EVALUATION OF AIRPORT PAVEMENT MAINTENANCE AND REHABILITATION STRATEGIES: A CASE STUDY OF KIGALI INTERNATIONAL AIRPORT

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ABSTRACT

EVALUATION OF AIRPORT PAVEMENT MAINTENANCE AND REHABILITATION STRATEGIES: A CASE STUDY OF KIGALI INTERNATIONAL AIRPORT

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Airport pavement preservation is an economic imperative for developing nations, yet pavement management often remains reactive under severe resource constraints. In the developing-country context, limited historical records and rigid budgets prevent proactive planning and timely preventive maintenance. This study assesses the airfield pavement network at Kigali International Airport (KIA) to identify a feasible Maintenance and Rehabilitation (M&R) strategy that restores safety and improves long-term performance. A digital inventory and condition database was developed in FAA PAVEAIR using Pavement Condition Index (PCI) results to represent functional condition and support M&R planning. Structural adequacy requirements were verified using FAARFIELD outputs to identify critical sections. Four maintenance scenarios were evaluated: (1) Unlimited Budget, (2) Consequence of Local Repair (CLR), (3) Minimum Condition, and (4) Limited Budget ($1million/year). Over a 10-year analysis period, strategies were compared using first-year funding needs, 10-year life-cycle costs, terminal network condition, and financial feasibility. Results show a critical pavement condition, with a weighted average PCI of 39.7 in 2024. The Unlimited Budget and Minimum Condition scenarios achieve full restoration but require unaffordable first-year capital of $26.8

million. Similarly, the Limited Budget strategy is ineffective; by deferring mandatory safety repairs and allows sections to reach failure. Therefore, CLR is recommended as the best safety-to-cost strategy, requiring $4.6 million in initial funding to mitigate safety risks and stabilize the network within the operational safety window of PCI 40-55. The study contributes a quantified, KIA-specific M&R framework transferable to other resource-constrained airports transitioning to data-driven, safety-focused pavement management.

Keywords: Pavement Condition Index (PCI), FAA PAVEAIR, Airport Pavement Management Systems (APMS), Kigali International Airport (KIA)

ÖZ

HAVALİMANI KAPLAMA BAKIM VE ONARIM STRATEJİLERİNİN DEĞERLENDİRİLMESİ: KİGALİ ULUSLARARASI HAVALİMANI ÖRNEK OLAY İNCELEMESİ

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Havalimanı kaplamalarının korunması, gelişmekte olan ülkeler için ekonomik bir zorunluluktur; ancak kaplama yönetimi, ciddi kaynak kısıtları altında çoğu zaman reaktif kalmaktadır. Gelişmekte olan ülke bağlamında, sınırlı tarihsel kayıtlar ve katı bütçeler proaktif planlamayı ve zamanında önleyici bakımı engellemektedir. Bu çalışma, Kigali Uluslararası Havalimanı (KIA) havaalanı kaplama ağını değerlendirerek emniyeti yeniden sağlayan ve uzun vadeli performansı iyileştiren uygulanabilir bir Bakım ve Rehabilitasyon (M&R) stratejisi belirlemeyi amaçlamaktadır. İşlevsel durumu temsil etmek ve M&R planlamasını desteklemek üzere, Kaplama Durum İndeksi (PCI) sonuçları kullanılarak PAVEAIR içinde dijital bir envanter ve durum veritabanı oluşturulmuştur. Kritik kesimleri belirlemek için yapısal yeterlilik gereksinimleri FAARFIELD çıktıları kullanılarak doğrulanmıştır. Dört bakım senaryosu değerlendirilmiştir: (1) Sınırsız Bütçe, (2) Yerel Onarımın Sonuçları (CLR), (3) Asgari Koşul ve (4) Sınırlı Bütçe (yıllık 1 milyon ABD doları). 10 yıllık analiz dönemi boyunca stratejiler; ilk yıl finansman gereksinimi, 10 yıllık yaşam döngüsü maliyetleri, dönem sonu ağ durumu ve finansal uygulanabilirlik ölçütleriyle karşılaştırılmıştır. Sonuçlar, 2024 yılında ağırlıklı ortalama PCI’nin 39,7 olduğu kritik bir kaplama durumunu göstermektedir. Sınırsız Bütçe ve Asgari Koşul senaryoları tam iyileştirme sağlamakla birlikte, 26,8 milyon ABD doları tutarında karşılanamaz bir ilk yıl sermayesi gerektirmektedir. Benzer şekilde, Sınırlı Bütçe stratejisi etkisizdir; zorunlu emniyet onarımlarını erteleyerek kesimlerin başarısızlığa ulaşmasına neden olmaktadır. Bu nedenle CLR, emniyet–maliyet açısından en uygun strateji olarak önerilmekte; emniyet risklerini azaltmak ve ağı PCI 40–55 aralığındaki operasyonel emniyet penceresinde stabilize etmek için 4,6 milyon ABD doları başlangıç finansmanı gerektirmektedir. Çalışma, veri temelli ve emniyet odaklı kaplama yönetimine geçiş yapan, kaynak kısıtlı diğer havalimanlarına aktarılabilir nicel bir KIA-özgü M&R çerçevesi sunmaktadır.

Anahtar Kelimeler: Kaplama Durum İndeksi (PCI), FAA PAVEAIR, Havalimanı Kaplama Yönetim Sistemleri (APMS), Kigali Uluslararası Havalimanı (KIA).

To my lovely wife Lisa, our adorable daughter Bliss, and METU Transportation LAB friends

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Finally, my heart belongs to my family, who have been my anchor. To my beautiful wife, Lisa, and my adorable daughter, Bliss, thank you for your unwavering daily company, your love, and your emotional support. You were my source of strength on the difficult days and my greatest joy on the good ones. This achievement is as much yours as it is mine.

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ABBREVIATIONS

AC: Asphalt concrete

ASTM: American Society for Testing and Materials

FAA AC: Federal Aviation Administration Advisory Circular

ACRP: Airport Cooperative Research Program

CAN/PCN: Aircraft Classification Number / Pavement Classification Number

ACR-PCR: Aircraft Classification Rating / Pavement Classification Rating

APMS: Airport Pavement Management System

PMP: Pavement Management Program

FAA: Federal Aviation Administration

FWD: Falling Weight Deflectometer

HWD: Heavy Weight Deflectometer

DCP: Dynamic Cone Penetrometer

LCCA: Life-Cycle Cost Analysis

M&R: Maintenance and Rehabilitation

NDT: Non-Destructive Testing

USACERL: United States Army Civil Engineering Research Laboratory

PCI: Pavement Condition Index

FOD: Foreign Object Debris

SCI: Surface Condition Index

IRI: International Roughness Index

CLR: Consequences of the Local Repair

FV: Future Value

PV: Present Value

KIA: Kigali International Airport

CHAPTER 1

INTRODUCTION

Airport pavement management is a systematic approach to keep airfield pavements safe and serviceable through planned inspections, condition assessment, prioritization, and timely maintenance and rehabilitation (M&R). It is strategically important because pavement performance directly affects operational safety, airport continuity, and long-term life-cycle costs. However, in many developing countries, limited funding, weak data systems, and constrained technical capacity often force airports to rely on reactive, worst-first repairs rather than preventive preservation, increasing safety risks and escalating future rehabilitation costs. Kigali International Airport (KIA) is Rwanda's primary aviation gateway, supporting trade, tourism, and regional connectivity. The performance of its airfield pavement network is therefore critical for operational safety, serviceability, and cost-effective airport operations. Like many airports in developing countries, KIA faces two persistent challenges: aging pavement infrastructure and limited financial resources for maintenance and rehabilitation (M&R). Historically, pavement interventions have been largely reactive; repairs are frequently implemented after pavement conditions fall below acceptable performance thresholds rather than through planned, preventive strategies. Such an approach tends to increase life-cycle costs, accelerate deterioration, and expand the maintenance backlog. To address these inefficiencies, this thesis evaluates the current condition of the KIA pavement network and develops a feasible, data-driven M&R planning approach using the Federal Aviation Administration (FAA) PAVEAIR and FAARFIELD software. PAVEAIR is applied for network inventory, condition assessment, and scenario-based M&R planning, while FAARFIELD is employed to analyze structural adequacy and design requirements for critical sections. The overall aim is to support KIA's transition from reactive repairs to proactive, performance-based pavement management under realistic budget constraints.

1.1 Problem Statement and Research Gap

Preventive maintenance is widely recognized as an economic advantage for extending pavement service life and minimizing life-cycle costs. Babashamsi et al. (2022) demonstrate that postponing preservation actions can exponentially increase total expenditure, reporting life-cycle cost surges of up to 50%, with a mere one-year delay associated with an approximate 16% cost escalation. Despite this empirical evidence, airports in developing nations predominantly rely on reactive maintenance, intervening only after distress becomes severe or serviceability declines below acceptable levels. This reliance is largely driven by limited budgets, insufficient technical capacity, and a lack of systematic data for decision-making.

In the specific context of Rwanda, these constraints severely hinder the ability of airport authorities to plan and prioritize Maintenance and Rehabilitation (M&R) interventions effectively. As noted by Kumar et al. (2024), the deferral of routine maintenance, particularly in the early stages of pavement life, accelerates deterioration and inevitably demands extensive, economically inefficient repairs. The absence of a digitized Pavement Management System (PMS) and standardized condition-performance records further limits the capacity to forecast deterioration, quantify funding needs, and allocate scarce resources to high-risk sections. Consequently, maintenance backlogs expand, safety-related defects persist, and rehabilitation costs escalate beyond financial feasibility.

Beyond these operational challenges, a critical gap exists within the academic literature regarding geographic representation. De Moura et al. (2021), in a review of 400 studies on airport pavement evaluation systems, highlighted a stark global imbalance: none of the reviewed studies were conducted in Africa, nor did they address the specific challenges of Sub-Saharan tropical environments comparable to

Rwanda. This absence suggests that deterioration models, trigger thresholds, and M&R frameworks developed in Europe or North America may not be directly transferable to Sub-Saharan airports without significant calibration to local climate conditions, material availability, traffic spectra, and budgetary realities.

Therefore, a key research gap remains the lack of a context-specific, data-driven M&R planning framework for airports in Sub-Saharan tropical climates that clearly accounts for resource constraints. This thesis addresses this gap through a case study of Kigali International Airport, integrating functional condition to support prioritization and sustainable investment planning.

1.2 Research Objectives

The primary objective of this study is to assess the current condition of the Kigali International Airport (KIA) airfield pavement network and to develop a feasible, data-driven Maintenance and Rehabilitation (M&R) planning framework using FAA PAVEAIR software, thereby supporting KIA's transition from reactive repairs to proactive, performance-based pavement management under realistic budget constraints.

In response to the problem statement and the identified research gaps, the following specific objectives are formulated:

- To assess the functional condition of the KIA pavement network by analyzing visual inspection data and calculating the Pavement Condition Index (PCI).
- To develop customized pavement performance prediction models (deterioration family curves) based on historical and current inventory data to forecast future network conditions and optimize the timing of M&R interventions.
- To conduct a comparative life-cycle analysis of M&R strategies by simulating four distinct scenarios and quantifying their impacts based on

initial capital funding, 10-year life-cycle costs, terminal network condition, and financial feasibility.

- To formulate a localized, standardized M&R framework for KIA that establishes data-driven decision triggers, prioritization logic, and budget allocation guidelines to ensure sustainable operation within a resource-constrained environment.

1.3 Research Questions

To achieve the outlined objectives and address the identified research gaps, this study seeks to answer the following key questions:

- What is the current functional condition (PCI) of the KIA pavement network, and to what extent do the pavement sections meet the structural requirements (FAARFIELD) necessary to support current aircraft traffic loads?
- Based on the developed pavement performance prediction models (family curves), how is the network condition forecasted to change over the 10-year analysis period?
- Among the simulated M&R strategies, which approach yields the ideal balance between financial feasibility (initial and life-cycle costs) and technical performance (terminal PCI and safety compliance) for a resource-constrained airport?
- How can these analytical findings be synthesized into a standardized, KIA-specific M&R Framework that effectively guides decision-making regarding treatment selection, prioritization, and budget allocation?

1.4 Outline of The Study

To systematically address the stated research objectives and develop the proposed pavement management framework, this thesis is organized into five interconnected chapters, structured as follows:

Chapter 1 introduces the study context, defining the critical challenges of pavement management in developing nations. It defines the specific problem statement and research gaps, and establishes the primary research objectives and guiding questions that drive the investigation.

Chapter 2 provides a comprehensive review of the relevant academic and technical literature. It examines theoretical frameworks for Airport Pavement Management Systems (APMS), preventive maintenance concepts, and standardized condition assessment methodologies. Furthermore, it critically evaluates the capabilities and limitations of FAA PAVEAIR and FAARFIELD software while highlighting the specific geographic and climatic research gaps in Sub-Saharan tropical environments.

Chapter 3 details the research methodology and data acquisition protocols. It describes the development of the digital pavement inventory, the procedures for visual condition assessment (PCI), and the verification of structural adequacy using FAARFIELD. Additionally, the chapter defines the development of local performance prediction models, analysis assumptions, decision thresholds, and the configuration of the four distinct M&R scenarios simulated.

Chapter 4 presents the analysis of results and the discussion of findings. It first reports the diagnostic status of the KIA network, detailing current functional conditions (PCI), structural deficiencies, and forecasted deterioration trends. Subsequently, it conducts a comparative life-cycle analysis of the four M&R strategies, evaluating them against capital requirements, 10-year costs, and terminal network conditions. The chapter concludes by recommending the optimal strategy and synthesizing these findings into the proposed KIA-specific M&R Framework.

Chapter 5 concludes the thesis by summarizing the key findings and their implications for airport management. It articulates the study's practical contributions, acknowledges research limitations, and provides actionable recommendations for implementation alongside directions for future research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Airport pavements require substantial capital investment for construction and preservation and serve as the essential backbone for the movement of goods and people in both developed and developing regions (Zaki et al., 2021). Nevertheless, the preservation of this infrastructure faces dual challenges. As noted by Babashamsi et al. (2022), the non-linear deterioration of fatigued pavements, coupled with shrinking agency budgets, has made the scheduling of future maintenance difficult, frequently resulting in the deferral of critical repairs.

The combination of aging infrastructure and rising air traffic volumes places significant stress on pavements that are already operating beyond their original service life. This reality has driven a transition in asset management, in which authorities' primary objective is no longer new construction but the preservation of existing assets through maintenance and repair (M&R) activities (Seven & Yardim, 2024). Defects in airport pavement are among the key factors that can halt airport operations or reduce its transportation capacity.

To guarantee passenger safety and comfort while achieving cost-effective extensions of pavement lifespan, a proactive pavement maintenance strategy is paramount. Kumar et al. (2024) emphasized that pavements may fail to reach their design life without consistent upkeep. Therefore, maintenance protocols are typically triggered by functional deficiencies; if the surface condition breaches a defined limit, repairs are prioritized even if structural integrity remains intact.

This chapter critically reviews airport pavement maintenance and rehabilitation, detailing the shift from reactive maintenance to data-driven APMS. It evaluates key methodologies for condition assessment, performance prediction, and Life-Cycle Cost Analysis (LCCA), alongside different software tools. Finally, the review highlights maintenance gaps in African developing countries, establishing the theoretical framework for the optimized case study of Kigali International Airport.

2.2 Fundamentals of Airport Pavement Maintenance and Rehabilitation (M&R)

Airport pavements are a significant user of public funds and serve as the economic lifeline for the transportation of goods and people in both industrialized and developing countries (Jacquillat, 2017). Nevertheless, Tofail (2022) warns that these critical assets are increasingly compromised by rising traffic demands, which exert heavier loads on pavements that are often operating beyond their original design limits. Consequently, airport authorities face the continuous challenge of maintaining airside pavements in a safe and efficient condition within constrained budgets. The primary difficulty lies not in selecting technical Maintenance and Rehabilitation (M&R) treatments, but in employing an objective process to justify their necessity for securing required funding (Hajek et al., 2011).

