal, which indicates that interventions were mostly ineffective in restoring the pavement's initial structural capacity. As a result, many segments remained in suboptimal states even though they were treated. The PMS, however, shows that maintenance interventions can be not only targeted but also effective. For instance, micro surfacing is used preemptively to halt the progression of segments that display moderate rutting, while mill and overlay treatments are used to restore the parts that are getting close to the allowed threshold of deterioration. Full reconstruction only applies to severely deteriorated segments; thus resources can be allocated in the optimal way.

Actual data demonstrates a trend of deterioration that is increasing over time when discussing long-term sustainability, with the most significant period being from 2020 to 2023. It can be interpreted that the conventional maintenance strategy is likely to be unsustainable and there will be a need for frequent and periodic rehabilitations to maintain acceptable pavement conditions. The PMS is displayed as a way of taking care of the environment and is characterized by fewer network zones at the points of critical deterioration. The PMS emphasizes preventive maintenance and the careful reallocation of resources to keep the network in a good condition for a long time.

Along with that, as far as resource allocation is concerned, the actual data with the highest number of low-condition segments and the widespread decline show that resources have been invested in a less-than-optimal way under the traditional policy. Contrarily, the PMS is indicative of a maintenance budget that has been deployed in a thoughtful manner, starting with the prioritization of low-cost treatments at the initial stages of deterioration and keeping the use of high-intensity interventions for those situations that are out of control. This smart allocation not only extends the life of the entire network but also provides cost savings.

The comparison of TPMs reveals the obvious benefits of the PMS over Alberta's conventional approach to maintaining its roads. The PMS performs better through the direct damage indicators of rutting, maximizing the allocation of resources, and prioritizing proactive maintenance. This approach leads to increased control of the pavement conditions, less deterioration, and enhanced sustainability over a longer period.

The results highlight the need to shift from conventional maintenance practices to a Data-Driven Pavement Management System. The direct damage indicators and systematic optimization tools, if employed, would enable the treatments to be made in correspondence with the pavement network's actual structural requirements. This not only improves pavement performance but results in safer, longer lasting, and sustainable roadways, ultimately benefiting both the transportation agencies and the users of roads.

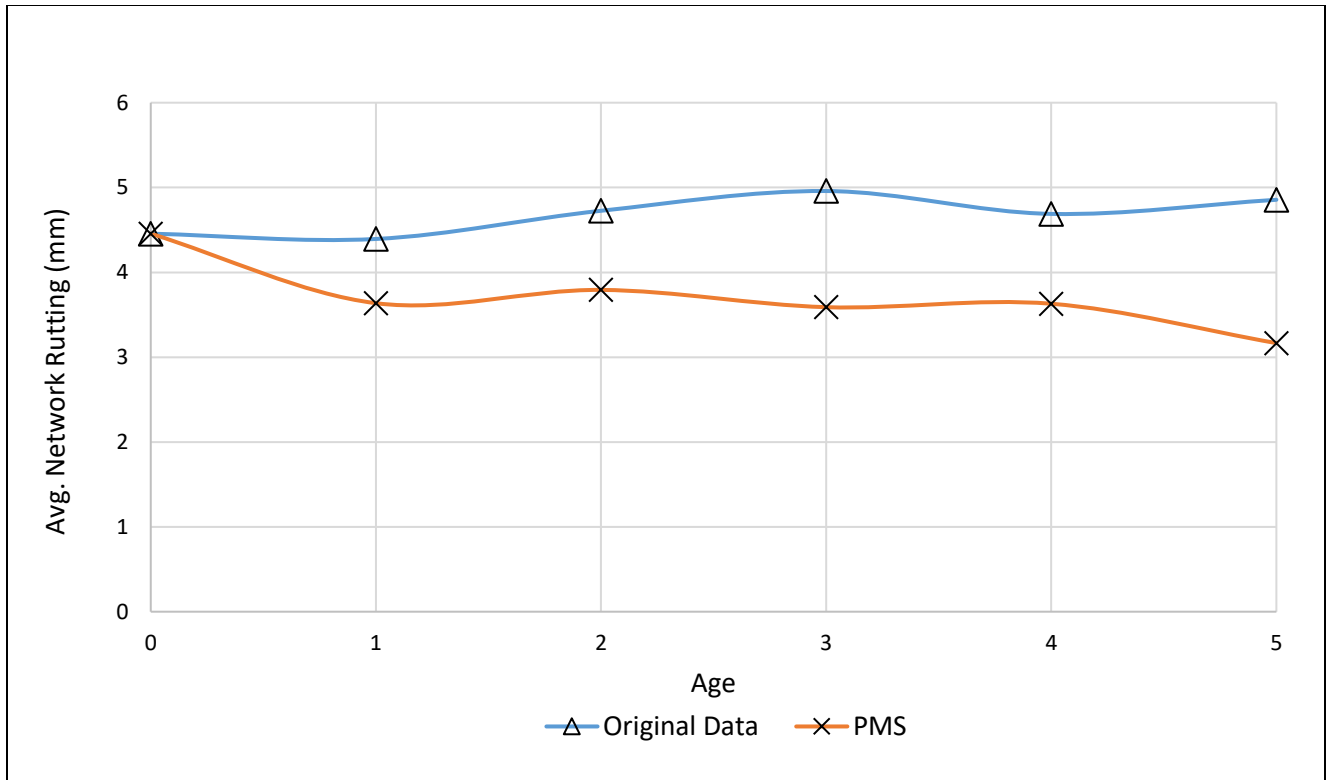


Figure 4-26: Original Vs. PMS Average Network Rutting

Figure 4-26 illustrates two major sets of data: "Original Data" to portray the real maintenance policy made available to the road agency and "PMS" (Pavement Management System) to represent the outcome of an optimized pavement management system. The figure graphically illustrates the PMS strategy leading to better average pavement rutting at all times compared to the original data. The supremacy of the PMS hardly becomes evident through conventional presentations. To better comprehend the deterioration dynamics and improvement after the maintenance action, the application of a TPM mechanism has been proposed.

Transition probability matrices provide a useful mechanism for modeling probabilistic movement from one pavement condition state to another over time. With the inclusion of these matrices, researchers are able to simulate the impact of different intervention activities on the probability of transitioning from one state to another. This enables a better understanding of the longer-term impact of various strategies, including the timing and nature of the intervention activities. The TPM mechanism gives a realistic picture of what happens to pavement conditions under various circumstances, thus delivering insights hard to obtain from static information or even averages.

In summary, while the figure indicates the PMS method has better overall pavement conditions, the optimal benefit of the method only manifests when supplemented by the TPM mechanism. This blend not only indicates the best performance of the optimized strategy but provides a detailed, multi-faceted picture of the underlying process responsible for pavement deterioration and rehabilitation. By considering this approach, it becomes possible for road agencies to make

better decisions regarding rehabilitation and maintenance, and eventually achieve better resource efficiency and longer-lived infrastructure.

There should be further work on incorporating these results into larger policy agendas in a manner that makes the strategies not only financially sound but also effective in maintaining the structural integrity of the pavement for the life of the pavement.

4.3.3 Results discussion

This portion of the study illustrated the shortcomings of traditional IRI-based methodologies to convincingly represent the annual trends of M&R activities. Compared to traditional methodologies, which may overlook the cohort effect of treatment alternatives over the extended period, the proposed method applies TPMs to track the development of pavement conditions - specifically, rutting - during the time frame 2018-2023. This leads to a closer and more nuanced assessment of treatment performance.

Through a consistent annual budget, the performance gap between a PMSs-optimized approach and the current policies of maintenance was noticeable. TPM analysis demonstrated current maintenance strategies led to widespread deterioration, exemplified by the trend towards deeper states of conditions over the 2020–2021 and 2022–2023 biennia. Under the PMS strategy, deterioration was better controlled, pavement condition was maintained, and fewer intensive treatment segments were in demand.

The major result is the inefficacy of the current policy in practice, since several treatments were unable to restore pavements to as-good-as-new conditions. By 2023, a considerable percentage of the segments already had over 20 mm of rutting and, therefore, needed the costly full reconstruction. Optimizing PMS, on the contrary, virtually eradicated the poor-condition segments along the same budget.

Success with the PMS strategy lies in the employment of a sequential and targeted approach. Pre-emptive treatments, such as micro-surfacing, were utilized during 2018–2019 for medium rutted (7–12 mm) areas and then milling and overlay during 2019–2020 to eliminate further deterioration from progressing. The approach then switched to low-cost, widespread micro-surfacing during 2020–2021 and again during 2022–2023. Following the monitor period, almost all of the segments were in an exceptionally good state of condition and had rut values below the crucial 12 mm mark.

Completed TPMs offered insightful evidence of the effectiveness of treatments across traffic intensity categories. For instance, a transformation from F25 to F1, signifying the poorest to the best pavement condition, implied the use of highly effective interventions like full reconstruction or extensive rehabilitation. A movement to a similar or a bit better or worse state indicated that the treatments used exerted a limited effect on the improvement of structural integrity. These matrices facilitated a quantitative evaluation of treatment efficacy, enabling comparison between the original dataset and the PMSs dataset. A comparison of the two sets of data by the study indicated variations in treatment effectiveness when utilizing direct damage indicators like Rutting versus

indirect indicators like the IRI. The TPMs ultimately proved to be a very effective means of assessing and optimizing maintenance measures to ensure that resources are funneled to the most effective interventions and to promote the formulation of sustainable pavement management practices.