2.2.1 Evolution of Pavement Management

The operational safety of an airport relies heavily on its pavement network, a vital infrastructure asset. Armeni and Loizos (2022) emphasize that the primary objective of these pavements is to maintain sufficient load-carrying capacity to support uninterrupted airport operations. White (2024) noted that since their introduction in the early 1900s, aircraft have become larger and heavier. Modern aviation demands superior pavement strength to accommodate higher tire pressures. A regulation established in 1958 once capped aircraft impact using the 159-tonne DC8-50 as a threshold, but this restriction is no longer in force. Since the FAA retracted its protection policy in 2009, the industry has been free to introduce aircraft that exert substantially greater loads on existing infrastructure (FAA, 2009). From there, airport agencies were responsible for the provision and maintenance of airport pavements capable of accommodating future, more demanding aircraft, a responsibility that has continued to grow since (White, 2024).

Seven and Yardim (2024) note that the U.S. Air Force, through the Civil Engineering Research Laboratory (CERL), pioneered the first APMS in the 1970s. This initiative culminated in the creation of the Pavement Maintenance Management System (PAVER) and its microscale counterpart, MicroPAVER. The FAA then formalized these practices by issuing Advisory Circular 150/5380-6 in 1983, which established specific guidelines for pavement maintenance. According to Babashamsi (2022), this was followed by a series of supplementary documents aimed at optimizing the technical and economic aspects of pavement management, which were disseminated to airports worldwide. Recent advancements have addressed earlier economic limitations through the Enhanced APMS, which now integrates comprehensive economic variables, including flight delays and operating costs, into life-cycle cost analysis of M&R alternatives to optimize funding.

2.2.2 Traditional Approaches to M&R

Pavement M&R has historically suffered from a reactive management style. According to Miah et al. (2020) and Kumar et al. (2024), this trend persists, with many agencies planning work based on immediate distress or past routines rather than using optimization strategies for cost and timing. Earlier pavement management systems often encoded “engineering judgment” as simple rules or look-up guides; while practical, such pre-set choices can miss the least-cost strategy over the asset life (Gendreau & Soriano, 1998).

ACRP (2011), during its synthesis survey dated 2011, found that 60% of all airports in the USA operate an Air Pavement Management System (APMS), 23% are developing one, while 17% do not have an APMS. This indicates a shift from traditional practices toward a more optimized and cost-effective approach in developed countries such as the USA.

Although significant progress has been made in pavement management technologies, maintenance planning in developing nations remains largely reliant on subjective expert opinion and administrative discretion. Babashamsi et al. (2022) argue that the absence of a systematic methodology hinders the evaluation of the economic efficiency of alternative strategies, resulting in suboptimal financial expenditures.

In the U.S. context, three canonical approaches are described by Shahin et al. (1987):

- Ad hoc approach: Select a treatment from experience to fix the observed problem; fast, but the habitual choice may be sub-optimal economically.
- Present-condition approach: Diagnose using condition indicators (e.g., PCI) and choose a treatment accordingly; useful for consistency, but it does not evaluate life-cycle costs.
- Life-cycle approach: Assess current condition, forecast deterioration, and select the alternative with the minimum life-cycle cost; this is the preferred method because it explicitly trades timing, performance, and cost over the analysis period.

Convincingly, the literature signals a necessity to shift from experience-driven, short-term actions to life-cycle-based planning that prioritizes preventive interventions before rapid decline, hence reducing whole-of-life costs (Miah, 2020; Gendreau & Soriano, 1998; Kumar et al., 2024; Shahin et al., 1987).

2.2.3 Preventive Maintenance Strategy

The strategy of preventive maintenance involves implementing treatments on pavements that are still in good condition to decelerate the natural process of degradation (Trejos et al., 2022). Delaying pavement maintenance in its early stages can lead to serious pavement distress, which may require costly and extensive repairs Figure 2.1. Babashamsi et al. (2022) emphasized this theory by affirming that postponing preventive maintenance for airport pavement could increase the repair costs by more than 50%.

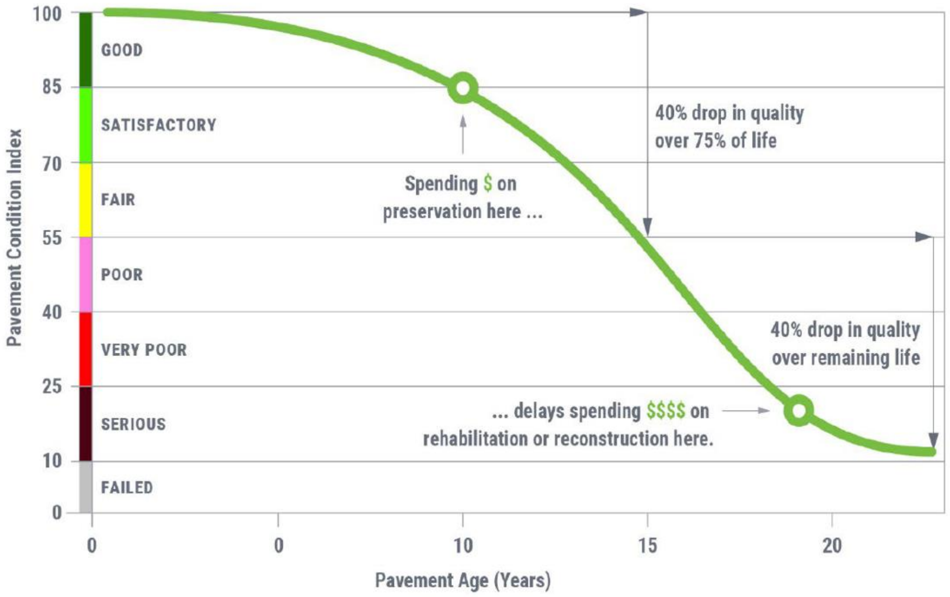


Figure 2.1 Preventive maintenance costs against the significant repair costs (Trejos et al., 2022).

di Mascio et al. (2021) utilized data from Cagliari Airport to argue that scheduled preventive treatments are essential for mitigating deterioration rates and sustaining optimal operational standards. Figure 2.2 depicts the core concept of pavement preservation, which emphasizes applying treatments to assets in good condition to prevent serious deterioration.

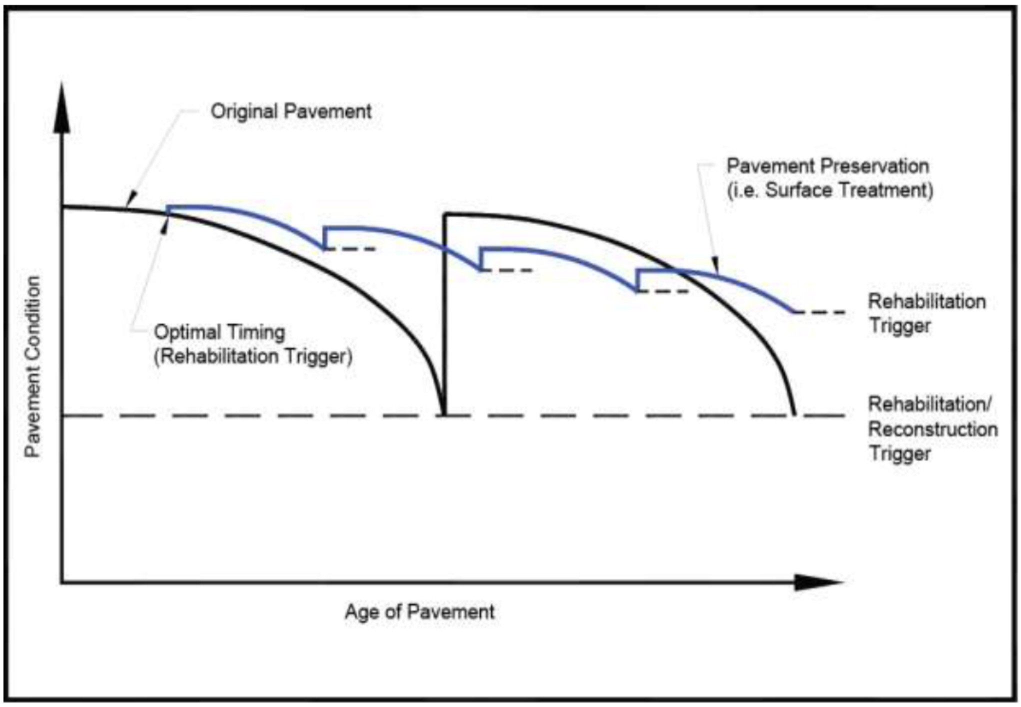


Figure 2.2 An effective pavement preservation concept (FAA, 2014)

The timely application of cost-efficient treatments significantly enhances pavement condition. Furthermore, the FAA (2014) emphasizes the operational benefits of implementing a series of successive preservation treatments over the asset's lifecycle, noting that this approach minimizes the severe disruptions typically associated with extensive reconstruction projects.

To maximize economic efficiency, preventive interventions should be implemented before minor distress escalates into failures that necessitate costly corrective repairs. The ACRP (2011) indicates that the optimal window for the initial preservation treatment typically occurs when the pavement surface is between three and five years old.

ACPR (2011) conducted a survey titled "Implementation of preventive maintenance treatments at the right time", where the findings revealed a clear gap between having a preventive-maintenance program and the timing of use. The majority of respondents in Figure 2.3 specified that they apply these measures sometimes (nearly

60%), and only approximately 29% of agencies reported consistently implementing treatments at the optimal time.

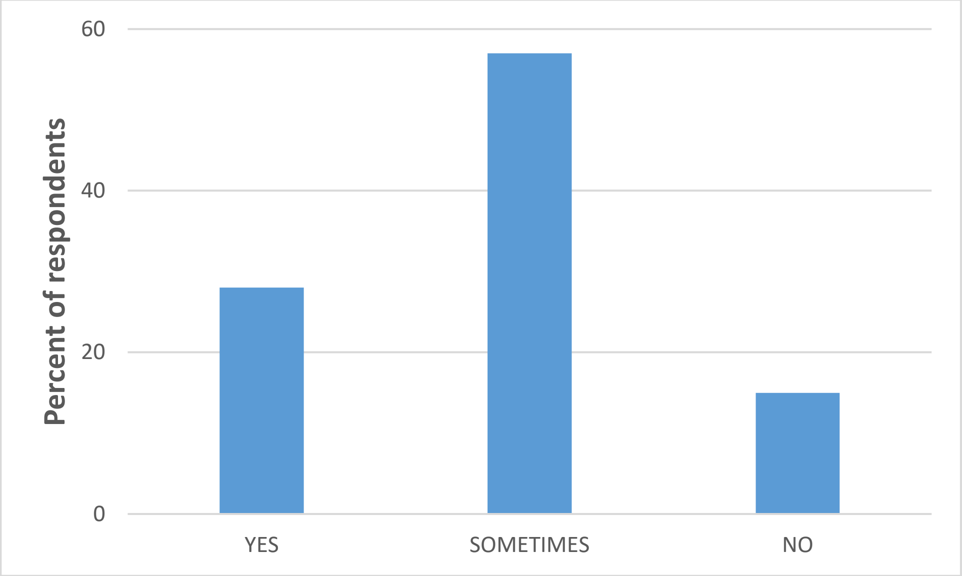


Figure 2.3 Optimal timing for the deployment of preventive maintenance interventions (ACRP, 2011).

The ACRP findings in airport pavements contrast with those in the road sector, where a 1999 AASHTO survey reported that 85% of state transportation agencies had already established formal preventive maintenance programs. In developing nations, the effective management of airport pavements remains a significant challenge, primarily because maintenance strategies are often limited to reactive interventions triggered only by critical necessity, which leads to the accumulation of distress and necessitates costly treatments. (Kumar et al., 2024).

2.2.4 Frequency of Inspection and Thresholds

According to FAA (2014) guidelines, the baseline frequency for detailed inspections is annual. However, this requirement can be relaxed to every three years upon successful completion of a PCI survey conducted in accordance with ASTM D5340.

Miah et al. (2020) proposed a standardized inspection schedule requiring functional assessments every 36 to 48 months and structural bearing capacity evaluations every 60 months. This framework is further supported by Mascio and Moretti (2019), who emphasized the correlation between traffic intensity and inspection frequency; specifically, for pavements accommodating between 61 and 180 daily movements, they validated these same intervals as the optimal standard.

In the study of "Monitor Activity for the Implementation of a Pavement Management System at Cagliari Airport," di Mascio et al (2021) used pavement survey frequency from the Italian guidelines as presented in Table 2.1**,** which confirms the conclusions of (Miah et al., 2020).

Table 2.1 Survey frequency from Italian guidelines (di Mascio et al., 2021).

	Daily Aircraft Movements	**Macro Texture Survey and Analysis**	**Longitudinal Roughness Survey and Analysis**	**PCI Survey**	**Bearing Capacity Survey (ACN/PCN)**
RUNWAY	<30	48	48	48	
	30–60 61–180 181–300	36	36	36	60
	301–420 >420	24	24	24	36
TAXI and APRON	<30		60	48	
	30–60 61–180 181–300		48	36	60
	301–420 >420		24	24	36

Advisory Circular (AC) 150/5200-18D recommends that an effective safety self-inspection program include procedures for capturing and tracking information on deficiencies from inspection checklists. According to the protocols for airport safety self-inspection, the program is comprised of four distinct elements:

- Daily inspection schedule
- Continuous surveillance inspection
- Special inspection
- Periodic condition inspection.

2.3 Use of Airport Pavement Management System (APMS) in M&R

The underlying principles of the Pavement Management System (PMS) were initially formulated in the United States and Canada during the late 1960s (Finn, 1998; Haas et al., 2015). Initially, they were developed exclusively for the road sector; their application to airport infrastructure was extended in the 1980s, with a primary focus on runway pavements (Ismail et al., 2009a).

The primary function of an APMS is to assist authorities in selecting maintenance and rehabilitation (M&R) strategies that preserve pavement serviceability for a specified duration while maximizing economic efficiency (Babashamsi et al., 2022). Furthermore, these systems investigate deterioration trends within the pavement framework to scientifically forecast future conditions, shifting management practice from reactive to proactive (Sami & Qabaja, 2020). Underscoring the system's effectiveness, U.S. legislation, specifically Public Law 103-305 (1994), conditioned the receipt of federal grants on the implementation of a functional APMS (FAA, 2004). This mandate has driven widespread adoption, with nearly 84% of state aviation agencies in the U.S. utilizing these systems to manage their infrastructure (Broten et al., 2004).

The APMS serves as a crucial planning tool, identifying the most appropriate life-cycle activities even when physical indicators cannot be seen on the ground. The FAA (2014) affirms that the greatest capability of an APMS lies not in the evaluation of current conditions, but in its predictive capability regarding future performance and rehabilitation costs. The predictive capability is the core foundation of all other APMS functions since the point at which maintenance is most cost-effective is not visually identifiable through noticeable signs of distress (di Graziano et al., 2021).

Miah et al. (2020) published a flowchart summarizing the implementation of an APMS Figure 2.5. It follows a structured lifecycle that begins by defining who will use the platform and the appropriate software selection. This foundation supports the creation of a detailed pavement inventory and condition evaluation to provide data for performance models. These data inputs drive the prioritization and budgeting phase, where rehabilitation policies and costs are analyzed to evaluate potential strategies. The process concludes by generating different reports from which the optimal maintenance strategy is adopted.