The outcomes verify the potential of the TPM-guided PMS strategy to maximize pavement performance and life optimally at a constrained budget. By focusing on timely, proactive treatments and resources, the optimized maintenance plan enhanced the network condition as a whole and significantly minimized lifecycle costs. This proves the embedding of modern, data-driven approaches in pavement management practice for efficient and sustainable infrastructure results.

Some challenges occurred in the value transfer from the pivot table to the TPMs. For some instances, the TPMs were partially filled, with blank ranges where no treatment was available or could be applied. It represented instances where no intervention corresponded to a particular condition state or where limitations in the data did not allow a full analysis. There were also values that persisted along the main diagonal of the TPMs, signifying that no effective treatments were applied or measurements were within the range of errors of the measuring devices used to collect the data. These instances represented areas where treatments could not make a meaningful improvement in the pavements or where measurement inaccuracies could have affected the results.

5 Conclusion

5.1 Introduction

The integration of MEPDG into PMSs represents a considerable advancement in pavement engineering and has the potential to enhance both prediction accuracy and policy efficacy in maintenance. This thesis has explored such an integration using data from three different regions - Alaska, Uganda, and Alberta - each representing diverse geographic, economic, and data availability scenarios. When considered as a whole, the studies represent a holistic understanding of how MEPDG can successfully be integrated into PMS systems to enhance decision-making processes, resource optimization, and service life extension of road networks.

This final chapter synthesizes the key findings from the cases mentioned earlier and examines the broader implications of the research on pavement management practices. It assesses the efficacy, flexibility, and scalability of the proposed integration methodology and how the integration of empirical and mechanistic approaches leads to more resilient and sustainable pavement systems. Furthermore, the chapter discusses why a transition away from traditional condition-indexed management practices to data-driven and performance-oriented systems is important. The chapter concludes with focused recommendations on research and development in the future and highlights the importance of increased data infrastructure, climate resilience, and the integration of emerging technologies in pavement management.

5.2 Summary of Key Findings from Case Studies

The study has shown the possibility and advantage of incorporating the MEPDG into PMSs in three different contexts. Most of the existing literature is different from this study as they either treat the MEPDG and PMSs separately or only apply them in small-scale pilot projects. This research, however, discloses that it is possible to realize integration even in data-limited, data-scarce, and data-rich environments. Besides accomplishing the integration in different situations, this work also gains originality by providing direct comparative indication that MEPDG-based PMSs have higher performances than those conventional systems, which are still used by the majority of the transportation agencies and mainly rely on indirect indicators, e.g., the IRI or the PCI.

In Alaska, the study showed that a PMS supported by MEPDG can also be successful in a data-limited environment. Local calibration of mechanistic models for rutting and cracking led to the achievement of reliable pavement deterioration projections that, even with very few severe condition datapoints occurring at different times, are close to the true condition of the pavement. In other words, the finding is significant because it defies the widely held assumption that only continuous datasets of great length can be used for mechanistic approaches. Without doubt, an integrated system is empowered to provide a solid rationale for preventive maintenance and rehabilitation scheduling, as shown by the Alaskan case, which thereby establishes that such a mechanistic PMS can be functionally reliable even in areas with infrequent and high-cost

traditional data collection. Consequently, the low-data setting becomes the knowledge base for decision support of science-based PMS.

Another example is the Ugandan case, where this integration was developed further, such as stepping into a more challenging area, namely the scarcity of data in a developing country. New empirical relationships that approximate rutting and cracking from IRI were created to fill the gap. The proxy modeling introduced by the study has opened the way for running an MEPDG-based PMS in such places where mechanistic applications are usually not possible due to a lack of data. Besides, the study also found unique patterns of maintenance influenced by the budget cycle in the area, which led to cyclic rehabilitation peaks. This discovery shows how an integrated system not only gives more realistic deterioration forecasts but also points out inefficiencies of funding allocation and maintenance planning that traditional PMSs cannot uncover. The methodological contribution here is showcasing that the MEPDG integration can actually be a strategic tool for resource-constrained settings if one uses the techniques of imputation, calibration, and tailored modeling for such locations, which thus facilitates the use of mechanistic approaches for those beyond developed countries.

The Alberta case allowed showing the advantages of MEPDG-enhanced PMSs over traditional practice as clearly as possible. It was possible with a detailed dataset from 2018 to 2023, where a mechanistic PMS using the rutting indicator was compared directly with the existing policy that relied on IRI thresholds and visual indices. The current evaluation utilized Pavement Treatment Effectiveness performed through Transition Probability Matrices to measure the results obtained. The results clearly indicated that all else being equal, the integrated PMS was able to perform better in terms of controlling pavement condition, slowing down the rate of deterioration, increasing the number of preventive maintenance interventions, and achieving greater cost-efficiency in the long term. The main difference about this case is that it not only goes as far as calibration or pilot integration that are prevalent in previous literature, but also carries out a side-by-side benchmarking against the system currently in use by a transportation agency. This is the first study to give empirical evidence that mechanistic PMSs outperform IRI or PCI-driven approaches, thus setting a new standard for policy development.

Collectively, the previous three studies provide a major contribution to the development of the knowledge base of pavement management. The studies outline that MEPDG integration is adaptable across different geographical areas, such as remotely located, less monitored networks, resource-limited developing countries, and data-rich, highly monitored networks of advanced economies. Moreover, they reveal methodological innovations, for example, calibration frameworks with minimal data and distress estimation models of an empirical nature, which open the use of mechanistic methods for those areas where data are lacking. The Alberta results, above all, bring about a change in thinking by demonstrating that mechanistic prediction, as the PMSs are embedded, achieves a better performance than the traditionally used indirect indices. As a result, this research supersedes the agency practice of IRI- and PCI-based PMSs by offering strong,

comparative evidence of the mechanistic integration being the most accurate, preventive, and cost-effective maintenance strategies.

5.3 Effectiveness, Adaptability, and Scalability of the Integrated Approach

Across all the examined scenario, the integration of MEPDG-PMS was effective at forecasting pavement performance and optimizing maintenance strategies. Through the integration of mechanistic-empirical performance models with management decision structures, the methodology identified the actual mechanisms of pavement deterioration (e.g., structural rutting and fatigue cracking) and did not depend solely on surface measurements (e.g., IRI or PCI). This led to maintenance schedules that maintained pavement structural condition above acceptable threshold levels and optimized life-cycle costs. In both Alaska and Uganda, for example, the integrated models precisely predicted when and where distress would pass acceptable thresholds, enabling engineers to organize maintenance promptly and escape the additional costs of delayed maintenance. The effectiveness is also proven by the condition trending improvements seen in the simulations: under optimized-PMS, average network rutting and cracking exhibited a reduction and then a stabilizing (as noted in **Figure 4-4**, **Figure 4-5**, **Figure 4-11** and **Figure 4-12**), showing the correct treatments were in place at the correct times to mitigate deterioration. The effectiveness of pavement maintenance treatments in Alberta was also evaluated using efficacy metrics, revealing that the integrated approach achieved a higher number of condition improvements per treatment. This outcome substantiates that MEPDG-guided methods can optimize the allocation of maintenance resources, thereby delivering greater performance gains per dollar invested. Overall, the research showed that combining MEPDG and PMS is far more than a theoretical exercise but a practical means to improving pavement performance and extending service life.

An important advantage of the proposed integration is its adaptability to different climates, levels of traffic, and data availability. Through the previous three regions data covered a range from a cold, developed location (Alaska) to a tropical developing country (Uganda) and a high-volume provincial network (Alberta). The integrated PMS-MEPDG methodology was implemented successfully in all settings, and examples of flexibility were demonstrated. Central to the adaptability is model calibration to local conditions - as demonstrated by this study, global deterioration models were calibrated to local climate, materials and traffic to retain validity. In Alaska, calibration meant adjusting models of fatigue cracking and rutting to account for performance as seen in a freeze-thaw climate. In Uganda, adaptation extended to the inclusion of imputation methods to cover gaps in missing data and creating novel correlations to the local environment (e.g., correlation of IRI with structural distress). Although little historical data was available, the Ugandan model was able to capture realistic deterioration by using the localized relations. This proves the integration method to be context-aware: it can incorporate local knowledge and even expert judgment (when data are in short supply) to work. Moreover, the employment of MEPDG automatically allows accounting for different climates (through its climate module) and materials and it follows that the framework can be relocated to other locales with calibrated modification. The ability to work in varied environments and economies (well-

funded to resource-poor) proves the methodology to be resilient and malleable as long as practitioners invest in utilizing whatever local data are available and calibrating predictive models accordingly. The flexibility also applies to varying levels of application – whether in a handful of strategic road sections or a whole network, the methodology can be replicated by varying data granularity and computing intensity.