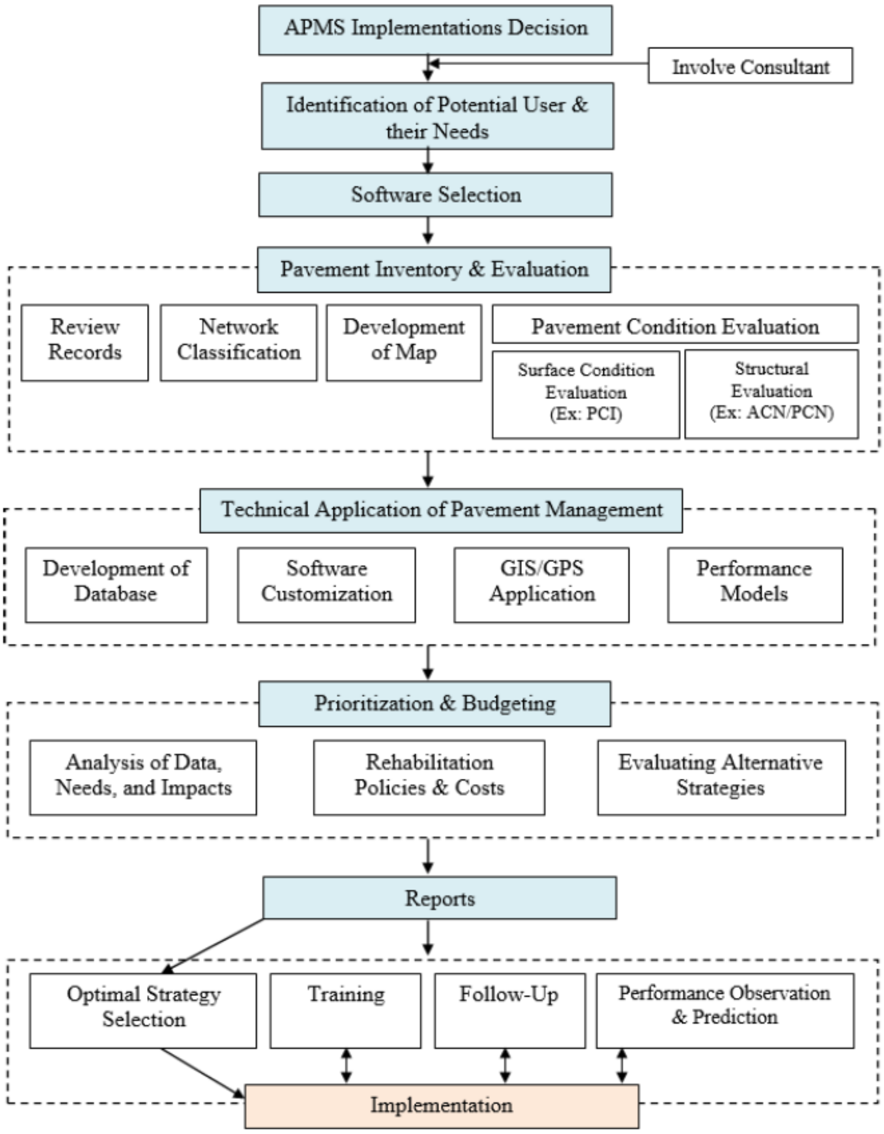


Figure 2.4 Implementation process of APMS (Miah et al., 2020)

2.4 Evaluation of Airport Pavements

According to di Graziano et al. (2021), the ability to estimate the condition of pavement infrastructure is a critical operational requirement for any APMS. The selection of a pavement evaluation methodology is a critical determinant of management outcomes. The chosen pavement assessment methodology serves as the foundation for all APMS recommendations; therefore, it must be objective, standardized, and repeatable (Tighe & Covalt, 2008).

In Synthesis 22, Common Airport Pavement Maintenance Practices, ACRP (2011) formally defines airport pavement evaluation as "Field measurements of the current state of pavement characteristics and recording them for future use." This process encompasses a broad range of assessments, including surface distress, roughness, friction characteristics, and structural strength. Furthermore, Tighe & Covalt (2008) discuss the components of airport pavement evaluation, which include four key elements:

- Surface condition
- Strength
- Roughness, and
- Skid resistance

In addition to that, they clarified that the involved assessment components at the network and project levels are different, as shown in Figure 2.6.

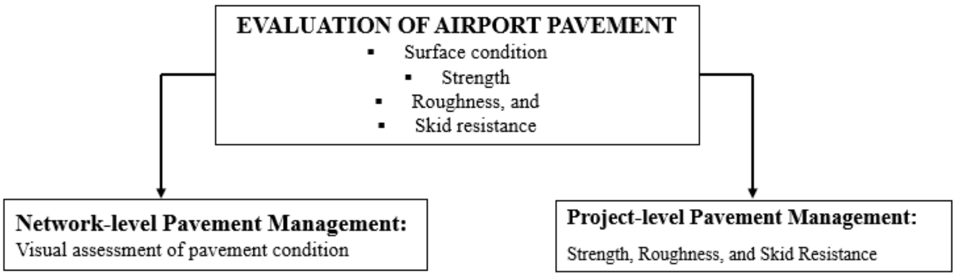


Figure 2.5 Airport pavement evaluation components (Tighe & Covalt, 2008).

The Pavement Condition Index (PCI) is a critical metric for assessing the structural integrity and functional serviceability of pavement infrastructure. Its application is not limited to airfield surfaces but extends broadly to roadway networks and pedestrian walkways (Zoccali et al., 2017; Shahin, 2005; di Mascio et al., 2021). The PCI is widely acknowledged as the preeminent standard for evaluating the technical condition of airport pavements and remains the preferred tool among engineering professionals and aviation authorities (Wesolowski & Iwanowski, 2020; Tighe & Covalt, 2008).

2.5 Surface Condition Evaluation

Assessing the surface condition is essential to verify whether the infrastructure remains adequate for its current operational demands. This process typically uses the Pavement Condition Index (PCI), a standardized methodology detailed in FAA AC 150/5380-7B and ASTM D5340. The PCI provides a comprehensive view of functional serviceability and basic structural data. Within this framework, the FAA uses the Structural Condition Index (SCI) to monitor load-related deterioration, focusing on critical structural distresses such as alligator cracking and rutting. (FAA, 2014; ACRP, 2011). di Graziano et al. (2021) mentioned that indicators relating to irregularity, through the International Roughness Index (IR), can be used to acquire functional data of airport pavement.

2.5.1 Structural Capacity Evaluation

Structural capacity describes a pavement's ability to carry traffic without developing severe distress. Miah et al. (2020) note that structural evaluation is essential to assess this load-bearing potential, establishing both the maximum allowable traffic volume and the pavement's projected service life.

FAA AC 150/5320-6G provides guidance on the evaluation of existing flexible pavement, which should at least include determining layer thickness from coring surveys or as-built drawings, and determining subgrade stiffness in terms of the CBR or modulus (E), obtained as back-calculated subgrade modulus values from Non-Destructive Test (NDT) results. The determination of structural capacity may depend on the execution of specific tests, ranging from nondestructive methods to destructive sampling.

Nondestructive Testing (NDT) is characterized by its ability to analyze infrastructure without extracting samples or damaging the existing material. According to the FAA (2021), the Falling Weight Deflectometer (FWD) and the Heavy Falling Weight Deflectometer (HWD) are the premier instruments used by airport agencies to assess pavement load-bearing capacity.

As a non-destructive technique, FWD measures deflection to assess structural capacity, supporting both network- and project-level evaluations (Loganathan et al., 2019). Numerous agencies also use the Aircraft Classification Number-to-Pavement Classification Number (ACN/PCN) system to quantify pavement load-bearing capacity. Developed by the International Civil Aviation Organization (ICAO), this methodology sets specific weight limits for aircraft operations on airfield pavements (Shahin, 2005). Although ICAO (2021) replaced the ACN/PCN standard with the ACR-PCR (Aircraft Classification Rating–Pavement Classification Rating) system, the intended scope remains narrow. ICAO explicitly states that this system is designed solely to determine operational suitability and cannot be used as a valid tool for design or maintenance decision-making.

Miah et al. (2020) identify aircraft mix, annual departures, and structural condition as the critical variables utilized to determine pavement capacity and estimate its remaining useful life. The FAARFIELD is used in the reverse process of design as an evaluation procedure to determine the structural life of the existing pavement for a given traffic mix (FAA, 2021).

2.5.2 Other Pavement Distress Indices

Specialized indices can be calculated using the PCI framework by isolating specific distresses. Shahin (2005) uses low-severity alligator cracking as an indicator of structural health, contrasting it with shoving, which reflects surface operational status. Shahin (2005) identifies a range of indices developed to measure distinct pavement characteristics. Key examples include the International Roughness Index (IRI) which quantifies roughness, the FOD Index which assesses the potential for foreign object damage, and the Skid Number (SN) which measures skid resistance.

Recognizing that PCI alone may not accurately capture the heterogeneity of structural and functional deterioration, Mansour et al. (2024) employed a machine learning approach. Their study expanded the evaluation framework to include three distinct metrics: PCI, SCI, and FOD.

Di Mascio et al. (2021) conducted a study at Cagliari Airport in Italy titled "Monitor Activity for the Implementation of a Pavement Management System" The following condition indices were considered during pavement evaluation, the PCI index which evaluated the functional pavement condition, the IRI quantified the synthesis of longitudinal pavement irregularities, while the Mean Depth Profile (MDP) offered a different geometric assessment which represented the calculated difference between the arithmetic mean of two specific peaks and the mean level established over a defined baseline distance.

To provide a more complete view of pavement condition, some agencies employ composite indices that combine PCI with functional parameters, ensuring that maintenance decisions address not only structural integrity but also operational safety and user comfort. Some of the functional parameter indices include:

- **FOD index:** The FOD Index is derived by isolating specific data within the PCI calculation, focusing exclusively on distresses and severity levels that are liable to generate debris. However, the ACRP (2011) indicates that this specific metric is infrequently utilized at major airports.
- **Roughness index**: From a piloting standpoint, rough pavement not only causes discomfort and instrument vibration but also constitutes a significant safety hazard for the aircraft and its passengers. For this reason, the assessment of primary pavements must rigorously account for roughness as a key indicator of condition (Shahin, 2005). It is measured in accordance with

the guidelines and procedures outlined in AC 150/5380-9. According to the FAA (2014), roughness assessments provide the most insight when the pavement is in excellent condition. However, their practical utility declines substantially when the infrastructure has deteriorated to the point that reconstruction is imminent.

- **Skid resistance index:** Pavement friction, which the ACRP (2011) describes as the resistive force between a tire and the pavement surface, is a significant safety consideration for aircraft operating at high weights and landing speeds. The FAA (2014) advocates regular assessment of runway skid resistance, citing the progressive accumulation of contaminants and physical wear resulting from aircraft tire interaction as primary concerns. The FAA AC 150/5320-12 provides guidance and procedures to measure skid resistance.

2.5.3 Pavement Performance Prediction Models

Miah et al. (2022) define prediction modeling, also referred to as family modeling, as a methodology for mapping deterioration patterns of pavement sections with identical construction characteristics, traffic loading profiles, and environmental conditions. As integral components of an APMS, performance models are designed to predict pavement behavior over time, thereby assisting in identifying the optimal timing for maintenance or rehabilitation interventions (Tighe & Covalt, 2008).

Rahman (2013), in a dissertation titled “Alternatives to PCI and MicroPAVER-based maintenance solutions for airport pavements,” emphasizes that condition prediction serves as a primary tool for identifying pavements in need of maintenance or rehabilitation, which subsequently facilitates the development of budgetary plans for both the current year and the foreseeable future. As summarized by Shahin (2005), prediction models are fundamental to pavement management, serving critical roles in condition forecasting, budget formulation, and strategic planning. These models are visually represented as deterioration curves (Figure 2.7), which plot pavement condition on the vertical axis against time on the horizontal axis. The graph illustrates a characteristic non-linear decline where the pavement initially sustains a good condition with minimal degradation (Point A) but eventually reaches a critical inflection point where deterioration accelerates rapidly (Point B) before plateauing in a poor state (Point C).

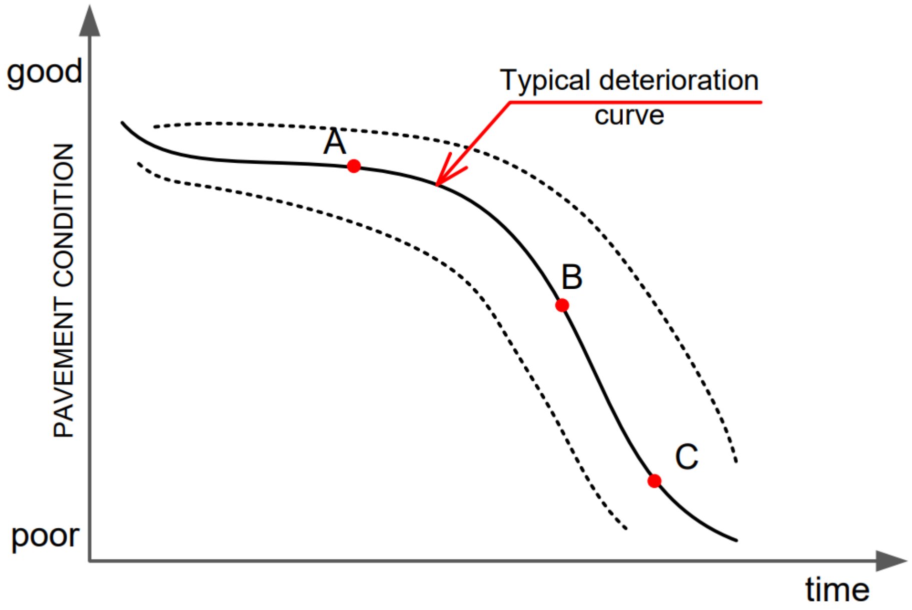


Figure 2.6 Typical pavement deterioration curve (Scînteie et al., 2010).

Once the prediction model has been built within an APMS, the ACRP (2011) synthesis 22 summarized six benefits the model can offer to the agency managing an airport pavement:

- Estimation of when the pavement will require M&R treatment.
- Estimation of treatment type
- Estimation of the life span of M&R treatments.
- Deterioration rate
- Estimation of the remaining service life
- Timing of preventive maintenance treatments.

According to de Moura et al. (2021), pavement performance prediction models fall into three primary categories: empirical, mechanistic, and empirical-mechanistic. Empirical-mechanistic model is the most used in different literatures, Figure 2.8, as it was verified after the review of 24 papers that developed performance prediction models (de Moura et al., 2021).

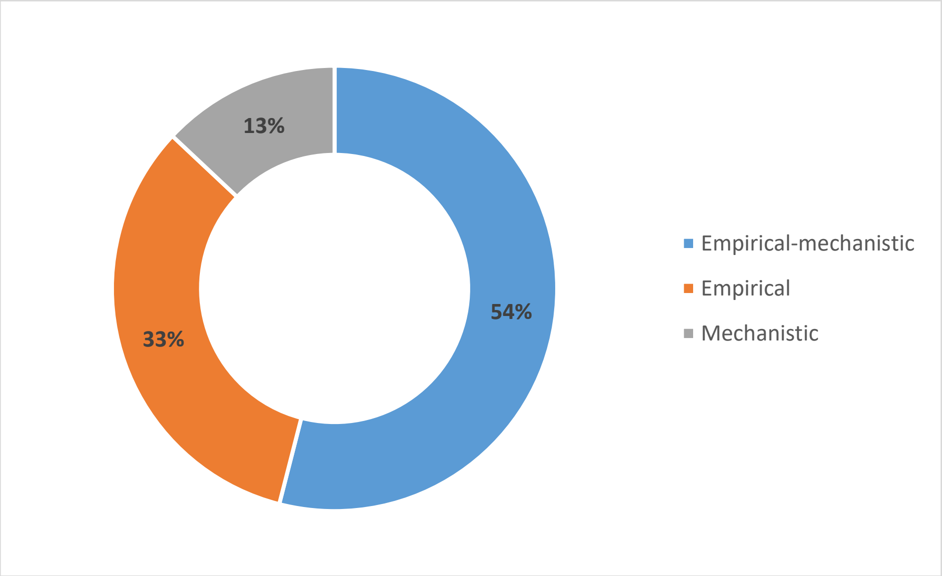


Figure 2.7 Prediction modelling categories (de Moura et al., 2021).

While Table 2.2 illustrates the numerous methods available for developing pavement performance models, the final selection relies heavily on the availability of existing data and the specific APMS software used (Tighe & Covalt, 2008; ACRP, 2011). The following techniques are commonly applied:

Table 2.2 Pavement performance modelling techniques

S/N	Modelling technique	Remarks
1	The expert modeling approach	This methodology is specifically applicable in scenarios where historical data regarding pavement performance is absent or insufficient.
2	Modeling using families of performance curves	This approach relies on the expectation that airport pavements with matching characteristics will behave consistently when exposed to similar traffic conditions.
3	Markov modeling	While this technique has been widely utilized for predicting the performance of highway pavements, there is currently no evidence of its application within the specific context of airfield pavements.
4	Extrapolation of existing trends	In instances where the pavement has undergone multiple historical evaluations, regression analysis can be utilized to extrapolate the specific trend, effectively calibrating the family curve to the observed past data points.

The mandatory accuracy of a pavement prediction model is directly influenced by its intended application. Moreover, because performance models typically lack transferability across diverse airport settings, selecting an appropriate model requires consideration of three pivotal factors: the availability of local data, the agency's specific requirements for estimating preservation needs, and the capabilities of the deployed APMS software (ACRP, 2011).

2.5.4 Software Tools Used in Airport Pavement Management

The effective management of a pavement database, along with the critical tasks of identifying and prioritizing Maintenance and Rehabilitation (M&R) projects, requires robust data processing capabilities, best handled by specialized software. While numerous commercial pavement management software products are available, the choice is ultimately driven by the specific needs and operational requirements of agencies and engineers (ACRP, 2011).

The FAA AC 150/5380-7B notes that PMP software is designed to store essential records, including condition history, NDT data, and construction or maintenance history with cost information. Furthermore, it is capable of evaluating current conditions, predicting future conditions, identifying M&R needs, scheduling inspections, performing economic analysis, and budget planning.

Findings from the ACRP (2011) confirm that every agency with an active APMS employs a software application. In terms of distribution, MicroPAVER is the most widely adopted tool (53%), followed by various other commercial software packages (13%). Apart from PAVER or MicroPAVER, which is US public software, the FAA gives a directive that any software that meets the minimum requirements for a PMP is acceptable (FAA, 2014).

The ACRP (2011) notes that the conceptual framework initially established in PAVER has been used by various firms to develop similar software solutions for pavement evaluation and management. Both PAVER and MicroPAVER were developed to maximize the efficiency of funds allocated for pavement maintenance and rehabilitation (M&R). The original PAVER system was designed specifically for mainframe computing environments, whereas MicroPAVER is a microcomputer version of the PAVER system. MicroPAVER retains most of the capabilities of mainframe PAVER while leveraging the more user-friendly features of a microcomputer (Shahin & Walther, 2002).

Developed by the United States Army Corps of Engineers Research Laboratories (USACERL), MicroPAVER is recognized as the world's leading Pavement Management System (PMS), with a development history extending back to the early 1970s (Shahin et al., 2002). MicroPAVER facilitates budget estimation for maintaining specific condition levels by applying four maintenance categories, as shown in Figure 2.9**,** namely localized preventive, localized safety, global preventive, and major maintenance work to restore pavement at different PCI triggers (Rahman, 2013).

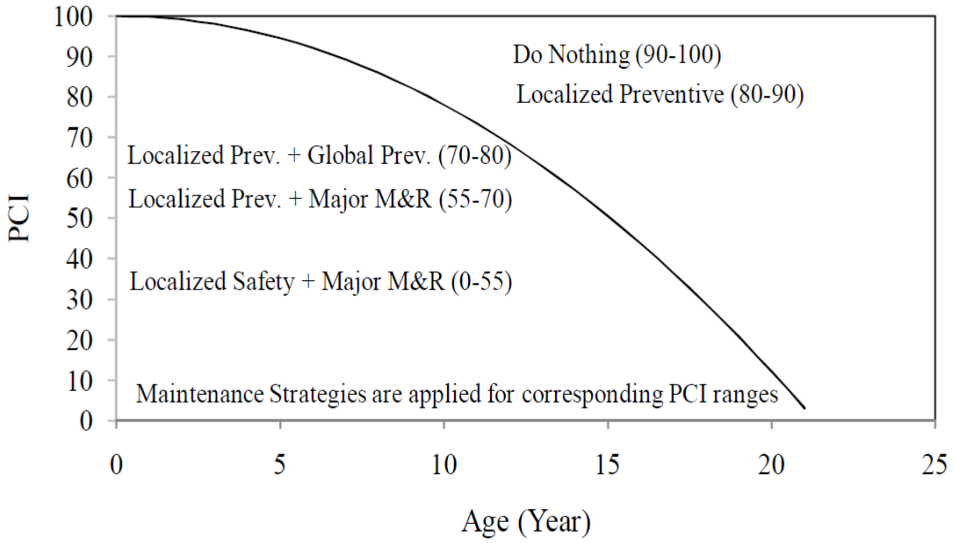


Figure 2.8 Pavement deterioration curve and MicroPaver M&R strategies (Rahman, 2013).

FAA PAVEAIR is a web-based APMS tool that supports public and private sectors in evaluating, managing, and maintaining airport pavements. It is freely available to users with similarities in application and operational features to MicroPAVER. The initial release of PAVEAIR has the functionality of MicroPAVER Version 5.3 (Miah et al. 2022).

FAA PAVEAIR contains different core modules, each performs a particular function, and some are public and can be accessed without a user account (FAA PAVEAIR, 2021). The following are FAA PAVEAIR modules:

- Inventory
- Work
- PCI
- Prediction modelling
- Condition analysis
- M&R

- Reports

Tofail (2022) in his dissertation, produced airport pavement deterioration models using two software and came to the following conclusion:

- The FAA PAVEAIR models achieved a better coefficient of correlation than the PAVER models. However, the PAVER models produced fewer errors than the FAA PAVEAIR models.
- PAVER needs five inspection data points to calculate the prediction model, whereas FAA PAVEAIR only needs three points.
- PAVER shows curves in a more conservative prediction, which is likely to prompt earlier maintenance interventions which revealing early deterioration and a shorter span of pavement functional condition than FAA PAVEAIR.

Historically, the complexity and licensing restrictions associated with specialized APMS software have limited their use to a small group of trained experts, thereby restricting broader access to critical pavement data (ACRP Research Report 203, 2019). The report further highlighted that technological advancements enabled easy, user-friendly data retrieval through pre-programmed querying capabilities. Simplifying this process significantly extends the usability of these tools to a wider range of stakeholders.

2.6 Life Cycle Cost Analysis (LCCA) For Airport Pavement M&R

Orabi & Shatila (2024) defined LCCA by referring to the Transportation Equity Act for the 21st Century (TEA- 21) which defined a life cycle cost analysis as “a process for evaluating the total economic worth of a usable project segment by analyzing initial costs and discounted future costs, such as maintenance, user costs, reconstruction, rehabilitation, restoring, and resurfacing costs, over the life of the project segment.”

By calculating the Net Present Value (NPV) over a specified horizon using deterministic or probabilistic models, the LCCA approach guides decision-makers in selecting the optimal economic solution among options (Orabi & Shatila, 2024).

There are numerous generally accepted economic models to conduct economic feasibility analysis of pavement projects. The following techniques are used to conduct LCCA (Assaduzzaman Nur, 2022):

- Net Present Value (NPV) method
- Equivalent Uniform Annual Cost (EUAC) method
- Benefit over Cost Ratio (BCR) method
- Incremental Benefit over Cost Ratio (IBCR) method
- Rate-of-Return (RR) method
- Incremental Rate-of-Return (IRR) method

The FAA (AC 150/5320-6G) recommends carrying out LCCA for the purpose of determining the cost-effectiveness. FAA recommends the following steps:

- Establish alternative design strategies to compare and evaluate the relative benefits of various pavement types
- Determine activity timing (the analysis period should be sufficient to reflect long-term cost differences, including at least one rehabilitation of each alternative)
- Estimate direct costs (future costs should be estimated in constant dollars and discounted to the present using the real discount rate)

Zaki et al. (2021) identify the estimation of unit costs covering construction and M&R as the core of LCCA. They advise that this analysis should be grounded in historical bid records, preferably utilizing data from the previous seven years. Zaki et al. (2021), in their study titled “The impact of economic analysis methods on project decision-making in airport pavement management," provided a detailed flowchart of LCCA for airport pavement management.

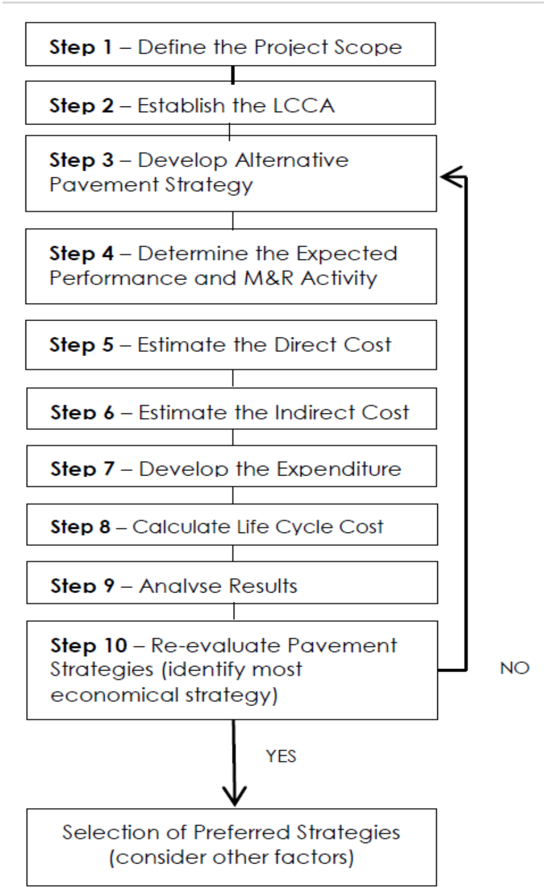


Figure 2.9 Flowchart of LCCA for airport pavement management (Zaki et al., 2021)

Orabi and Shatila (2024) conclude that LCCA empowers decision-makers to select the most cost-effective project option by utilizing metrics such as Net Present Value (NPV) or the duration of work execution.

2.7 Airport Pavement M&R Practice in African Developing Countries

Phumzile (2016), in a study titled “Regulation, Securitization and Financing of Airport Infrastructure in Sub-Saharan Africa,” indicated that despite offering superior economic returns compared to other transport sectors, African airport infrastructure has historically faced significant underinvestment, primarily due to the diversion of funding toward rail and road development. In their book titled “African Air Transport Management Strategic Analysis of the African Aviation Market, Seck et al. (2023) identify the inadequacy of airport infrastructure as a primary obstacle preventing the region from realizing its significant economic potential. Gwilliam (2011), in the book “Africa’s Transport Infrastructure Mainstreaming Maintenance and Management,” conducted a satellite survey to evaluate 173 African airport pavements; 25 percent were in marginal or poor condition, and 21 percent were in poor condition.

Miah et al. (2020) emphasize that, although maintenance and rehabilitation (M&R) decisions have traditionally relied on engineering experience and best practices, the costs associated with these activities are increasing. This financial burden is particularly acute in developing countries, where funding shortages often lead to deferred maintenance, accelerating deterioration and ultimately higher restoration costs (Orabi & Shatila, 2024).

Okafor & Ezeoyili (2020) examined the maintenance plans and strategies used by three airports in Nigeria. All the airports investigated exhibited poor operational efficiency, dilapidated infrastructure and facilities, and inadequate maintenance. The findings indicate that most airports in Nigeria are poorly maintained, and that infrastructure maintenance practices are inadequate.

(Horak et al., 2009) investigated the status of South African regional airports in a study titled “Addressing Maintenance Backlogs for Commercial Regional Airports in Southern Africa.” The study concluded that some South African regional airports face maintenance challenges, including backlog maintenance and rehabilitation needs, insufficient funding, and a lack of knowledgeable personnel or relevant equipment.

Various studies have shown that Sub-Saharan African airport infrastructure significantly declines due to predominant reactive maintenance practices and a critical shortage of skilled personnel. This issue is further compounded by a lack of region-specific research on African airport pavement practices. Additionally, it was observed that many African countries follow a budgeting policy that favors surface transportation over aviation, despite the sector's potential as an economic driver. Therefore, implementing a systematic Airport Pavement Management System (APMS) is not just a technical upgrade but a strategic necessity to close these gaps and secure the region's aviation future.

2.8 Research Gap

A review of the literature indicates that maintenance in developing nations is predominantly reactive. This approach entails significant financial risks; Babashamsi et al. (2022) demonstrated that postponing preventive maintenance can increase overall costs by up to 50%, with a one-year delay resulting in an approximately 16% increase in the life-cycle cost of airport pavements.

Kumar et al. (2024) observe that in many developing nations, deferring routine maintenance in the early stages of pavement life is a significant challenge. This neglect inevitably leads to severe pavement distress, necessitating extensive repairs that are economically inefficient. This study aims to address this gap in developing African countries by analyzing the pavement at Kigali International Airport and proposing a maintenance framework.

In their systematic literature review regarding airport pavement evaluation systems, de Moura et al. (2021) presented a geographical map Figure 2.11 illustrating the regional distribution of academic studies. This visualization identifies which nations have prioritized investment in pavement research and facilitates comparison of conditions in surveyed countries with those elsewhere. None of the 400 reviewed studies were conducted in Africa, specifically in the Sub-Saharan tropical climate region.

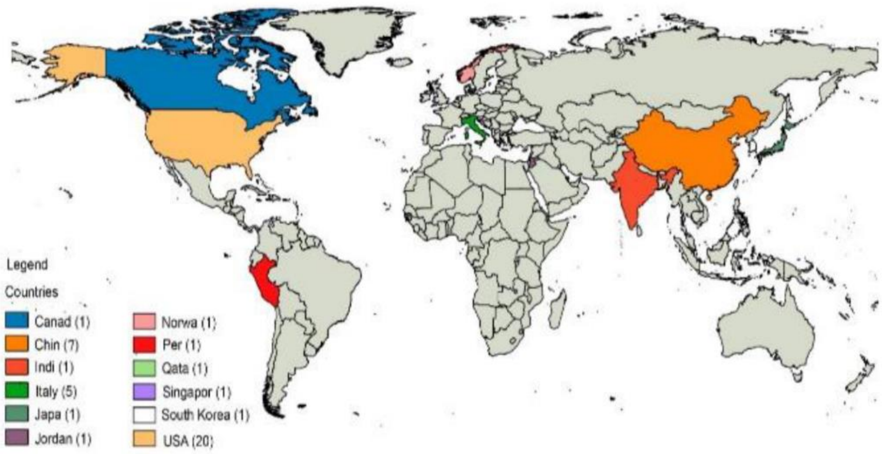


Figure 2.10 Countries from which 400 studies were reviewed (de Moura et al., 2021).