The scalability of the integrated methodology refers to its applicability to the network level and the ability to deal with large data and long planning horizons. In Alberta, the study emphasized scalability by applying the framework in a multi-year, network-level dataset comprising hundreds of thousands of highway sections across the six years available data). It showed how MEPDG-based analysis can be extended to network-level PMS decisions to produce insights on an entire network instead of project-level design. One identified problem is computational intensity: iterating through fine-grained mechanistic-empirical simulations on many pavement sections and tens of years is a heavy compute job. This study alleviated the problem by restricting attention to key distresses and using representative traffic and climate data as a proxy for groups of segments (e.g., grouping by traffic level or climate region). The results imply the integrated methodology can extend to state or national networks using commodity computing power and data efficiency. In addition, the reliance on tools such as TPMs to summarize network results is itself a scalable analytic methodology – instead of following every segment in detail, TPMs summarize the stochastic trends of network condition transitions and are also easy to update as additional data arrives. The study further suggests that the integration will be facilitated as agencies expand their data and increase automation of processes. For example, improved data collection automation and more rapid pavement performance software (or surrogate models) will make even large networks feasible to manage using mechanistic techniques. Briefly, the technical scalability is feasible and alignment with existing agency PMSs and scalable in an institutional sense as well – it has the ability to fit into existing agency PMSs with a corresponding training and phased rollout. The Alberta pilot success is a blueprint to roll out larger scale and could be scalable to an entire province or a country to shape network-wide maintenance planning.

5.4 Broader Implications for Pavement Management and Infrastructure Planning

The implications of integrating MEPDG in PMSs extend well beyond the three contexts analyzed, they imply a paradigm-shifting effect on transportation infrastructure planning and pavement management practice more broadly. Some of the main wider implications are discussed in the following sections.

Such results from an analytical investigation have a big influence on the evolution of pavement management systems. Identifying the nature of decay, coupled with the evaluation of model prediction capabilities, creates a fundamental base for better asset management. The knowledge gained from this work especially supports the following progressions:

1. Accurate scheduling of pavement maintenance and rehabilitation activities.
2. Development of more effective and targeted maintenance strategies

3. Improvement of long-term planning and budgeting for road infrastructure projects
4. Facilitating the adoption of environmentally friendly and affordable methods of road network management in developing countries with limited resources available.

Through the judicious integration of pavement management system methods and the use of real-world data, the research enables the selection of proper maintenance and rehabilitation actions supported by logical reasoning. This integrated analytical framework deepens the competence to forecast pavement longevity scenarios and assists in the establishment of durable and eco-friendly transport facilities at the national level.

5.4.1 Data-Driven Decision Making

This integrated approach elevates pavement management from relying on rough indices and heuristics to a more rigorous, data-driven paradigm. Creating the link between PMSs decisions with mechanistic performance predictions enables infrastructure agencies to optimize the timing, location, and choice of interventions across road networks using a more robust evidence base. This leads to interventions that are justified by predicted structural needs and future conditions, rather than solely past trends. In practice, this means pavement managers can confidently prioritize projects that will yield the greatest benefit in preserving the network, using tools that quantify future deterioration and risk. Over time, such data-driven practices improve accountability and transparency in infrastructure spending, since each decision is backed by modeled outcomes and lifecycle cost analysis.

5.4.2 Optimized Resource Allocation

Transportation agencies continually face budget constraints, and the research shows that an MEPDG-integrated PMS can significantly improve the efficiency of resource allocation. By forecasting deterioration more accurately, the system helps identify the optimal timing for maintenance – intervening neither too early (wasting resources on pavements still in good condition) nor too late (when rehabilitation becomes very costly). The case studies demonstrated that with the integrated approach, maintenance funds can be directed to the right place at the right time, yielding a more balanced expenditure profile over the pavement life cycle. Notably, the analysis of maintenance cost trends (e.g., Figure 4-6 in the Alaska study) indicated that a proactive, optimized strategy may involve higher initial spending to clear any maintenance backlogs, but it leads to lower and more stable costs in later years as the network stabilizes in a good condition state. On the other hand, the Uganda application highlighted the cyclical pattern of the expenditures that was largely due to the fact that most sections were already in a poor state of the base year, and this was aggravated by the tightly budget constraints. These restrictions led to the implementation of reactive strategies that concentrated on urgent needs only, thus more sections could decline. Nevertheless, the optimized PMS, when put into practice, provided a very good performance in decreasing the network average rutting and cracking (refer to Figure 4-11 and Figure 4-12) thereby, achieving a significant technical contribution beyond expenditure smoothing. Hence, a theoretical evaluation of the results of the optimization cannot be drawn only

from the trends of the expenditures but also from the extent of the network through performance indicators and condition improvements.

5.4.3 Lifecycle planning and Long-Term Maintenance

The incorporation of MEPDG into PMS inherently introduces a long-term perspective to pavement management decisions. PMS traditionally might consider the current condition and short-term objectives, but the mechanistic-empirical integration requires long-term performance to be considered (e.g., projecting out to 20–30 years). This means that strategic plans and capital programs for pavements are considered and analyzed not only on near-term performance but on long-term sustainability on a timescale of many decades. That is vital to infrastructure planning: it synchronizes maintenance and rehabilitation timing to pavements' design expectations to ensure the infrastructure lasts out to its design life with minimal unanticipated failure. The case studies' employment of a 30-year simulation provided road agencies a look to the future – allowing them to look ahead to timing major rehabilitation might be required and to even out the costs of required rehabilitation in the long term. Generally, the methodology is in alignment with asset management and enables transportation agencies to support long-time financing by projecting condition paths under different financing scenarios. The methodology also facilitates risk management – determining which pavements sections are candidates to become critical if kept untreated. Overall, the integration of design and management completes the loop between maintenance and construction and results in more resilient infrastructure planning.

5.4.4 Enhanced Network Performance and User Benefits

By focusing on actual structural distresses and their prevention, the integrated approach ultimately leads to better pavement conditions and thus a higher level of service for road users. The Alberta case indicated that switching to an optimized-PMSs strategy can result in lowering roads rutting which in turns helps in improved safety for the road users. Such improvements have multiplicative benefits: road users experience more comfortable and safer travel, vehicle operating costs decrease, and the need for disruptive repairs (which cause traffic delays) is reduced. For society and the economy, well-maintained roads support reliable transportation of goods and people. The implication is that modernizing pavement management with tools like MEPDG can have a direct positive impact on socio-economic outcomes, by preserving critical infrastructure at a higher level of service. This resonates with a growing emphasis on sustainability and quality of life, infrastructure managers are now expected not only to build roads but to maintain them at standards that support communities. An integrated PMS-MEPDG system is a step in that direction, enabling a more proactive and preventive maintenance culture that keeps infrastructure in a better level of service.

5.4.5 Policy and Standardization

The success of this integrated approach would imply that transportation agencies and policymakers would consider revising standards and guidelines for pavement management. Many agencies currently make maintenance decisions on the basis of indices such as IRI or superficial condition

ratings. One of the main ideas behind conducting this research is to recommend using structural performance models and locally-calibrated models of deterioration as part of the decision process. In the long-term, it is expected that road management criteria both at the national and regional levels will progressively require the utilization of mechanistic–empirical methods, especially after the MEPDG has been universally accepted as the foundation for pavement design by more agencies. This transition demands a change in the way pavement performance is reported and monitored. Agencies could start incorporating predicted condition trajectories - with or without interventions - in their asset management reports as a possible means of encouraging a more proactive approach to infrastructure preservation. Moreover, there will definitely be a need for a lot of training and skill-building as the engineers and decision-makers will be required to have expertise in mechanistic-empirical design concepts as well as optimization-based management practices before they can acquire them.

Through the integration showcased in this research, the incorporation of policy ideas can be facilitated, thus, the agencies located anywhere in the world can be led to the overcoming of the design-maintenance function division for gaining more sustainable and cost-effective pavement performance results as the ultimate goal.

5.5 Recommendations for Future Research and Development

Although this study has demonstrated the promise of incorporating MEPDG into a PMS system, it has also identified the areas requiring additional research and development. In order to further advance the state of the art in pavement management, the following directions are suggested as areas of research.

5.5.1 Enhanced Data Frequency and Quality

One of the repeated issues across all case studies was data quality and availability. Future research would investigate ways to increase pavement data collection in terms of frequency and quality. These involve increased utilization of automated condition surveys like Light Detection and Ranging (LiDAR) and high-speed imagery for distress identification and the employment of Internet of Things (IoT) sensors and remote sensing to capture real-time pavement performance data. More continuous and extensive data on rutting, cracking, deflection, and environmental conditions captured would permit models to be calibrated and validated more confidently. Exploring low-cost, distributed sensor networks (e.g., smart pavement systems) would enable real-time monitoring of pavement condition, which could directly feed into PMS databases. The convergence of new developments like IoT and remote sensing is poised to boost the accuracy of performance models significantly by enabling richer datasets. Moreover, establishing standard data formats and databases (possibly cloud-based) to share pavement performance data could in turn assist agencies with a paucity of data in accessing information from neighboring regions.

5.5.2 Adaptation to Climate Change in Pavement Management

Given the projected effects of climate change, it becomes essential to make climate resilience a part of pavement design and management. The research of the future includes the integration of climate change forecasts (e.g., warming temperatures, shifting rainfall patterns, increased frequency of extreme weather events) into MEPDG modeling and PMS decision rules. This could include altering rate of deterioration models to respond to faster aging under warm temperatures or excess moisture damage under heavier rainfall. Studies established that warmer climate will result in decreased pavement performance and decreased service life and more maintenance required if adaptation is not used. Hence, the PMS-MEPDG framework has to extend to include climate change scenario analysis – i.e., how a projected increase in average temperature by 2°C or 4°C over a period of 30 years would impact pavement life and what adaptive actions (material selection, alternative maintenance scheduling) would reduce these impacts. The Enhanced Integrated Climate Model (EICM) in MEPDG is among the tools that can help model future climate. In the end, making climate adaptation a part of the planning and the long-term plans developed through integrated PMS will make the plans resilient under long-term environmental states and maintain infrastructure resilience.

5.5.3 Emerging Technologies – Digital Twins, AI, and Machine Learning

Digital transformation technologies will possibly revolutionize next-generation pavement management. One such technology is digital twin technology with a robust platform to combine data from multiple sources (historical records, models, and sensors) into a virtual representation of real-time pavement networks. By developing digital twins of pavements, the agencies could conduct real-time monitoring, predictive simulation of scenarios, and optimization virtually, greatly enhancing decision-making capability. There need to be investigations regarding how digital twins of road networks can be constructed and updated and how the mechanistic-empirical models can be integrated into the digital copies. Preliminary studies suggest that the combination of digital twins and machine learning algorithms can provide cost-effective and enhanced pavement structural monitoring, with automatic distress detection and failure prediction. Machine learning in general can be used to improve pavement management in a number of ways: creating surrogate models that can predict MEPDG outcomes much faster (allowing for network-level analysis), analyzing trends in large PMS databases to improve deterioration models, and optimizing maintenance scheduling using AI-based decision support. For example, ML can be used to calibrate performance models in data-poor regions by learning from data-rich regions – basically transferring knowledge. Further studies are needed to validate such techniques and ensure AI/ML models are interpretable and reliable for applications in engineering. Similarly, exploration of how cloud computing and big data analytics can be utilized will be necessary to scale up such computations. In summary, the use of digital twins, IoT, and ML can go far to improve the functionalities of integrated PMS-MEPDG systems, and researchers should embark on pilot testing of such technologies in pavement management.

5.5.4 Localized Calibration and Model Enhancement

The study highlighted the need for calibration of MEPDG performance models to local conditions, but getting credible calibration coefficients requires significant data that are not always forthcoming. Future research must be directed at localization techniques with sparse data, including statistical techniques and Bayesian techniques that can combine expert opinion with sparse data to update model parameters. There is also a need for regional studies that provide calibration factors for different climates and types of pavements – for instance, providing default or ranges of calibration values for tropical climates (e.g., Uganda) versus cold climates (e.g., Alaska) to guide practitioners who are beginning to apply MEPDG in those regions. Investigation of adaptive calibration procedures that progressively refine model predictions as additional performance data become available could be a promising research direction (i.e., PMSs that learn over time). Additional research could also enhance the distress prediction models by adding other failure modes (e.g., potholing, structural cracking in lower layers, etc.) to the integrated framework, enabling the PMS to track an even broader set of performance measures. It is important that international models and codes are effectively adapted to suit context-specific conditions, and guidelines or computer packages for accomplishing this will enable wider application. For instance, collaborations between highway authorities and universities could yield localized MEPDG calibration databases or even region-specific new empirical models for regions that have traditionally been underrepresented in pavement research. Lastly, continual model validation and calibration need to become standard practice within any integrated PMS – an area that must be the subject of ongoing research efforts to establish best practices.

5.5.5 Life-Cycle Economic Analysis and Sustainability Metrics

Extending the integrated process, subsequent research activities could incorporate life-cycle analysis (LCA) along with sustainability metrics as integral components of the PMS-MEPDG process. This thesis considered primarily engineering performance and short-term costs; still, environmental (e.g., carbon footprint of maintenance work) and social (e.g., user costs and disruption) effects are becoming more popular topics in pavement management decision making. Such investigations could entail integrating the mechanistic predictions with LCA models to compare, for instance, how different maintenance schedules perform in terms of greenhouse gas emissions or energy consumption over the pavement life. Risk-based approaches could also be incorporated – using the probabilistic outputs (from TPMs or Monte Carlo runs within MEPDG) to estimate the risk of certain performance outcomes and incorporate risk tolerance into decision-making. This would enable agencies not only to keep pavements in a cost-effective manner but also contribute towards overall sustainability and resilience objectives.

5.6 Concluding Remarks

Finally, this thesis has illustrated the great potential that can be harnessed through the incorporation of mechanistic-empirical design principles into pavement management systems. Through closing the gap between pavement management and design, the research illustrated that one can engineer

a more integrated pavement management framework that is anticipatory, proactive, and customized to specific local conditions. The three case studies, which encompass three different continents, climates, and data environments, collectively demonstrate that the synthesis of PMS and MEPDG is both versatile and advantageous. A company in a developed country can utilize this synthesis to further enhance and advance an already advanced PMS, whereas a company in a developing country can jump directly to an advanced management paradigm even in the presence of data limitations. The suggested holistic approach provides infrastructure managers with improved tools for maintaining road networks in an efficient and sustainable way, thereby prolonging the lifespan of assets and making journeys safer for the general public. Looking ahead to the future, while transport organizations are confronted with limited budgets, deteriorating infrastructure, and uncertainty associated with climate change, the findings from this research work can guide practice and policy improvement. The route to comprehensive integration at large scale requires consistent efforts in the collection of data, implementation of technology, and development of capabilities; yet, the benefits concerning increased maintenance efficiency, lower costs, and improved pavement performance are apparent. By embracing mechanistic-empirical PMS integration and extending it with emerging innovations, pavement managers and engineers can radically enhance the resilience and reliability of transportation infrastructure for future generations. This study therefore not only offers a methodological framework and proof-of-concept for integrated pavement management, but also identifies a broader vision for advancing pavement engineering into a smarter, adaptive, and sustainability-oriented discipline. The findings and recommendations within this paper constitute a handbook for researchers and practitioners to continue developing pavement management in the face of modern challenges so that roads worldwide are constructed, maintained, and managed using the best available knowledge and tools.

References

- AASHTO. (1993). AASHTO Guide for Design of Pavement Structures. Washington, D.C: American Association of State Highway and Transportation Officials. Asphalt. In *Proceedings of the International Conference on Sustainable Waste Management and Recycling: Construction Demolition Waste*.
- AASHTO. (2001). *Pavement Management Guide* (1st ed.).
- Aashto. (2012). *Pavement Management Guide - 2nd Edition, 2012*.
- Abejide, S., Mostafa, M. M. H., Das, D., Awuzie, B., & Rahman, M. (2021). Pavement quality index rating strategy using fracture energy analysis for implementing smart road infrastructure. *Sensors*, 21(12). <https://doi.org/10.3390/s21124231>
- Achebe, J., Oyediji, O., Saari, R. K., Tighe, S., & Nasir, F. (2021). Incorporating flood hazards into pavement sustainability assessment. In *Transportation Research Record* (Vol. 2675, Issue 10, pp. 1025–1042). SAGE Publications Ltd. <https://doi.org/10.1177/03611981211014525>
- Ahmed, A., Labi, S., Li, Z., & Shields, T. (2013). Aggregate and disaggregate statistical evaluation of the performance-based effectiveness of long-term pavement performance specific pavement study-5 (LTPP SPS-5) flexible pavement rehabilitation treatments. *Structure and Infrastructure Engineering*, 9(2), 172–187. <https://doi.org/10.1080/15732479.2010.524224>
- Al-0mari, B., & Darter, M. I. (1995). *Effect of Pavement Deterioration Types on IRI and Rehabilitation*.
- Alaska Department of Transportation & Public Facilities. (n.d.). *Historic Road Pavement Condition Data*. Retrieved September 10, 2025, from https://dot.alaska.gov/stwddes/asset_mgmt/pave_mgt.shtml
- Albayati, A. H., Al-Ani, A. F., Byzyka, J., Al-Kheetan, M., & Rahman, M. (2024). Enhancing Asphalt Performance and Its Long-Term Sustainability with Nano Calcium Carbonate and Nano Hydrated Lime. *Sustainability (Switzerland)*, 16(4). <https://doi.org/10.3390/su16041507>
- Alberta Infrastructure and Transportation. (2006). *GUIDELINES FOR ASSESSING PAVEMENT PRESERVATION TREATMENTS AND STRATEGIES EDITION 2*.
- Alharbi, F., & Smadi, O. (2019a). Predicting Pavement Performance Utilizing Artificial Neural Network (ANN). *International Journal of Advanced Engineering, Management and Science*, 5(8), 504–508. <https://doi.org/10.22161/ijaems.58.4>
- Alharbi, F., & Smadi, O. (2019b). Predicting Pavement Performance Utilizing Artificial Neural Network (ANN). *International Journal of Advanced Engineering, Management and Science*, 5(8), 504–508. <https://doi.org/10.22161/ijaems.58.4>
- Alhasan, A., Nlenanya, I., Smadi, O., & MacKenzie, C. A. (2018a). Impact of pavement surface condition on roadway departure crash risk in Iowa. *Infrastructures*, 3(2). <https://doi.org/10.3390/infrastructures3020014>