2.9 Conclusion of Literature Review

The literature indicates that a shortcoming in airport pavement management practices in developing countries is that maintenance and repair (M&R) is predominantly reactive rather than preventive. Many studies, including Babashamsi et al. (2022) and Kumar et al. (2024), have emphasized the consequences of delaying maintenance interventions. Despite this, practical frameworks tailored to early-stage preventive maintenance in sub-Saharan African contexts remain scarce. Furthermore, as de Moura et al. (2021) show, the literature contains no research on maintenance and rehabilitation (M&R) practices for African airports. This gap underscores the critical need for region-specific studies to address the continent's unique challenges.

Despite the effectiveness of APMS in optimizing pavement longevity, a significant knowledge gap remains concerning their application within the resource-constrained context of Sub-Saharan Africa. Consequently, this study addresses this void by adapting established global methodologies to the specific operational realities of Kigali International Airport (KIA), thereby providing a framework for transitioning its management strategy from reactive repair to proactive, data-driven preservation.

CHAPTER 3

MATERIALS AND METHODS

This chapter details the methodology employed to optimize airport pavement longevity through preventive maintenance and long-term deterioration modeling using Kigali International Airport (KIA) as a case study. The chapter begins by outlining the data collection procedures, which include studying KIA's pavement construction, maintenance, and inspection histories and establishing the current Pavement Condition Index (PCI). It then describes the comprehensive data analysis process by discussing the use of different software tools for PCI calculation. The chapter focuses on the specific application of FAA PAVEAIR to create the pavement inventory, perform deterioration modeling, conduct condition analysis, and compute PCI. The process continues with a structural evaluation that integrates field results from coring, DCP, and HFWD with the analytical design outputs from FAARFIELD. Afterward, the framework for developing and analyzing various maintenance and rehabilitation (M&R) scenarios within PAVEAIR is presented to determine an optimal plan and budget. The chapter concludes by proposing a complete Pavement Management Program (PMP) framework for implementation at KIA. The methodology approach followed in this study is outlined in the flow diagram demonstrated in Figure 3.1.

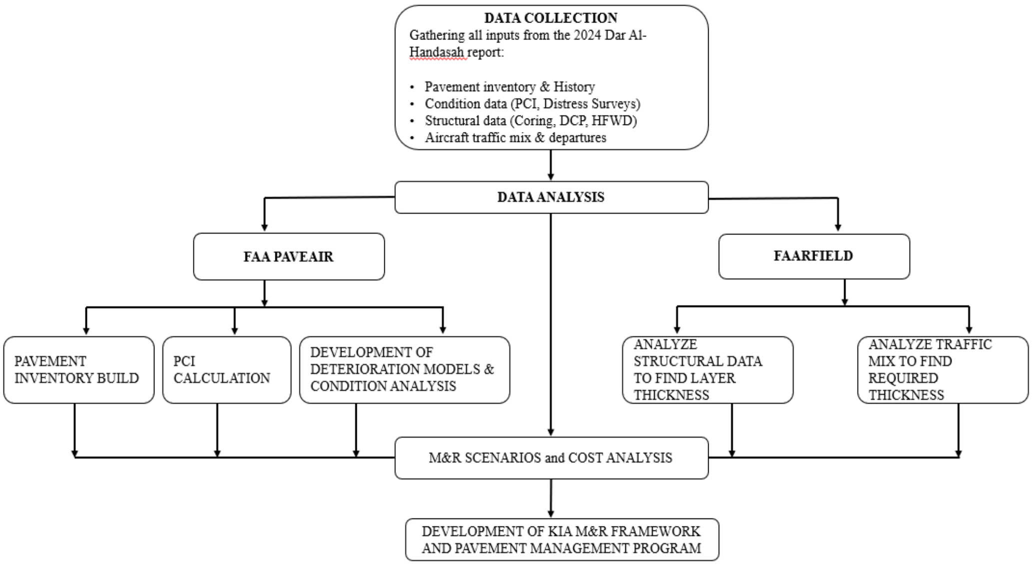


Figure 3.1 Flowchart of the study methodology

3.1 Data Collection

The data used in this study were acquired from the Rwanda Airport Company (RAC), the institution responsible for managing Kigali International Airport (KIA). This thesis constitutes a secondary analysis of operational pavement datasets originally collected in 2024 by the international consulting firm Dar Al-Handasah (DAR).

Figure 3.2 Kigali International Airport (Ndegeya, 2024).

The data was gathered as part of a consulting firm's project titled, "Consulting Services for Re-Designing and Monitoring of Airfield Pavement Re-Surfacing at Kigali International Airport (KIA)" under the contract with RAC. The consultant's report confirmed that all data were collected using standardized airport pavement evaluation procedures, in alignment with current FAA Advisory Circulars and

International Civil Aviation Organization (ICAO) recommendations. The specific datasets provided by RAC for this research include:

- Pavement Condition Index (PCI) survey results
- Dynamic Cone Penetrometer (DCP) test logs
- Heavy Falling Weight Deflectometer (HFWD) test results
- Asphalt coring and test pit logs
- Aircraft traffic mix and departure data

This thesis used the above-provided data to create the pavement database, perform deterioration modeling, conduct condition analysis, compute PCI, and analyze various maintenance and rehabilitation (M&R) scenarios through the FAA PAVEAIR tool, while FAARFIELD was employed to evaluate pavement thickness.

3.1.1 KIA Pavement Sections

For pavement detailed analysis, the KIA pavement network is divided into distinct sections, adopted from the 2024 Dar Al-Handasah inspection report provided by RAC. This standardized inventory is essential for building the pavement database in FAA PAVEAIR and is maintained consistently throughout all subsequent analyses in this study. The KIA pavement network sections are classified as shown in Figure 3.3:

- Runway: Comprises three sections, runway End 10, runway End 28, and the remediated section (Touchdown zone).
- Taxiways: Includes taxiway Alpha, taxiway Bravo, and taxiway Charlie.
- Aprons: Consists of apron Alpha (subdivided into the main apron and general aviation sections), apron Bravo, and apron Charlie.

Figure 3.3 KIA pavement sections adopted in this study

3.1.2 KIA Pavement Construction and Maintenance History

Shahin (2005), in his second edition book titled “Pavement Management for Airports, Roads, and Parking Lots,” stressed that Historical construction and maintenance records are required to plan future rehabilitation and to understand which past strategies were effective for the site.

The original pavement network at KIA was constructed in 1983, as shown in Table 3.1, which consisted of the 3,500-meter main runway, taxiway Bravo, and apron Alpha, which included both the main apron and general aviation stands. The entire pavement system underwent a major rehabilitation in 2005. The network was subsequently expanded with the construction of taxiways Alpha and Charlie in 2016, followed by the addition of apron Charlie in 2020. A significant partial rehabilitation also occurred in 2019, during which a 30-meter-wide by 900-meter-long strip in the touchdown zone of runway end 28 was resurfaced as part of an Airfield Ground Lighting (AGL) upgrade project. This history of phased construction and rehabilitation provides the basis for the network-level pavement inventory in FAA PAVEAIR.

Table 3.1 KIA pavement construction, maintenance, and inspection history

Year	Event	Activity
1983	Initial construction	Runway, Taxiway Bravo, and Apron Alpha
2001	First pavement inspection	Entire pavement network
2005	Major rehabilitation	Entire pavement network
2016	Pavement network expansion	Construction of Apron Bravo, Taxiway Alpha & Charlie
2019	Partial rehabilitation	Runway End 28 (Touchdown zone)
2020	Pavement network expansion	Construction of Apron Charlie
2024	Second pavement inspection	Entire pavement network

3.1.3 KIA Pavement Inspection History

A review of the provided data revealed only two comprehensive and detailed pavement inspections since its original construction. The first inspection was conducted in 2001 by SOFREAVIA, which involved a thorough assessment of the existing pavement condition to recommend rehabilitation measures. The second and most recent inspection was performed in 2024 by the international consulting firm Dar Al-Handasah (DAR). This evaluation was part of DAR's "Consulting Services for Re-Designing and Monitoring of Airfield Pavement Re-Surfacing at Kigali International Airport (KIA)" project. The extensive data from this 2024 inspection, including PCI surveys and structural tests, form the primary dataset for the analysis conducted in this thesis.

3.1.4 KIA Aircraft Traffic Mix and Departures

The 2024 Dar Al-Handasah inspection report served as the primary source for the current aircraft traffic mix and annual departure figures. This data details the specific aircraft models and their operational frequencies, which are fundamental inputs for the structural evaluation and pavement design verification. As illustrated in Figure 3.4 below, the traffic at KIA is dominated by a few key aircraft. The Airbus A350 is by far the most frequent, with 8,122 annual average departures. The Cessna C680 (4,043 departures) and the Airbus A330 (2,720 departures) also represent a significant volume of the traffic. This traffic information was used as a direct input into the FAARFIELD software to design the required pavement layer thickness to verify if the current pavement structure can adequately support the available traffic.

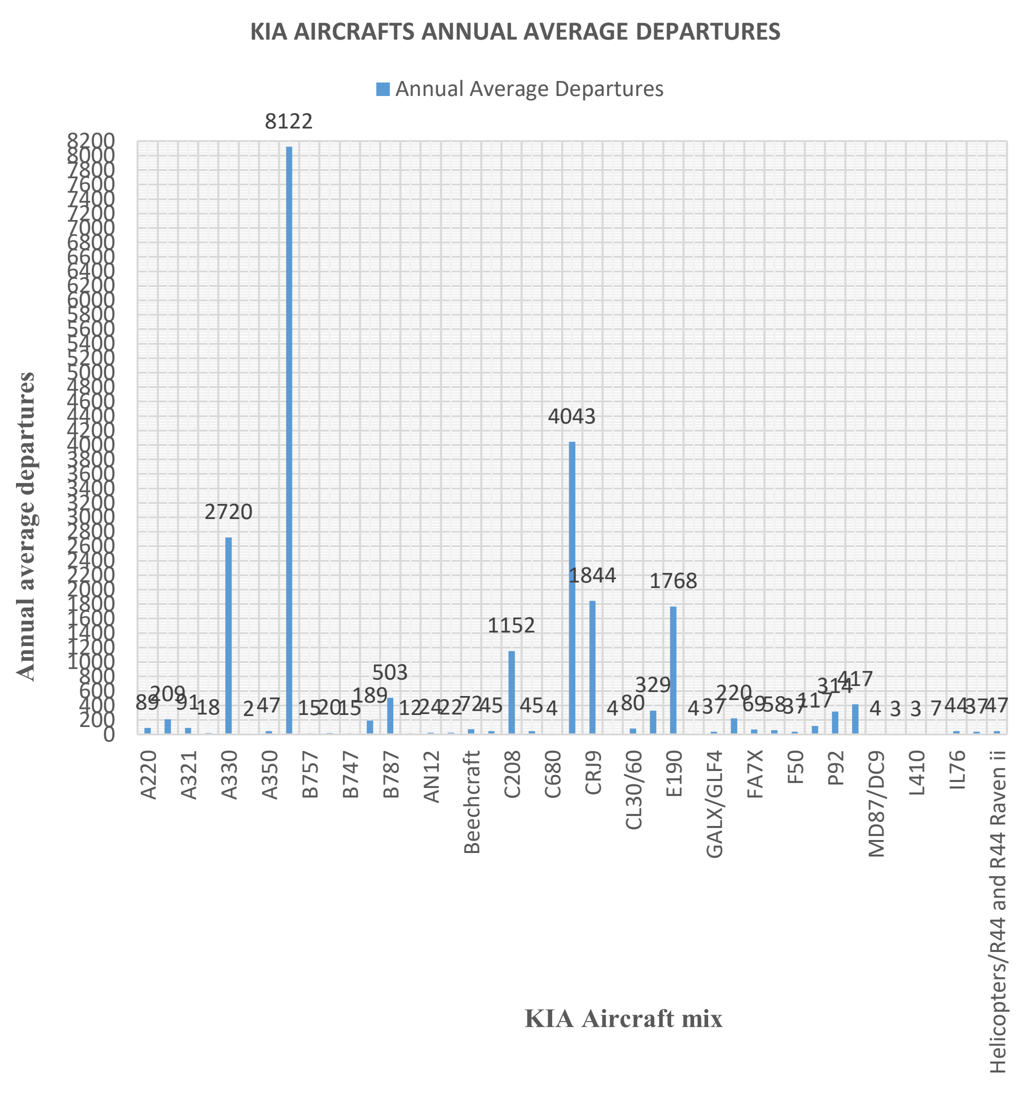


Figure 3.4 KIA Aircraft annual average departures (Source: Dar Al-Handasah, 2024)

3.1.5 Current Pavement Condition Index (PCI)

The Pavement Condition Index (PCI) dataset for the KIA network from the 2024 Dar Al-Handasah evaluation report was extracted and used in this thesis. According to the report, these values were derived after a detailed distress survey (identifying, measuring, and estimating severity) and were classified according to ASTM D5340 standards. The results summarized in Table 3.2 were generated using the MICROPAVER software. The PCI dataset serves as the primary baseline for this study and will be validated using the FAA PAVEAIR tool in the data analysis section.

Table 3.2 KIA Pavement Condition Summary (Source: Dar Al-Handasah, 2024)

Pavement sections	PCI from KIA 2024 pavement valuation report	ASTM PCI thresholds	ASTM PCI classification
Runway	38.45	25-40	Very poor
Apron	42.1	40-55	Poor
Taxiway	40.7	40-55	Poor
Overall pavement	40.41	40-55	Poor

3.2 Data Analysis

This section presents a comprehensive analysis of the data collected in Section 3.1. It begins by outlining the standard PCI calculation procedures and the selection and use of FAA PAVEAIR in this study. A significant portion of this section is dedicated to building the complete KIA pavement inventory in PAVEAIR, validating the PCI, and performing deterioration modeling. Subsequently, a structural evaluation of the KIA pavement is conducted by analyzing aircraft traffic data using FAARFIELDS to verify structural adequacy. Following the evaluation of multiple M&R scenarios within PAVEAIR, this research presents a tailored M&R framework and a comprehensive plan for the long-term implementation of a Pavement Management Program (PMP) at KIA.

3.2.1 Pavement Condition Index (PCI)

The PCI survey is a methodology used to assess pavement condition by analyzing the visual and functional pavement condition, and indicates the degree of M&R efforts that will be required to sustain functional pavement.

As noted by Pietersen et al. (2022), the PCI is considered one of the most critical metrics for assessing the condition of rigid and flexible pavements. While initially designed by the Army Corps of Engineers for the U.S. Air Force, the methodology has been formally verified and adopted by the FAA (FAA, 2014).

Miah et al. (2020) explain that PCI calculations rely on the visual identification of distress type, severity, and quantity on the pavement surface. This assessment is conducted in strict accordance with the protocols established in ASTM Standard D 5430 (ASTM International, 2020) and FAA AC 150/5380-7B (FAA, 2014).

According to Hermawan et al. (2024), who conducted a bibliometric analysis of 568 publications on the current status and future trends of the PCI method for airport pavements, PCI is a key tool for evaluating pavement distress in roads and airports.

3.2.1.1 Sampling and Sample Units in The PCI Process

PCI calculation requires dividing the network into branches, sections, and sample units, with visual inspections conducted to assess distress type and severity. To ensure valid results, sample units must be drawn from pavement sections that exhibit consistent characteristics, particularly in construction, maintenance records, traffic loading, and overall condition as illustrated in Figure 3.5.

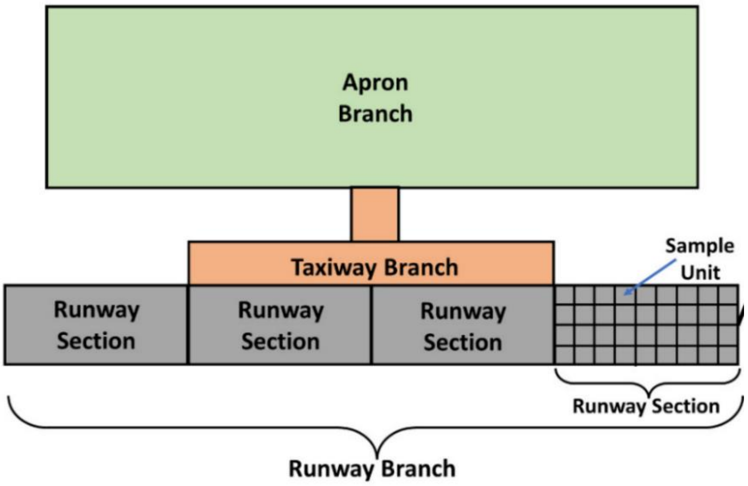


Figure 3.5 The relationship between airfield branches, sections, and sample units in the PCI process (Pietersen et al., 2022).

To obtain a PCI estimate with 95% confidence, the minimum number of sample units (n) must be calculated in accordance with ASTM Standard D5340-20. The standard prescribes the following formula for determining the required number of sample units to survey:

$$n = \frac{Ns^2}{\left(\left(\frac{e^2}{4}\right)(N-1)+s^2\right)} \tag{3.1}$$

Where:

e = acceptable error in estimating the section PCI.

s = standard deviation of the PCI from one sample unit to another within the section.

N = total number of sample units in the section.

3.2.1.2 Calculating the PCI

The Pavement Condition Index (PCI) is a numerical rating from 100 to 0, where 100 indicates a perfect functional pavement condition and 0 indicates a failed pavement. The PCI is determined through a visual inspection that records the type, severity, and quantity of surface distress in each sample unit. According to the Pavement Improvement Center (2021), PCI is calculated by applying specific equations to convert distress severity and extent into deduct values, which are then totaled and subtracted from 100. The stages involved in pavement condition evaluations are illustrated in Figure 3.6 (Irfan et al., 2015).

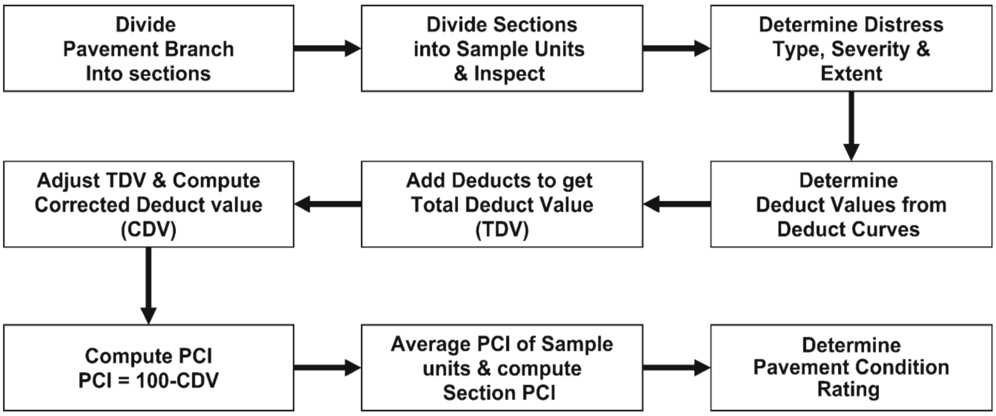


Figure 3.6 Steps involved in PCI calculation

Wesołowski et al. (2020) emphasize that the definitive PCI for a pavement section is typically calculated as the arithmetic mean of the indices across all analyzed sample units. However, when sample units vary in surface area, a weighted average must be used to determine the final PCI value. The result is a PCI on a scale of 0 to 100 as shown by Figure 3.7.

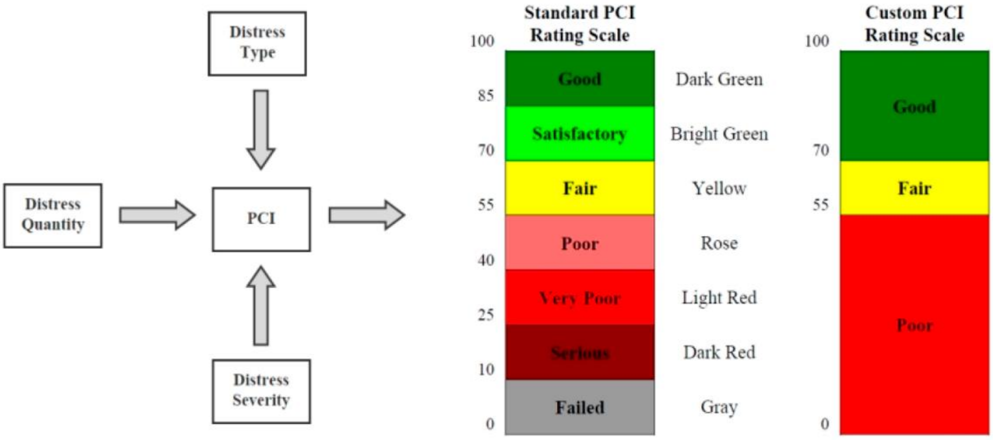


Figure 3.7 Standard and custom PCI Rating Scale (Wesołowski et al., 2020).

3.2.2 Types of Distresses Considered During PCI Evaluation

The Pavement Condition Index (PCI) evaluation relies on the accurate identification and quantification of surface distress, which serves as a primary indicator of both functional and structural pavement health. As noted by Noori and Sarkar (2024), distinguishing between functional and structural defects is essential for selecting cost-effective rehabilitation strategies, as these distresses directly impact the safety of high-speed aircraft operations.

The evaluation process involves identifying specific distress types, measuring their severity and density, and categorizing their probable causes. The PCI methodology categorizes distresses separately for flexible pavement as shown in Table 3.3 (Shahin, 2005). The evaluation considers 16 distinct distress types for asphalt concrete. Key structural (load-related) distresses include alligator cracking and rutting. Functional and environmental distresses include block cracking, weathering, raveling, and longitudinal/transverse cracking.

Table 3.3 Flexible pavement distresses considered during PCI evaluation

S/N	**Distress**	**Cause**
1	Alligator cracking	Load
2	Bleeding	Other
3	Block cracking	Climate
4	Corrugation	Other
5	Depression	Other
6	Jet blast	Other
7	Joint reflection/cracking	Climate
8	Longitudinal and transverse cracking	Climate
9	Oil spillage	Other
10	Patching	Other
11	Polished aggregate	Other
12	Weathering/raveling	Climate
13	Rutting	Load
14	Shoving	Other
15	Slippage cracking	Other
16	Swelling	Other

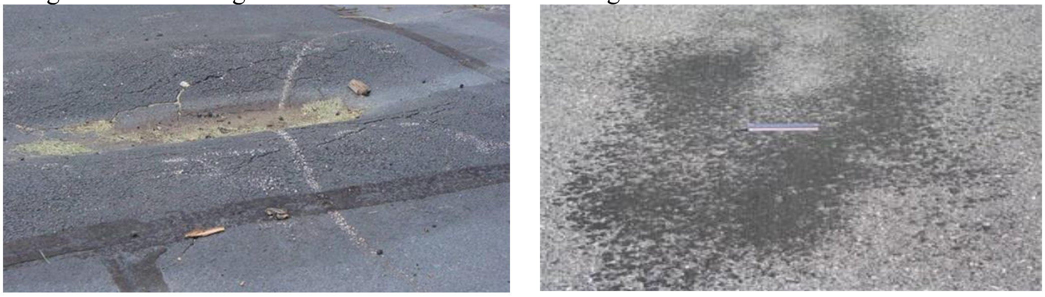
Since the airfield pavement network at KIA consists exclusively of flexible pavement, the condition survey focused strictly on the 16 distress types specific to this material. The following images, Figure 3.8 illustrate visual evidence of the primary defects identified during the field survey.

Alligator Cracking

Block Cracking

Longitudinal Cracking

Rutting



Depression

Bleeding

Weathering

Raveling

Figure 3.8 Illustrate the visual distress of the primary defects identified during the PCI survey from Applied Pavement Technology, Inc. (2023).

3.2.3 Calculation of The PCI Using Different Tools

ASTM D5340 establishes the theoretical foundation for manual PCI calculation, a process that is notably time-intensive due to the combined requirements of in-situ inspections and subsequent complex computations. As stated in FAA AC 150/5380-7B, implementing a practical pavement management program requires a robust computational tool to manage extensive inventory data and complex distress algorithms. This automation has evolved from the initial mainframe-based PAVER to the widely adopted desktop version MicroPAVER and the most recent web-based platform FAA PAVEAIR. This section reviews these critical tools, outlining their evolution and comparative functionalities to justify the selection of the software platform used for the analysis in this study.

3.2.3.1 PAVER or MicroPAVER

The PAVER refers to the original pavement management methodology and mainframe computer program developed by USA-CERL. In 1979, the American Public Works Association (APWA) adopted the original PAVER for use in microcomputers and the system was re-titled MicroPAVER (APWA, 2008).

MicroPAVER employs field inspection data, along with the Pavement Condition Index (PCI), to characterize the current state of the pavement and forecast future maintenance and rehabilitation (M&R) requirements.

In his dissertation, Tofail (2022) highlights the extensive capabilities of PAVER 7.0.11. This subscription-based software provides a suite of essential tools, including network inventory and inspection management, PCI family modeling, and the assessment of both current and future pavement conditions. Furthermore, it supports the analysis of diverse M&R scenarios, ranging from stopgap and localized preventive measures to major global interventions, as well as complex budget formulations and customizable reporting.

3.2.3.2 FAA PAVEAIR

FAA PAVEAIR is a web-based software application that helps public and private entities evaluate, manage, and maintain airport pavements, ensuring compliance with the standards in Advisory Circular (AC) 150/5380-7B. Duah et al. (2021) note that PAVEAIR can predict future airfield pavement performance using specific indicators, namely the Structural Condition Index (SCI), Foreign Object Damage (FOD) potential, and the Pavement Condition Index (PCI). The PCI analysis is conducted in strict adherence to the protocols outlined in ASTM D5340.

FAA PAVEAIR (2021) includes core modules for tasks such as condition analysis, predictive modeling, and reporting. These tools are divided between a "Public" zone for open access and a secure "Member Area" where users can manage, edit, and administer the pavement database.

3.2.3.3 Advantages And Disadvantages of Each Software

The choice between PAVER/MicroPAVER and FAA PAVEAIR depends on one's specific goals, budget, technical resources, and management viewpoint. Key trade-offs include the platform (desktop vs. web-based), the cost (commercial vs. free), and the minimum data required for modeling (five inspection points vs. three). The following Table 3.5 outlines the distinct advantages and disadvantages of each system.

Table 3.4 Key trade-offs between PAVER / MicroPAVER and FAA PAVEAIR

Software	Advantages	Disadvantages
PAVER / MicroPAVER	• Can be used to manage all pavement types, including airfields, roads, streets, and parking lots. • As a desktop application, it does not require a constant internet connection for use.	• It is commercial software that requires a paid license. • Needs a minimum of five inspection data points to develop a prediction model. • Being a desktop tool, data is decentralized on local computers. This can make data sharing, version control, and remote access difficult.
FAA PAVEAIR	• It is free and web-based, which makes it easily accessible. • Only needs three inspection data points to develop a model. This is a major advantage for airports with limitations in terms of the number of inspection data points, like the KIA case • As a web-based (cloud) tool, the database is centralized, secure, accessible from anywhere, and always up-to-date. • It is designed exclusively for airfields and is fully aligned with FAA standards.	• It is entirely web-based and requires a constant internet connection to function. • It cannot be used to manage an airport's other assets, like landside roads or parking lots.

3.2.4 Use of FAA PAVEAIR In This Study

The FAA PAVEAIR software was selected as the primary analytical tool for this study due to its unique and ideal suitability for the research objectives. PAVEAIR’s availability as a free, web-based platform is a significant practical advantage over licensed commercial software like MicroPAVER.

In addition to that, PAVEAIR is a tool developed by the FAA exclusively for airfield pavement management, which aligns perfectly with this study’s focus on Kigali International Airport. It provides the complete suite of functions required by this research, which include Pavement Condition Index (PCI) calculation, detailed pavement inventory management, advanced deterioration modeling, and condition analysis.

Furthermore, the lower data requirement for modeling, requiring only three inspection points versus PAVER's five, makes it the ideal platform due to the limited available inspections at KIA. Therefore, PAVEAIR was used to analyze various M&R scenarios to select the optimal, cost-effective options and develop the final maintenance framework for KIA.

3.2.4.1 Creating the KIA Pavement System Inventory in FAA PAVEAIR

The KIA pavement inventory was built within the FAA PAVEAIR environment Figure 3.9, following the software's required hierarchical structure (FAA PAVEAIR, 2021). The database was established under the project name KIA01PROJECT. The primary network was defined as KIGALI INTERNATIONAL AIRPORT, which was divided into its main functional branches: RUNWAY1028, TAXIWAY ALPHA, TAXIWAY BRAVO, TAXIWAY CHARLIE, APRON ALPHA, APRON BRAVO, and APRON CHARLIE. These branches were further subdivided into the specific management Sections adopted for this study, including RUNWAY END 10, RUNWAY END 28, TOUCHDOWN ZONE, MAIN APRON ALPHA, and GENERAL AVIATION STANDS. Once this structure was built, it was populated with all available work history and M&R records, as well as the detailed available inspection records. This comprehensive database is the foundation for the automated PCI computation, deterioration modeling, and condition analysis performed by PAVEAIR.

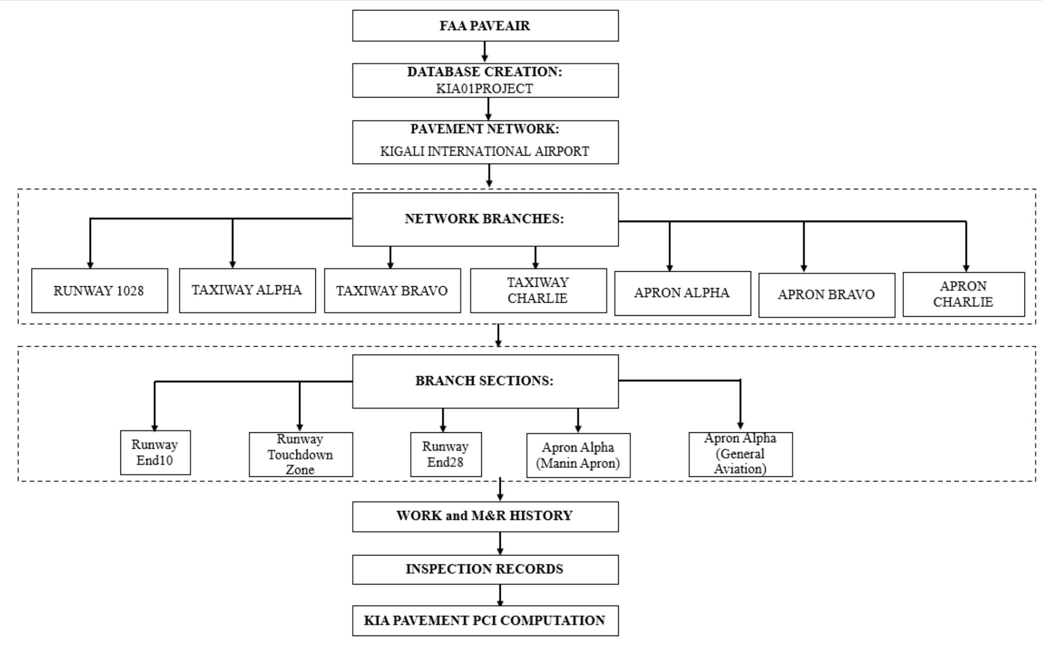


Figure 3.9 KIA pavement database built within the FAA PAVEAIR for this study

3.2.4.2 Pavement Prediction Modeling Using FAA PAVEAIR

Within FAA PAVEAIR, predictive modeling is used to identify deterioration trends by clustering similar pavement types and applying regression analysis to correlate age with condition. By organizing these pavements into specific families, the software generates curves that enable estimation of a pavement’s condition at any stage of its service life.