- Alhasan, A., Nlenanya, I., Smadi, O., & MacKenzie, C. A. (2018b). Impact of pavement surface condition on roadway departure crash risk in Iowa. *Infrastructures*, 3(2). <https://doi.org/10.3390/infrastructures3020014>
- Alhasan, A., Nlenanya, I., Smadi, O., & MacKenzie, C. A. (2018c). Impact of pavement surface condition on roadway departure crash risk in Iowa. *Infrastructures*, 3(2). <https://doi.org/10.3390/infrastructures3020014>
- Ali, A., & Milad, A. (2023). Application of Machine Learning Techniques for Asphalt Pavement Performance Prediction. *Journal of Pure & Applied Sciences*, 22(3), 35–40. <https://doi.org/10.51984/jopas.v22i3.2733>
- Al-Mansour, A. I., & Shokri, A. A. (2022). Correlation of Pavement Distress and Roughness Measurement. *Applied Sciences (Switzerland)*, 12(8). <https://doi.org/10.3390/app12083748>
- Amador-Jimenez, L., & Afghari, A. P. (2015). Pavement management: Capturing surface treatment effectiveness. *ICTIS 2015 - 3rd International Conference on Transportation Information and Safety, Proceedings*. <https://doi.org/10.1109/ICTIS.2015.7232062>
- Amador-Jiménez, L. E., & Mrawira, D. (2009). Roads performance modeling and management system from two condition data points: Case study of Costa Rica. *Journal of Transportation Engineering*, 135(12). [https://doi.org/10.1061/\(ASCE\)TE.1943-5436.0000074](https://doi.org/10.1061/(ASCE)TE.1943-5436.0000074)
- Anis, M., & Abdel-Raheem, M. (2024). A Review of Electrically Conductive Cement Concrete Pavement for Sustainable Snow-Removal and Deicing: Road Safety in Cold Regions. *Transportation Research Record*. <https://doi.org/10.1177/03611981231225210>
- Asres, E., Ghebrab, T., & Ekwaro-Osire, S. (2022). Framework for Design of Sustainable Flexible Pavement. In *Infrastructures* (Vol. 7, Issue 1). MDPI. <https://doi.org/10.3390/infrastructures7010006>
- Austrroads. (1992). *DESIGN OF NEW FLEXIBLE PAVEMENTS*.
- Bashar, M. Z., Elseifi, M. A., Mousa, M. R., Zhang, Z., & Gaspard, K. (2019). Optimizing the Performance of Microsurfacing Treatments in Flexible Pavements and Assessing Its Effects on Moisture Damage. *Transportation Research Record*, 2673(1), 217–229. <https://doi.org/10.1177/0361198118821874>
- Beng, M. A. (2017). *LOCAL CALIBRATION OF MEPDG FOR SUPERPAVE PAVEMENTS IN ONTARIO: ENHANCE RUTTING CALIBRATION AND PRELIMINARY STUDY ON IRI MODEL*.
- Bianchini, A., & Bandini, P. (2010). Prediction of pavement performance through neuro-fuzzy reasoning. *Computer-Aided Civil and Infrastructure Engineering*, 25(1), 39–54. <https://doi.org/10.1111/j.1467-8667.2009.00615.x>
- Ceylan, H., Coree, B., & Gopalakrishnan, K. (2009a). Evaluation of the mechanistic-empirical pavement design guide for implementation in Iowa. *Baltic Journal of Road and Bridge Engineering*, 4(1), 5–12. <https://doi.org/10.3846/1822-427X.2009.4.5-12>

- Ceylan, H., Coree, B., & Gopalakrishnan, K. (2009b). Evaluation of the mechanistic-empirical pavement design guide for implementation in Iowa. *Baltic Journal of Road and Bridge Engineering*, 4(1), 5–12. <https://doi.org/10.3846/1822-427X.2009.4.5-12>
- Chan, C. Y., Huang, B., Yan, X., & Richards, S. (2010). Investigating effects of asphalt pavement conditions on traffic accidents in Tennessee based on the pavement management system (PMS). *Journal of Advanced Transportation*, 44(3), 150–161. <https://doi.org/10.1002/atr.129>
- Chen, C., Song, Y., Wang, Y. D., Hu, X., & Liu, J. (2023). A machine learning-based approach to assess impacts of autonomous vehicles on pavement roughness. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 381(2254). <https://doi.org/10.1098/rsta.2022.0176>
- Chun, P.-J., Yamane, T., & Tsuzuki, Y. (2021). *Automatic Detection of Cracks in Asphalt Pavement Using Deep Learning to Overcome Weaknesses in Images and GIS Visualization*. <https://doi.org/10.3390/app>
- Chung, F., Doyle, A., Robinson, E., Paik, Y., Li, M., Baek, M., Moore, B., & Ashuri, B. (2024). Ensemble Machine Learning Classification Models for Predicting Pavement Condition. *Transportation Research Record*. <https://doi.org/10.1177/03611981241240766>
- Cuelho, E., Mokwa, R., & Akin, M. (2006). *THE STATE OF MONTANA DEPARTMENT OF TRANSPORTATION in cooperation with*.
- Dan, H. C., Zeng, H. F., Zhu, Z. H., Bai, G. W., & Cao, W. (2022). Methodology for Interactive Labeling of Patched Asphalt Pavement Images Based on U-Net Convolutional Neural Network. *Sustainability (Switzerland)*, 14(2). <https://doi.org/10.3390/su14020861>
- de Salles, L. S., & Khazanovich, L. (2021). Local calibration of pavement mechanistic-empirical faulting reliability using pavement management data. In *Transportation Research Record* (Vol. 2675, Issue 9, pp. 251–264). SAGE Publications Ltd. <https://doi.org/10.1177/03611981211001392>
- Department of Transportation and Public Facilities. (2024). *Fiscal Year 2024 Operating Budget Department of Transportation and Public Facilities*. www.legfin.akleg.gov
- Diana, M., Otieno, A., Onyango, M., Fomunung, I., Reddy, J., & Owino, B. J. (2024). *VALIDATING THE EMPIRICAL DISTRESS PREDICTION MODELS WITHIN THE AASHTOWARE PAVEMENT MECHANISTIC-EMPIRICAL DESIGN, USING TENNESSEE PAVEMENT PERFORMANCE DATA FROM THE LONG TERM PAVEMENT PERFORMANCE DATABASE*.
- Dong, S., Yuan, X. X., & Hao, P. (2020). An advanced local calibration method for mechanistic-empirical pavement design. *Computer-Aided Civil and Infrastructure Engineering*, 35(11), 1276–1290. <https://doi.org/10.1111/mice.12574>
- Elsahly, O., Alqahtani, M., & Abdelfattah, A. (2023). Estimation of the Depth of Flexible Pavement Layers Using Artificial Neural Network. *World Congress on Civil, Structural, and Environmental Engineering*. <https://doi.org/10.11159/icgre23.126>

- Elseicy, A., Alonso-Díaz, A., Solla, M., Rasol, M., & Santos-Assunção, S. (2022). Combined Use of GPR and Other NDTs for Road Pavement Assessment: An Overview. In *Remote Sensing* (Vol. 14, Issue 17). MDPI. <https://doi.org/10.3390/rs14174336>
- Fameso, F., Ndambuki, J., Kupolati, W., & Snyman, J. (2024). Boundary Layer Modelling of Flow Acceleration and Energy Transfer Effects in Smart Pavement Design. *Science, Engineering and Technology*, 4(2), First. <https://doi.org/10.54327/set2024/v4.i2.143>
- Farina, A., Kutay, E., & Anctil, A. (2024). Mechanistic-empirical pavement design to include mechanical performance of rubberized asphalt pavements in the use stage of life cycle assessment. *Resources, Conservation and Recycling*, 206. <https://doi.org/10.1016/j.resconrec.2024.107618>
- Feitosa, I., Santos, B., & Almeida, P. G. (2024). Pavement Inspection in Transport Infrastructures Using Unmanned Aerial Vehicles (UAVs). In *Sustainability (Switzerland)* (Vol. 16, Issue 5). Multidisciplinary Digital Publishing Institute (MDPI). <https://doi.org/10.3390/su16052207>
- Fernando, N., & Coelho, C. (2016). *MavMatrix MavMatrix Calibration of MEPDG Performance Models for Flexible Pavement Calibration of MEPDG Performance Models for Flexible Pavement Distresses to Local Conditions of Ontario Distresses to Local Conditions of Ontario*. https://mavmatrix.uta.edu/civilengineering_theseshttps://mavmatrix.uta.edu/civilengineering_theses/329
- FHWA. (2010). *Performance Evaluation of Various Rehabilitation and Preservation Treatments*.
- Fhwa. (2018). *HRT-17-089 Validation of Pavement Performance Measures Using LTPP Data: Final Report*. <http://www.ntis.gov>
- FHWA. (2022). *Pavement Management Roadmap: A 10-Year Strategic Plan*.
- Fritzen, M. A., da Motta, L. M. G., Ubaldo, M. de O., Aragão, F. T. S., Nascimento, L. A. H. do, & Franco, F. A. C. de P. (2025). Validation of a transfer function adopted in the Brazilian mechanistic-empirical pavement design guide based on accelerated HVS and real traffic loads. *Road Materials and Pavement Design*. <https://doi.org/10.1080/14680629.2025.2511237>
- Fuhaid, A. F. Al, Arifuzzaman, M., & Gul, M. A. (2022a). Application of Mechanistic Empirical Pavement Design Guide Software in Saudi Arabia. *Applied Sciences (Switzerland)*, 12(16). <https://doi.org/10.3390/app12168165>
- Fuhaid, A. F. Al, Arifuzzaman, M., & Gul, M. A. (2022b). Application of Mechanistic Empirical Pavement Design Guide Software in Saudi Arabia. *Applied Sciences (Switzerland)*, 12(16). <https://doi.org/10.3390/app12168165>
- Gao, L., Yu, K., & Lu, P. (2022). Missing Pavement Performance Data Imputation Using Graph Neural Networks. In *Transportation Research Record* (Vol. 2676, Issue 12, pp. 409–419). SAGE Publications Ltd. <https://doi.org/10.1177/03611981221095511>
- Gao, L., & Zhang, Z. (2008a). Robust optimization for managing pavement maintenance and rehabilitation. *Transportation Research Record*, 2084, 55–61. <https://doi.org/10.3141/2084-07>