Using predictive modeling, organizations can determine the funding levels needed to meet future network needs. Furthermore, these tools provide a baseline for risk analysis by showing the anticipated decline in pavement condition if the network is left untreated.

Fortney (2021) argues that improving the accuracy of pavement condition models can reduce operational disruptions caused by frequent manual inspections. The study notes that current industry practice groups similar pavement types across broad regions and applies statistical models, primarily based on age, to estimate current and future conditions.

Pavement performance forecasting is essential for determining the optimal timing of M&R interventions. As shown in Figure 3.10, two pavements may currently share the same PCI yet exhibit different degradation rates; for example, pavement B is declining more rapidly, necessitating earlier preservation efforts than pavement A. Ultimately, once a pavement reaches its threshold for minimum acceptable service, full rehabilitation must be scheduled.

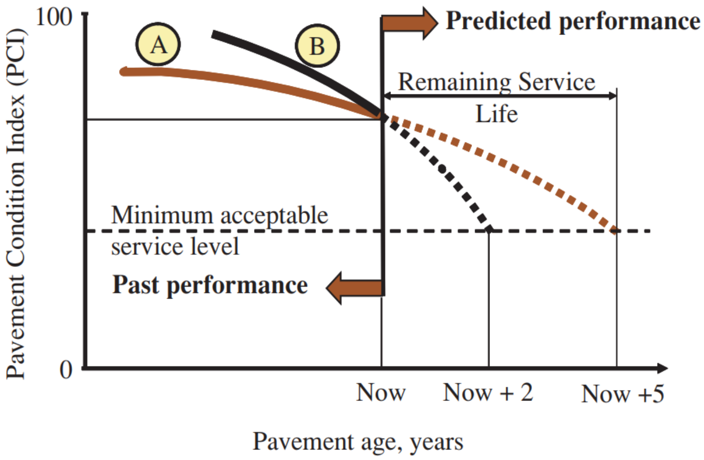


Figure 3.10 Pavement performance prediction model (ACRP, 2011)

For this study, the FAA PAVEAIR prediction modeling module was used to build deterioration curves at the section level by considering three factors: pavement material type, priority, and use.

3.2.4.3 Condition Analysis Using FAA PAVEAIR

The second edition of Shahin, (2005) book titled “Pavement Management for Airports, Roads and Parking Lots.” Explained the theory of condition analysis, revealing that pavement condition analysis is primarily used to track structural and functional changes. It provides a comparative framework for assessing how the current PCI has changed relative to prior years and for projecting the network's anticipated state over the coming years if no M&R activities are conducted.

The book further states that past pavement conditions are estimated by interpolating construction and previous inspection records Figure 3.11, whereas future conditions are forecast using family prediction models.

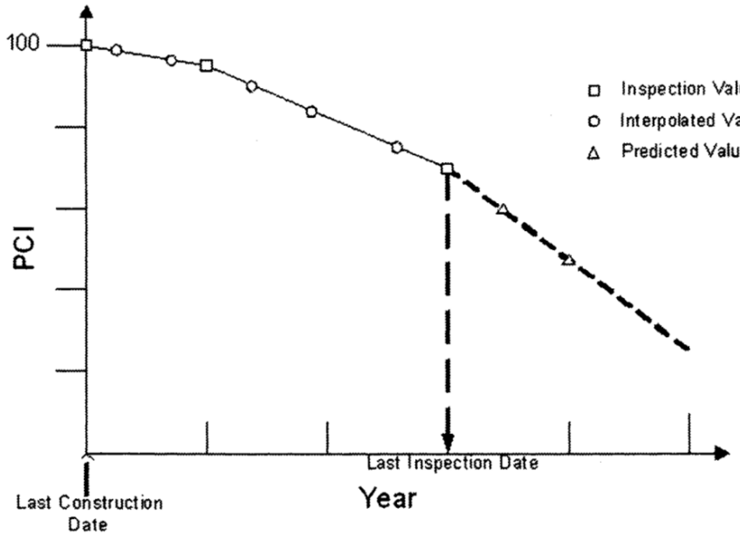
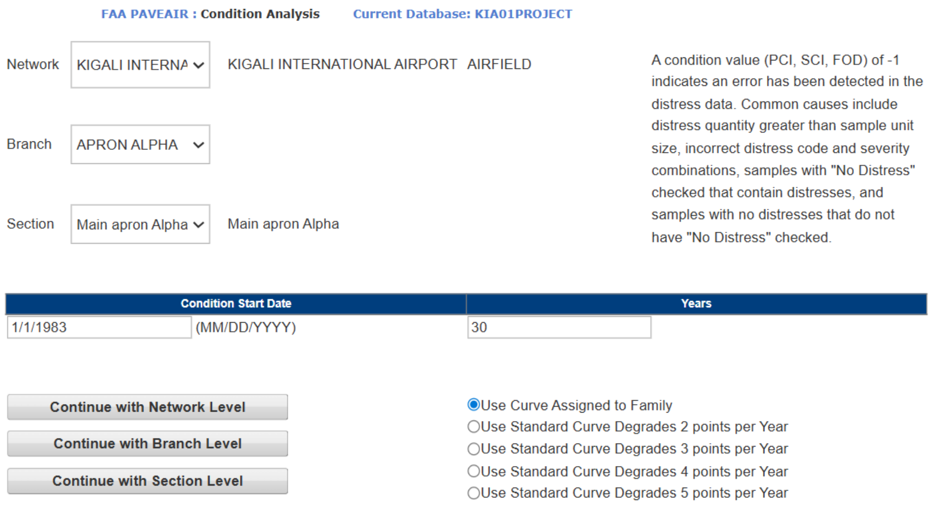


Figure 3.11 Estimating past and future pavement conditions (Shahin, 2005).

The condition analysis module within FAA PAVEAIR allows the user to make projections about the historical and estimated future condition of a specific pavement section of the pavement network. The analysis is based on built family curves (Prediction models), prior inspection data, and comparisons of values between previous inspections. The platform allows the user to select the pavement branch and sections to analyze from the pavement network. It also provides space to specify the start date of the condition analysis and its duration, with a maximum analysis period of 30 years.

The user has to direct the system on how to conduct the analysis, either using the family curve (Prediction models) assigned to the analysis section or a linear deterioration rate. Sections that are not assigned a family curve will be by default, deteriorate at 2 points per year. As demonstrated by Figure 3.12, condition analysis can be performed on the network, branch, or section level, and average the results on an annual basis. The results are in the form of a graph (PCI vs. Age) and a generated table showing the PCI values for the selected pavement over time.



FAA PAVEAIR : Condition Analysis   Current Database: KIA01PROJECT

Network: KIGALI INTERNA   KIGALI INTERNATIONAL AIRPORT AIRFIELD

Branch: APRON ALPHA

Section: Main apron Alpha   Main apron Alpha

A condition value (PCI, SCI, FOD) of -1 indicates an error has been detected in the distress data. Common causes include distress quantity greater than sample unit size, incorrect distress code and severity combinations, samples with "No Distress" checked that contain distresses, and samples with no distresses that do not have "No Distress" checked.

Condition Start Date		Years
1/1/1983	(MM/DD/YYYY)	30

● Use Curve Assigned to Family
○ Use Standard Curve Degrades 2 points per Year
○ Use Standard Curve Degrades 3 points per Year
○ Use Standard Curve Degrades 4 points per Year
○ Use Standard Curve Degrades 5 points per Year

Figure 3.12 Condition analysis customization in FAA PAVEAIR

3.2.5 Structural Evaluation of KIA Pavement

This section details the comprehensive assessment of the structural condition of the KIA pavement network, utilizing field data and traffic analysis provided by RAC from the 2024 inspection. The evaluation first, determined the asphalt concrete layer thickness from coring survey results and the bounding layer properties from Dynamic Cone Penetrometer (DCP) tests. Furthermore, the pavement’s load-bearing capacity is analyzed using Heavy Falling Weight Deflectometer (HFWD) test results to determine layer moduli.

These physical properties were integrated with the KIA aircraft traffic mix and departure data to perform pavement layer thickness design verification. Using the FAA FAARFIELD software, the required pavement thickness for the current traffic load was computed and compared against the existing structure to classify the structural adequacy of each pavement section.

3.2.5.1 Asphalt Concrete (AC) Layer Thickness from Coring Survey Results

The asphalt concrete (AC) layer thickness data, obtained from the coring survey detailed in the 2024 “Consulting Services for Re-Designing and Monitoring of Airfield Pavement Re-Surfacing at Kigali International Airport” report, revealed significant variability across the KIA pavement network.

The thickest pavement structure was identified at runway End 10, a critical take-off zone, with a 40 cm AC course laid in three layers, followed by a 21 cm, three-layer section. In contrast, a notably thinner AC layer of only 13-14 cm (two layers) was found between runway stations 0+600m and 1+000m. The remainder of the runway consists of variable thicknesses ranging from 18 cm to 21 cm.

Similar variability was observed on the taxiways, where Taxiway Alpha ranged from 14 cm to 25 cm, with reported failure at the runway interface. Taxiway Bravo had a consistent 17 cm two-layer structure, while Taxiway Charlie varied between 17 cm and 22 cm in three layers.

Table 3.5 Asphalt layer thickness from coring survey

S/N	Pavement use	Initial construction	Major M&R	1st Inspection	2nd Inspection	AC layer thickness(cm)
1	Runway	1983	2005 (7cm overlay)	2001	2024	18
2	Taxiway Alpha	2016	-	2024	-	21.28
3	Taxiway Bravo	1983	2005 (7cm overlay)	2001	2024	17
4	Taxiway Charlie	2016	-	2024	-	19.5
5	Apron Alpha (Main)	1983	2005 (7cm Overlay)	2001	2024	19.8
	Apron Alpha (GA)	1983	2005 (4cm overlay)	2001	2024	6.15
6	Apron Bravo	2016	-	2024	-	19.3
7	Apron Charlie	2020	-	2024	-	19.12

These diverse thickness profiles were considered critical inputs for this study and were analyzed against FAA AC 150/5320-6G standards to verify their structural adequacy, using computed design thicknesses from FAAFAARFIELD.

3.2.5.2 Pavement Bounding Layers Thickness from Dynamic Cone Penetrometer (DCP)Test Results

To understand the condition of the unbound pavement layers, this study used the Dynamic Cone Penetrometer (DCP) test results from the 2024 report. The consultant conducted these tests in accordance with ASTM D6951/D6951M to determine the in-situ California Bearing Ratio (CBR) and thickness of the granular base and subbase courses underlying the AC layers.

The findings revealed distinct profiles across the network. The Runway is generally supported by two layers: a 24 cm aggregate base course (average 86% CBR) and a 33 cm granular subbase (average 50% CBR). The Aprons showed significant variability; Apron Charlie was consistently strong (CBR > 89%), while Apron

Alpha’s main area was strong (CBR > 82%) but its General Aviation stands were weaker (CBR as low as 50%). Apron Bravo was the most variable (CBR 52-92%). The Taxiways (Bravo and Charlie) exhibited high strength (CBR > 70%), with the notable exception of Taxiway Alpha, where high variability and low in-situ CBR values were found. These CBR strength values for the base and subbase materials were considered foundational for the structural analysis and evaluated against the soil characteristics for coarse granular materials as specified in FAA AC 150/5320-6G.

3.2.5.3 Pavement Layer Modulus from Heavy Falling Weight Deflectometer (HFWD)Test Results

To determine the resilient modulus of the pavement layers and subgrade, this study analyzed the Heavy Falling Weight Deflectometer (HFWD) test results presented in the 2024 inspection report. The report confirms that all HFWD data points were processed using ELMOD v6 software, a back-calculation tool that is approved by the FAA and listed in AC 150/5370-11B.

The back-calculated layer moduli results revealed significant variations. The Runway Table 3.7 showed an average Asphalt Concrete (E1) modulus of 2293.2 MPa and a very strong corrected subgrade (E4) modulus of 232.9 MPa.

Table 3.6 KIA Runway HFWD back-calculated layer moduli

Layers	**E Avg (MPa)**	**E 15th Percentile (MPa)**	**E Range (MPa)**
Asphalt Concrete (E1)	2293.2	1239.4	1066–3795
Granular Base (E2)	1282.2	409.2	285–3781
Subgrade (Corrected E4)	232.9	174.8	139–384

In contrast, Apron Bravo Table 3.8 exhibited a much stiffer surface (E1 Avg 3127 MPa) but was founded on a weaker subgrade (E4 Avg 164 MPa).

Table 3.7 Apron Bravo back-calculated layer moduli

Layers	E Avg (MPa)	E 15th Percentile (MPa)	E Range (MPa)
Asphalt Concrete (E1)	3127	2085	566-5974
Granular Base (E2)	395	240	105-1352
Granular Base (E3)	1120	427	113-6132
Subgrade (Corrected E4)	164	82	51-300

A critical step for standardizing this analysis is the classification of the subgrade. For this thesis, the subgrades were classified using the ACR-PCR standard subgrade categories adopted from FAA AC 150/5335-5D. This circular defines four classes by elastic modulus as follows:

- Class A (High, E ≥ 150 MPa)
- Class B (Medium 100 ≤ E < 150 MPa)
- Class C (Low, 60 ≤ E < 100 MPa), and
- Class D (Ultra-Low, E < 60 MPa)

3.2.5.4 Designing Required KIA Pavement Thickness Using FAARFIELD Software

This subsection details the structural verification of the KIA pavement network, performed using FAARFIELD 2.1.1. This analysis assesses the structural adequacy of the current pavement layers, ensuring they can sustain the operational demands of today's traffic at KIA. The results of this structural verification are critical, as they provide a clear understanding of the maintenance required and its extent, supporting subsequent analysis of different M&R scenarios.

FAARFIELD (Federal Aviation Administration Rigid and Flexible Iterative Elastic Layered Design) is the FAA's current pavement-thickness design computer program for both rigid and flexible airport pavements. Fistcar et al. (2024) noted that in 2021 the FAA issued an updated standard for calculating airport pavement structures, namely AC (Advisory Circular) 150-5320-6G, which uses the FAARFIELD 2.1.1 assist program. The flexible pavement design module within FAARFIELD is based on layered elastic analysis of the pavement structure.

Using aircraft traffic data, annual departures, subgrade CBR, and intended layer types, FAARFIELD calculates the required pavement thickness through an iterative design process shown in Figure 3.13.