- Gao, L., & Zhang, Z. (2008b). Robust optimization for managing pavement maintenance and rehabilitation. *Transportation Research Record*, 2084, 55–61. <https://doi.org/10.3141/2084-07>
- Gaspard, K., Zhang, Z., Gautreau, G., Hanifa, K., Zapata, C. E., & Abufarsakh, M. (2019). Modeling the Resilient Modulus Variation of in Situ Soils due to Seasonal Moisture Content Variations. *Advances in Civil Engineering*, 2019. <https://doi.org/10.1155/2019/1793601>
- Gautam, G. P. (2015). *LOCAL CALIBRATION OF MEPDG RUTTING MODELS FOR ONTARIO'S SUPERPAVE PAVEMENTS*.
- Giustozzi, F., Crispino, M., & Flintsch, G. (2012). Multi-attribute life cycle assessment of preventive maintenance treatments on road pavements for achieving environmental sustainability. *International Journal of Life Cycle Assessment*, 17(4), 409–419. <https://doi.org/10.1007/s11367-011-0375-6>
- Government of Alberta. (n.d.). *International Roughness Index and Rut Data*. Retrieved September 10, 2025, from <https://www.alberta.ca/international-roughness-index-and-rut-data>
- Guest, G., Zhang, J., Maadani, O., & Shirkhani, H. (2020). Incorporating the impacts of climate change into infrastructure life cycle assessments: A case study of pavement service life performance. *Journal of Industrial Ecology*, 24(2), 356–368. <https://doi.org/10.1111/jiec.12915>
- Guha, S. K., Hossain, K., & Lawlor, M. (2022). An Economic Pavement Management Framework for Extremely Budget-and Resource-Constrained Agencies in Canada. In *Transportation Research Record* (Vol. 2676, Issue 8, pp. 554–570). SAGE Publications Ltd. <https://doi.org/10.1177/03611981221084687>
- Haas, R., & Hudson, W. R. (1978). *Pavement management systems*. McGraw-Hill.
- Hafez, M., Ksaibati, K., & Atadero, R. (2019). Integration of optimization methodology to evaluate pavement maintenance strategies for deteriorated low-volume roads. *Canadian Journal of Civil Engineering*, 46(2), 104–113. <https://doi.org/10.1139/cjce-2018-0194>
- Hall, K. D., Xiao, D. X., & Wang, K. C. P. (2006). *Calibration of the M-E Design Guide Final Report*.
- Hall, K., Xiao, D., & Wang, K. (2011). Calibration of the mechanistic-empirical pavement design guide for flexible pavement design in Arkansas. *Transportation Research Record*, 2226, 135–141. <https://doi.org/10.3141/2226-15>
- Hasan, M., & Sayed, A. (2017). *Determination of Consistency Limits of Different Agricultural Soils*. <http://internationalinventjournals.org/journals/IJAS>
- Hatoum, A., Khatib, J., & Elkordi, A. (2024). Comparison of Flexible Pavement Designs: Mechanistic-Empirical (NCHRP1-37A) Versus Empirical (AASHTO 1993) Flexible Pavement Design Using Available Local Calibration Models. *Transportation Infrastructure Geotechnology*, 11(2), 810–832. <https://doi.org/10.1007/s40515-023-00305-2>
- Highway Research Board. (1962). *The AASHO Road Test: Report 5-Pavement Research*.

- Hu, S., Zhou, F., & Scullion, T. (2017). Load spectra-incorporated fatigue cracking model implementation and case study. *Transportation Research Record*, 2640, 1–10. <https://doi.org/10.3141/2640-01>
- Huang, Y. Hsien. (1993). Pavement analysis and design, Parentice Hall. In *Deflection*.
- Hudson, W. R., McCullough, B. F., Scrivner, F. H., & Brown, J. L. (1970). *A SYSTEM APPROACH APPLIED TO PAVEMENT DESIGN AND RESEARCH*.
- Ijari, K., & Paternina-Arboleda, C. D. (2024). Sustainable Pavement Management: Harnessing Advanced Machine Learning for Enhanced Road Maintenance. *Applied Sciences (Switzerland)*, 14(15). <https://doi.org/10.3390/app14156640>
- Ikotun, J. O., Aderinto, G. E., Madirisha, M. M., & Katte, V. Y. (2024). Geopolymer Cement in Pavement Applications: Bridging Sustainability and Performance. In *Sustainability (Switzerland)* (Vol. 16, Issue 13). Multidisciplinary Digital Publishing Institute (MDPI). <https://doi.org/10.3390/su16135417>
- Intermodal Surface Transportation Efficiency Act of 1991, Pub. L. No. 102-240, United States Statutes at Large, Volume 105 1914 (1991). <https://www.govinfo.gov/app/details/STATUTE-105/STATUTE-105-Pg1914>
- INTERNATIONAL ORGANIZATION FOR STANDARDIZATION. (2014). ISO 55000 — Asset management — Overview, principles and terminology. *International Organization for Standardization*, 1.
- Jadoun, F., & Kim, Y. (2012). Calibrating mechanistic-empirical pavement design guide for North Carolina. *Transportation Research Record*, 2305, 131–140. <https://doi.org/10.3141/2305-14>
- Jannat, G. E. (2023). *Digital Commons @ Ryerson Database Development For Ontario's Local Calibration Of Mechanistic-Empirical Pavement Design Guide (MEPDG) Distress Models*. <http://digitalcommons.ryerson.ca/dissertations>
- Jannat, G., & Tighe, S. L. (2019a). Investigating Pavement Maintenance and Rehabilitation Requirement Based on Material Types and Traffic Levels through an Application of Probabilistic Approach for Ontario Highways. *Transportation Research Record*, 2673(11), 561–572. <https://doi.org/10.1177/0361198119852355>
- Jannat, G., & Tighe, S. L. (2019b). Investigating Pavement Maintenance and Rehabilitation Requirement Based on Material Types and Traffic Levels through an Application of Probabilistic Approach for Ontario Highways. *Transportation Research Record*, 2673(11), 561–572. <https://doi.org/10.1177/0361198119852355>
- Johanneck, L., & Khazanovich, L. (2010). Comprehensive evaluation of effect of climate in Mechanistic-Empirical Pavement Design Guide predictions. *Transportation Research Record*, 2170, 45–55. <https://doi.org/10.3141/2170-06>
- Karim, F. M. A., Rubasi, K. A. H., & Saleh, A. A. (2016). The Road Pavement Condition Index (PCI) Evaluation and Maintenance: A Case Study of Yemen. *Organization, Technology and Management in Construction: An International Journal*, 8(1), 1446–1455. <https://doi.org/10.1515/otmcj-2016-0008>

- Kaya, O., Ceylan, H., Kim, S., Waid, D., & Moore, B. P. (2020). Statistics and Artificial Intelligence-Based Pavement Performance and Remaining Service Life Prediction Models for Flexible and Composite Pavement Systems. *Transportation Research Record*, 2674(10), 448–460. <https://doi.org/10.1177/0361198120915889>
- Khamkhanpom, P., Nguyen, Q. P., La, V. C., Le, X. Q., & Nguyen, Q. T. (2025). Mechanistic-Empirical pavement design method and applicability in Laos. *Transportation Research Procedia*, 85, 18–25. <https://doi.org/10.1016/j.trpro.2025.03.129>
- Khurshid, M. B., Irfan, M., & Labi, S. (2011). An analysis of the cost-effectiveness of rigid pavement rehabilitation treatments. *Structure and Infrastructure Engineering*, 7(9), 715–727. <https://doi.org/10.1080/15732470902836566>
- Kim, S., Ceylan, H., Ma, D., & Gopalakrishnan, K. (2014a). Calibration of pavement ME Design and mechanistic-empirical pavement design guide performance prediction models for Iowa pavement systems. *Journal of Transportation Engineering*, 140(10). [https://doi.org/10.1061/\(ASCE\)TE.1943-5436.0000704](https://doi.org/10.1061/(ASCE)TE.1943-5436.0000704)
- Kim, S., Ceylan, H., Ma, D., & Gopalakrishnan, K. (2014b). Calibration of pavement ME Design and mechanistic-empirical pavement design guide performance prediction models for Iowa pavement systems. *Journal of Transportation Engineering*, 140(10). [https://doi.org/10.1061/\(ASCE\)TE.1943-5436.0000704](https://doi.org/10.1061/(ASCE)TE.1943-5436.0000704)
- Koh, D., Tokbolat, S., & Blaauw, S. A. (2024). Life cycle assessment of pavement construction: A case study. *IOP Conference Series: Earth and Environmental Science*, 1363(1). <https://doi.org/10.1088/1755-1315/1363/1/012065>
- Kumar, R., & Sharma, S. (2022). Perpetual Flexible Pavement vs. Rigid Pavement: An Economic and Environmental Cost Comparison. *IOP Conference Series: Earth and Environmental Science*, 1084(1). <https://doi.org/10.1088/1755-1315/1084/1/012053>
- Kwon, K., Choi, H., Pham, K., Kim, S., & Bae, A. (2024). Influence Analysis of Pavement Distress on International Roughness Index Using Machine Learning. *KSCE Journal of Civil Engineering*, 28(10), 4344–4355. <https://doi.org/10.1007/s12205-024-0093-9>
- Labi, S., Lamptey, G., Konduri, S., & Sinha, K. C. (2005). *Pavement Management*.
- Leben, B., Emery, J., & Scazziga, I. (2002). PAVEMENT SURFACE CONDITION INDICATORS. *PIARC Conference Proceedings*.
- Li, H., AzariJafari, H., Kirchain, R., Santos, J., & Khazanovich, L. (2024). Surrogate modelling of surface roughness for asphalt pavements using artificial neural networks: a mechanistic-empirical approach. *International Journal of Pavement Engineering*, 25(1). <https://doi.org/10.1080/10298436.2024.2434909>
- Li, J., Pierce, L. M., & Uhlmeier, J. (2009). Calibration of flexible pavement in mechanistic-empirical pavement design guide for Washington state. *Transportation Research Record*, 2095, 73–83. <https://doi.org/10.3141/2095-08>
- Li, Q., Xiao, D. X., Wang, K. C. P., Hall, K. D., & Qiu, Y. (2011a). Mechanistic-empirical pavement design guide (MEPDG): A bird's-eye view. *Journal of Modern Transportation*, 19(2), 114–133. <https://doi.org/10.3969/j.issn.2095-087X.2011.02.007>

- Li, Q., Xiao, D. X., Wang, K. C. P., Hall, K. D., & Qiu, Y. (2011b). Mechanistic-empirical pavement design guide (MEPDG): A bird's-eye view. *Journal of Modern Transportation*, 19(2), 114–133. <https://doi.org/10.3969/j.issn.2095-087X.2011.02.007>
- Li, Q., Xiao, D. X., Wang, K. C. P., Hall, K. D., & Qiu, Y. (2011c). Mechanistic-empirical pavement design guide (MEPDG): A bird's-eye view. *Journal of Modern Transportation*, 19(2), 114–133. <https://doi.org/10.3969/j.issn.2095-087X.2011.02.007>
- Liang, J., Zhang, Q., & Gu, X. (2024). Classification of Asphalt Pavement Defects for Sustainable Road Development Using a Novel Hybrid Technology Based on Clustering Deep Features. *Sustainability (Switzerland)*, 16(22). <https://doi.org/10.3390/su162210145>
- Lin, J. D., Hsu, C. Y., & Su, Y. M. (2013). Field assessment in permeability and surface run-off of permeable pavement. *Applied Mechanics and Materials*, 361–363, 1503–1506. <https://doi.org/10.4028/www.scientific.net/AMM.361-363.1503>
- Lin, P., Yuan, X. X., & Tovilla, E. (2019). Integrative modeling of performance deterioration and maintenance effectiveness for infrastructure assets with missing condition data. *Computer-Aided Civil and Infrastructure Engineering*, 34(8), 677–695. <https://doi.org/10.1111/mice.12452>
- Liu, J., Liu, F., Zheng, C., Zhou, D., & Wang, L. (2022). Optimizing asphalt mix design through predicting the rut depth of asphalt pavement using machine learning. *Construction and Building Materials*, 356. <https://doi.org/10.1016/j.conbuildmat.2022.129211>
- Louhghalam, A., Akbarian, M., & Ulm, F. J. (2015). Roughness-Induced Pavement–Vehicle Interactions Key Parameters and Impact on Vehicle Fuel Consumption. *Transportation Research Record*, 2525(1), 62–70. <https://doi.org/10.3141/2525-07>
- Luo, X., Wang, F., Gong, H., Tao, J., Qiu, X., & Wang, N. (2022). Effectiveness Evaluation of Preventive Maintenance Treatments on Asphalt Pavement Performance Using LTPP Data. *International Journal of Pavement Research and Technology*, 15(5), 1139–1154. <https://doi.org/10.1007/s42947-021-00078-2>
- Ma, H., Wang, D., Zhou, C., & Feng, D. (2015a). Calibration on MEPDG Low Temperature Cracking Model and Recommendation on Asphalt Pavement Structures in Seasonal Frozen Region of China. *Advances in Materials Science and Engineering*, 2015. <https://doi.org/10.1155/2015/830426>
- Ma, H., Wang, D., Zhou, C., & Feng, D. (2015b). Calibration on MEPDG Low Temperature Cracking Model and Recommendation on Asphalt Pavement Structures in Seasonal Frozen Region of China. *Advances in Materials Science and Engineering*, 2015. <https://doi.org/10.1155/2015/830426>
- Mandiartha, P., Duffield, C. F., Thompson, R. G., & Wigan, M. R. (2017). Measuring pavement maintenance effectiveness using Markov Chains analysis. *Structure and Infrastructure Engineering*, 13(7), 844–854. <https://doi.org/10.1080/15732479.2016.1212901>
- Mashaan, N. S., & Ouano, C. A. (2024). *Investigation on the Mechanical Properties of Concrete with Different Types of Waste Plastics for Rigid Pavement*. <https://doi.org/10.20944/preprints202410.1238.v1>

- Monismith, C. L., & Asce, M. (2012). *Flexible Pavement Analysis and Design-A Half Century of Achievement*.
- Mubaraki, M. (2016). *Study the Relationship between Pavement Surface Distress and Roughness Data*. <https://doi.org/10.1051/0>
- Mursaleen, M., Raja, , Affan, M., Sabih, ; Gauhar, & Iqbal, M. J. (2025). *Quantifying the Impact of Climatic Factors on JPCP Design and Performance in Pakistan*.
- Nair, H., & McGhee, K. (2022). Evaluation of Different Surface Treatments to Extend Pavement Life. In *Transportation Research Record* (Vol. 2676, Issue 8, pp. 312–321). SAGE Publications Ltd. <https://doi.org/10.1177/03611981221083604>
- Nantung, T., Lee, J., & Tian, Y. (2018). *Efficient Pavement Thickness Design for Indiana*. <https://doi.org/10.5703/1288284316649>
- NCHRP. (2004). Guide for mechanistic-empirical design of new and rehabilitated pavement structures, final report for project 1-37a. *Washington, DC: Board, T.R., NCHRP 1-37A*.
- Ndon, D. U. J. (2017). Trends in the Application of Permeable Pavement as Sustainable Highway Storm Water Management Option for Safe-Use of Roadways. *Journal of Civil & Environmental Engineering*, 07(06). <https://doi.org/10.4172/2165-784x.1000288>
- Noureldin, E. M., & Abdelrahman, M. (2014). Parametric analysis of resilient modulus modeling for recycled asphalt pavement in base layer. *Transportation Research Record*, 2401, 30–43. <https://doi.org/10.3141/2401-04>
- OFFICE OF THE CLERK TO PARLIAMENT. (2024). *A Report Of The Committee Of Physical Infrastructure On the Uganda Road Fund (Amednment) Bill, 2024*.
- Omenogor, K. O., Oh, W. T., & Vanapalli, S. K. (2025). Mechanistic-empirical method of pavement design extending unsaturated soil mechanics. *Transportation Geotechnics*, 52. <https://doi.org/10.1016/j.trgeo.2025.101569>
- Osman, S. A., Almoshaogeh, M., Jamal, A., Alharbi, F., Al Mojil, A., & Dalhat, M. A. (2023). Intelligent Assessment of Pavement Condition Indices Using Artificial Neural Networks. *Sustainability (Switzerland)*, 15(1). <https://doi.org/10.3390/su15010561>
- Özdemir, O. B., Soydan, H., Çetin, Y. Y., & Düzgün, H. Ş. (2020). Neural network based pavement condition assessment with hyperspectral images. *Remote Sensing*, 12(23), 1–20. <https://doi.org/10.3390/rs12233931>
- Pan, Y., Zhang, X., Cervone, G., & Yang, L. (2018). Detection of Asphalt Pavement Potholes and Cracks Based on the Unmanned Aerial Vehicle Multispectral Imagery. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 11(10), 3701–3712. <https://doi.org/10.1109/JSTARS.2018.2865528>
- Perera, R. W., & Kohn, S. D. (2001). *LTPP Data Analysis: Factors Affecting Pavement Smoothness*.

- Pittenger, D., Gransberg, D. D., Zaman, M., & Riemer, C. (2012). Stochastic life-cycle cost analysis for pavement preservation treatments. *Transportation Research Record*, 2292, 45–51. <https://doi.org/10.3141/2292-06>
- Porter, O. J. (1938). *The structural design of concrete pavements: How to determine the thickness of concrete pavements*.
- Qiao, Y., Dawson, A. R., Parry, T., Flintsch, G., & Wang, W. (2020a). Flexible pavements and climate change: A comprehensive review and implicatio. *Sustainability (Switzerland)*, 12(3). <https://doi.org/10.3390/su12031057>
- Qiao, Y., Dawson, A. R., Parry, T., Flintsch, G., & Wang, W. (2020b). Flexible pavements and climate change: A comprehensive review and implicatio. *Sustainability (Switzerland)*, 12(3). <https://doi.org/10.3390/su12031057>
- Radwan, M. M., Abo-Hashema, M. A., Hashem, M. D., & Faheem, H. B. (2020). Modeling pavement performance using LTPP database for flexible pavements. *Teknik Dergi/Technical Journal of Turkish Chamber of Civil Engineers*, 31(4), 10127–10146. <https://doi.org/10.18400/TEKDERG.476606>
- Ragnoli, A., De Blasiis, M. R., & Di Benedetto, A. (2018). Pavement distress detection methods: A review. In *Infrastructures* (Vol. 3, Issue 4). MDPI Multidisciplinary Digital Publishing Institute. <https://doi.org/10.3390/infrastructures3040058>
- Retherford, J., & McDonald, M. (2010). Reliability methods applicable to mechanistic-empirical pavement design method. *Transportation Research Record*, 2154, 130–137. <https://doi.org/10.3141/2154-13>
- Road and Transportation Association of Canada. (1977). *Pavement management guide*.
- Roberts, R., Giancontieri, G., Inzerillo, L., & Di Mino, G. (2020). Towards low-cost pavement condition health monitoring and analysis using deep learning. *Applied Sciences (Switzerland)*, 10(1). <https://doi.org/10.3390/app10010319>
- Romero-Chambi, E., Villarroel-Quezada, S., Atencio, E., & Rivera, F. M. La. (2020). Analysis of optimal flight parameters of unmanned aerial vehicles (UAVs) for detecting potholes in pavements. *Applied Sciences (Switzerland)*, 10(12), 1–33. <https://doi.org/10.3390/APP10124157>
- Sadek, H. A., Masad, E. A., Sirin, O., Al-Khalid, H., Sadeq, M. A., & Little, D. (2014). Implementation of mechanistic-empirical pavement analysis in the State of Qatar. *International Journal of Pavement Engineering*, 15(6), 495–511. <https://doi.org/10.1080/10298436.2013.837164>
- Saeed, T. U., Qiao, Y., Chen, S., Alqadhi, S., Zhang, Z., Labi, S., & Sinha, K. C. (2018). *Effects of Bridge Surface and Pavement Maintenance Activities on Asset Rating*. <https://doi.org/10.5703/1288284316573>
- Schwartz, C. W., Li, R., Ceylan, H., Kim, S., & Gopalakrishnan, K. (2013). Global sensitivity analysis of mechanistic-empirical performance predictions for flexible pavements. *Transportation Research Record*, 2368, 12–23. <https://doi.org/10.3141/2368-02>

- Shahin, M. Y., & Kohn, S. D. (1982). OVERVIEW OF PAVER PAVEMENT MANAGEMENT SYSTEM. *Transportation Research Record*, 846.
- SHAKHAN, M. R., TOPAL, A., & SENGOZ, B. (2022). Impact of Subgrade Strength on Pavement Performance. *Deu Muhendislik Fakultesi Fen ve Muhendislik*, 24(71), 501–508. <https://doi.org/10.21205/deufmd.2022247115>
- Shell International Petroleum Company. (1963). *Shell pavement design manual: asphalt pavements and overlays for road traffic. Addendum to the Shell pavement design manual*. Shell International Petroleum Co.
- Si, J., Ishikawa, T., Ren, D., Maruyama, K., & Ueno, C. (2023). Response Prediction of Asphalt Pavement in Cold Region with Thermo-Hydro-Mechanical Coupling Simulation. *Sustainability (Switzerland)*, 15(18). <https://doi.org/10.3390/su151813614>
- Singh, R. R., Lali, F., Muslim, H. Bin, Haider, S. W., & Dolan, K. D. (2025). Scaled Sensitivity of Pavement–Mechanistic–Empirical Transfer Function Coefficients for Flexible and Rigid Pavements. *Transportation Research Record*, 2679(4), 630–640. <https://doi.org/10.1177/03611981241295707>
- Stampone, M. D., Hartter, J., & Ryan, S. J. (2011). Trends and Variability in Localized Precipitation Around Kibale National Park. In *Africa Article in Research Journal of Environmental and Earth Sciences*. <https://www.researchgate.net/publication/49605118>
- Styer, J., Tunstall, L., Landis, A., & Grenfell, J. (2024). Innovations in pavement design and engineering: A 2023 sustainability review. In *Heliyon* (Vol. 10, Issue 13). Elsevier Ltd. <https://doi.org/10.1016/j.heliyon.2024.e33602>
- Subedi, S., Hassan, M. M., Nie, Q., Talaat Soliman, N. S., Gaspard, K., & Rupnow, T. (2018). Decision-Making Tool for Incorporating Cradle-to-Gate Sustainability Measures into Pavement Design. *Journal of Transportation Engineering, Part B: Pavements*, 144(4), 04018051. <https://doi.org/10.1061/jpeodx.0000082>
- Transport and Road Research Laboratory (TRRL). (1977). *Road Note 31: Structural design of bitumen-surfaced roads in tropical and sub-tropical*.
- Uglova, E., Tiraturyan, A., & Aslanyan, G. (2018). Reliability-Oriented Method of Flexible Pavement Management. *MATEC Web of Conferences*, 196. <https://doi.org/10.1051/matecconf/201819603005>
- Wang, H., Chen, Z., & Sun, L. (2013). Pavement roughness evaluation for urban road management. *ICTE 2013 - Proceedings of the 4th International Conference on Transportation Engineering*. <https://doi.org/10.1061/9780784413159.394>
- Wasanta, T., Subagio, B. S., Wibowo, S. S., & Hariyadi, E. S. (2024a). COMPARATIVE ANALYSIS OF OVERLAY THICKNESS USING THE ASPHALT INSTITUTE’S AND MEPDG WITH KENLAYER. *International Journal of GEOMATE*, 26(118), 57–64. <https://doi.org/10.21660/2024.118.4370>
- Wasanta, T., Subagio, B. S., Wibowo, S. S., & Hariyadi, E. S. (2024b). COMPARATIVE ANALYSIS OF OVERLAY THICKNESS USING THE ASPHALT INSTITUTE’S AND

- MEPDG WITH KENLAYER. *International Journal of GEOMATE*, 26(118), 57–64. <https://doi.org/10.21660/2024.118.4370>
- Watanatada, T., Harral, C. G., Dhareshwar, A. M., Bhandari, A., & Tsunokawa, K. (1987). *THE HIGHWAY DESIGN AND MAINTENANCE STANDARDS SERIES 9951 It ' I S 7 ' 0 Volume I Description of the HDM-III Model*.
- Wu, Z., Zhang, Z., & Abadie, C. (2013). Determining structural strength of existing asphalt layer using condition survey data. *International Journal of Pavement Engineering*, 14(7), 603–611. <https://doi.org/10.1080/10298436.2012.677845>
- Xu, H., & Prozzi, J. A. (2023a). Effect of Data Imbalance on the Performance of Pavement Deterioration Models. *Transportation Research Record*, 2677(12), 201–211. <https://doi.org/10.1177/03611981231167427>
- Xu, H., & Prozzi, J. A. (2023b). Effect of Data Imbalance on the Performance of Pavement Deterioration Models. *Transportation Research Record*, 2677(12), 201–211. <https://doi.org/10.1177/03611981231167427>
- Zafar, M. S., Shah, S. N. R., Memon, M. J., Rind, T. A., & Soomro, M. A. (2019). Condition Survey for Evaluation of Pavement Condition Index of a Highway. *Civil Engineering Journal (Iran)*, 5(6), 1367–1383. <https://doi.org/10.28991/cej-2019-03091338>
- Zagvozda, M., Dimter, S., Moser, V., & Barišić, I. (2019). Application of GIS technology in Pavement Management Systems. *Gradjevinar*, 71(4), 297–304. <https://doi.org/10.14256/JCE.1980.2017>
- Zhang, H., Keoleian, G. A., & Lepech, M. D. (2013a). Network-Level Pavement Asset Management System Integrated with Life-Cycle Analysis and Life-Cycle Optimization. *Journal of Infrastructure Systems*, 19(1), 99–107. [https://doi.org/10.1061/\(asce\)is.1943-555x.00000093](https://doi.org/10.1061/(asce)is.1943-555x.00000093)
- Zhang, H., Keoleian, G. A., & Lepech, M. D. (2013b). Network-Level Pavement Asset Management System Integrated with Life-Cycle Analysis and Life-Cycle Optimization. *Journal of Infrastructure Systems*, 19(1), 99–107. [https://doi.org/10.1061/\(asce\)is.1943-555x.00000093](https://doi.org/10.1061/(asce)is.1943-555x.00000093)
- Zhao, Y., Goulias, D., & Peterson, D. (2021). Recycled asphalt pavement materials in transport pavement infrastructure: Sustainability analysis & metrics. *Sustainability (Switzerland)*, 13(14). <https://doi.org/10.3390/su13148071>
- Zhuang, Y., Yue, J., Men, B., Tang, G., & Wang, R. (2023). Experimental Study on Mechanism, Aging and Fatigue Performance of Warm Mixing Speed Melting SBS Modified Asphalt Binders. *Coatings*, 13(2). <https://doi.org/10.3390/coatings13020311>