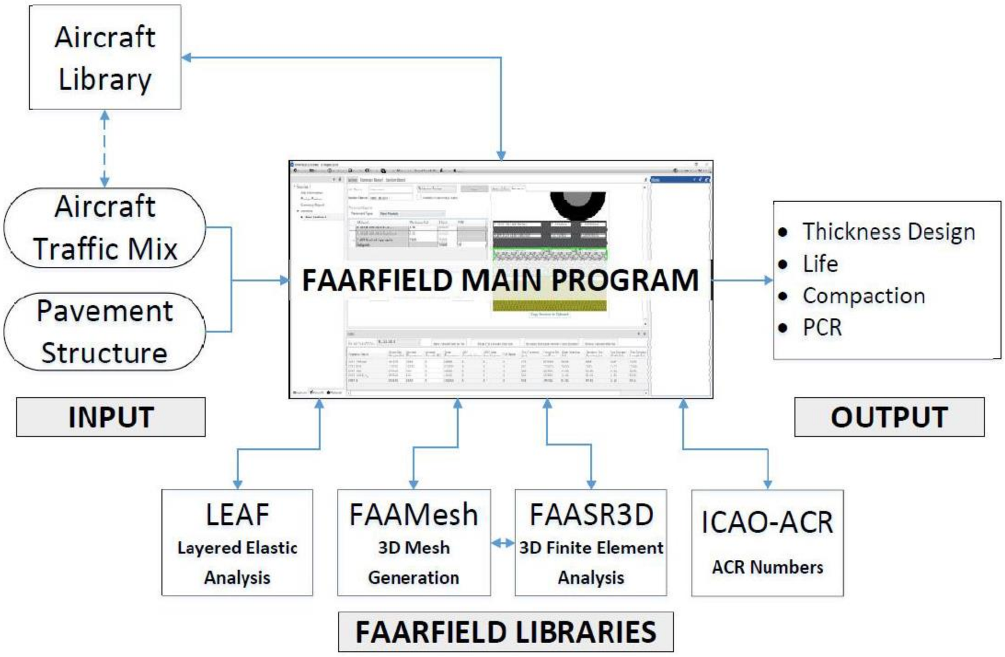


Figure 3.13 FAARFIELD Program (FAA, 2021)

According to the methodology established by Fatikasari et al. (2022), designing the structural thickness of pavement using FAARFIELD involves a series of sequential steps:

- Defining the specific material types for the pavement layers.
- Entering the California Bearing Ratio (CBR) for the subgrade.

- Specifying the anticipated aircraft fleet and traffic mix.
- Incorporating traffic growth projections, where applicable.
- Generating the software's recommended thickness for each pavement layer.

All the input data were extracted from the 2024 KIA inspection report, where the pavement layers were considered from the coring and DCP survey results, while the subgrade CBR was the result of the HFWD test. The aircraft mix of each pavement section of the KIA network was also extracted from the same report.

3.2.6 Maintenance and Rehabilitation (M&R) Strategies for KIA

Extending the service life of airfield pavements requires consistent Maintenance and Rehabilitation (M&R); however, the substantial capital required often makes it difficult for agencies to secure and justify the necessary funding. Historically, as highlighted in FAA AC 150/5380-7B, pavement management practices in the United States relied heavily on reactive, experience-based responses to distress rather than long-term, data-driven strategies. This reactive approach is particularly damaging in developing regions where, as noted by Orabi & Shatila (2024), chronic funding shortages frequently result in deferred maintenance. Such delays accelerate deterioration, ultimately inflating the total costs over the pavement's life cycle.

To counter these inefficiencies, the FAA (2014) emphasizes that understanding deterioration rates and simulating different M&R scenarios is critical for selecting the most economical and practical maintenance actions. Predictive modeling facilitates rigorous life-cycle cost comparisons, enabling airport managers to identify and deploy the optimal intervention at the precise moment required to prevent excessive future expenditures.

Effective pavement preservation is fundamentally driven by service-level expectations, utilizing Pavement Condition Index (PCI) trigger values to dictate repair timing. As outlined by the ACRP (2011), these service expectations are categorized into three levels: a Target (Desirable) level of service, a minimum acceptable level of service (defined by Critical PCI values), and a minimum safety-related level of service. While maintaining high service standards necessitates significant investment, the strategic use of trigger values ensures cost efficiency. By intervening early, for example, Figure 3.14, applying crack sealants to asphalt pavements while they are still in good condition, agencies can prevent minor defects from evolving into structural failures that require prohibitively expensive rehabilitation

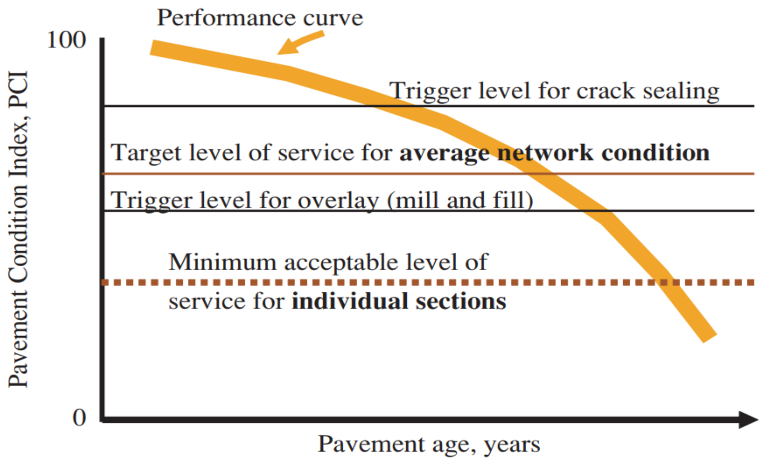


Figure 3.14 Example of levels of service and trigger levels (ACRP, 2011)

The ACRP (2011) report highlighted that PCI ratings are an effective tool for setting trigger values and planning M&R activities. Table 3.9 shows how the ASTM-standardized PCI pavement ratings align with the required maintenance actions for each pavement condition.

Table 3.8 Using PCI to set pavement maintenance triggers and treatment

PCI Rating	Description	Applicable Pavement Preservation Treatments
86–100	Good: Only minor distresses	Routine maintenance only
71-85	Satisfactory: Low and medium distresses	Preventive maintenance
56-70	Fair: Some distresses are severe	Corrective maintenance and rehabilitation
41-55	Poor: The severity of some of the distresses can cause operational problems	Rehabilitation or reconstruction
26-40	Very poor: Severe distresses cause operational problems	Rehabilitation and reconstruction
11-25	Serious: Many severe distresses cause operational restrictions	Immediate repairs and reconstruction
0-10	Failed: Pavement deterioration prevents safe aircraft operations	Reconstruction

Capital Improvement Program (CIP) is a planning tool that uses the pavement condition projections to indicate costs associated with different M&R strategies to develop budgets for each year in the multi-year plan. A wide range of M&R strategies can be analyzed for a given analysis period as illustrated in Table 3.10.

Table 3.9 M&R alternative scenarios in preparation for CIP for a given analysis period (ACRP report 203, 2019).

CIP M&R strategy	Outcome
No budget	Predict conditions if capital projects are not constructed during the analysis period.
Unlimited budget	Unrestricted funding is required to address all capital needs
Fixed-budget	Predict the condition if the capital budget is fixed at a given amount during the analysis period.
Maintain current PCI	Required budget to maintain the network PCI at current levels in the analysis period
Achieve a target PCI.	Required budget to increase the network PCI to a target level in the analysis period
Eliminate backlog	Required budget to fully address the backlog of capital needs over a given time period.

As demonstrated in Figure 3.15, this approach allows for a scientifically rigorous comparison of divergent maintenance strategies. The graph illustrates how varying investment levels, ranging from Unlimited funding (S3) to minimal Stopgap Only (S5), result in drastically different deterioration curves over a ten-year horizon.

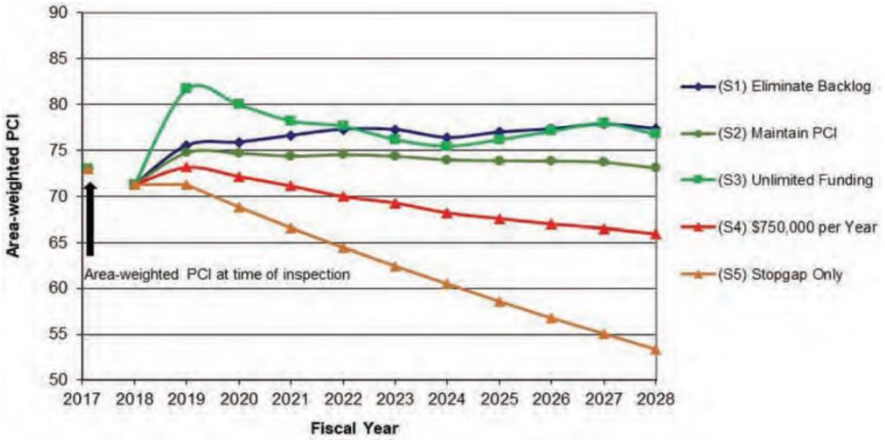


Figure 3.15 The impact of the budget on the PCI with different scenarios over 10 years (ACRP, 2019).

The methodology adopted for this study is grounded in the framework established by the Airport Cooperative Research Program (ACRP) in its 2019 report, “Guidelines for Collecting, Applying, and Maintaining Pavement Condition Data at Airports.” This framework posits that the long-term efficacy of pavement management cannot be assessed by cost alone but must be evaluated by simulating the impact of distinct financial capabilities on network performance over time.

3.2.6.1 FAA PAVEAIR M&R Strategies and Treatments

This subsection outlines the methodological framework utilized within FAA PAVEAIR to quantify maintenance costs and define treatment requirements for a pavement network. The FAA PAVEAIR Maintenance and Rehabilitation (M&R)

module functions as a critical decision-support system by integrating the inventory database with deterioration prediction models, the software simulates pavement performance over a defined analysis period to identify the most resource-efficient intervention strategies. According to FAA PAVEAIR documentation (2021), the system supports three distinct strategies of M&R planning, each designed to answer a specific management question:

Consequences of the local repair plan: This maintenance strategy evaluates the efficacy of localized preservation policies rather than global rehabilitation, estimating the budget required to maintain operational safety without triggering full-scale reconstruction.

Minimum condition plan: This Maintenance strategy calculates the budget required to perform major M&R to maintain a minimum PCI for the pavements set by the airport agency, and it is ideal for an airport that has a fixed level of service policy, but does not necessarily consider the most cost-effective timing.

Critical PCI plan: This is a condition-based management strategy designed to determine the Maintenance and Rehabilitation (M&R) activities necessary to maintain pavement sections above a user-defined critical threshold. Within FAA PAVEAIR, this strategy can be executed through two distinct analytical approaches:

Determine Budget Consequences: This mode functions to simulate how specific funding levels impact the future condition of the network by using two options:

- **Unlimited Budget:** A theoretical unconstrained scenario where the software assumes sufficient funds exist to execute every triggered maintenance policy immediately. This establishes the ideal performance baseline for the network.
- **Limited Budget:** A constrained resource simulation where a fixed annual funding cap is imposed. The software applies prioritization algorithms to fund only the most critical repairs, typically safety-related, while deferring remaining work as backlog.

Determine Budget Requirements: This mode functions by calculating the exact capital required to achieve specific performance targets through 3 different alternatives:

- **Backlog Elimination:** Estimates the total lump-sum investment required to immediately correct all existing distresses, effectively reducing the network's deferred maintenance debt to zero.
- **Reach a Preferred PCI:** Calculates the annual investment profile necessary to raise the network's area-weighted PCI to a specific user-defined target (e.g., improving from PCI 40 to Target PCI 70).
- **Maintain Current PCI:** Estimates the minimum recurring investment required to stabilize the network condition at its present level, preventing further deterioration throughout the analysis period.

3.2.6.2 Structure of the FAA PAVEAIR Treatment Plan

The FAA PAVEAIR treatment plan is organized into a hierarchical intervention strategy that selects maintenance activities based on the severity of deterioration and the pavement's position relative to the Critical PCI threshold. As illustrated in the Figure 3.16, the maintenance treatments are categorized into two: Preservation and Major M&R.

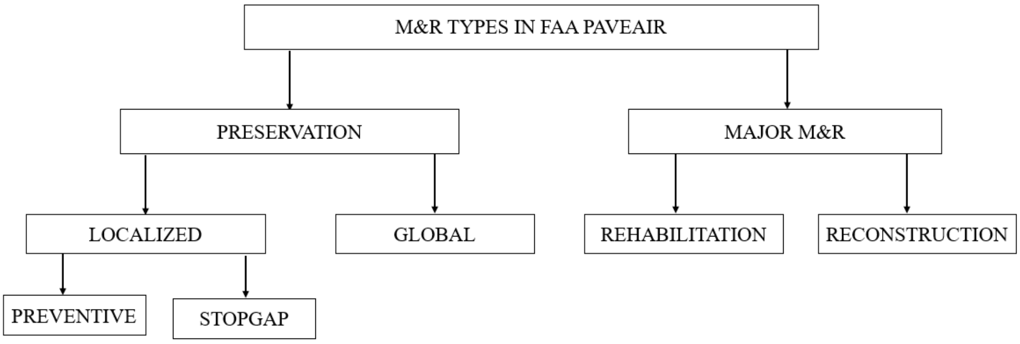


Figure 3.16 FAA PAVEAIR maintenance types

The preservation category includes all activities designed to maintain the existing pavement and slow deterioration. It is further subdivided by the scale of application into global maintenance activity applied to the entire pavement section, typically as a preventive measure, and localized maintenance, which refers to a repair at a specific location of the pavement section.

Localized Maintenance: Is split into two distinct operational policies: Policy > Critical (Preventive), which targets minor distresses in structurally sound pavements to slow the rate of deterioration, and Policy < Critical (Safety/Stopgap), which is triggered when the PCI falls below the critical value, prioritizing emergency repairs to mitigate operational hazards rather than improve asset value.

Global Maintenance: module evaluates the feasibility of surface-wide treatments that are applied to the entire pavement section to seal the surface and arrest oxidation before structural damage occurs.

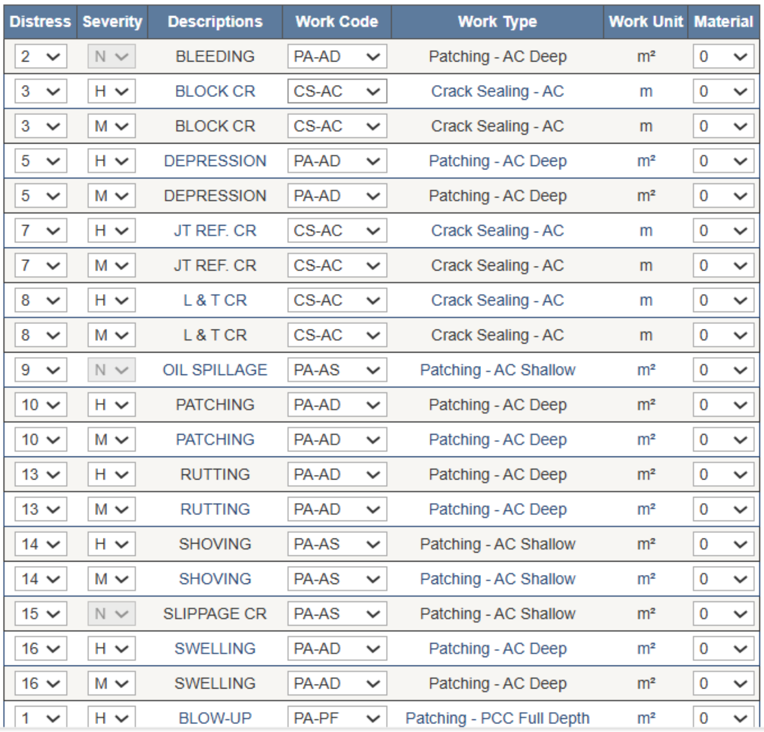
Major Maintenance and Rehabilitation (M&R): This category serves as the structural reset mechanism; it is triggered only when the pavement condition deteriorates beyond the capacity of localized or global preservation, necessitating capital-intensive interventions like overlay or full-depth reconstruction. In the simulation, PAVEAIR prioritizes these treatments hierarchically, ensuring that funds are first allocated to critical safety repairs before authorizing preventive or major rehabilitation projects.

3.2.6.3 FAA PAVEAIR M&R Policy and Cost

This subsection defines the maintenance rules and cost data used to run the M&R scenarios in FAA PAVEAIR. The analysis used the software’s default maintenance policies, which are automatically applied when policy triggers are met. Since specific maintenance cost data for KIA were unavailable, the default unit costs embedded in the PAVEAIR program were adopted for this study and applied directly to the distress and work quantities identified during the 2024 inspection, ensuring that all cost estimates are based on the same data used for the PCI calculations.

Localized Maintenance Policy and Unit Costs

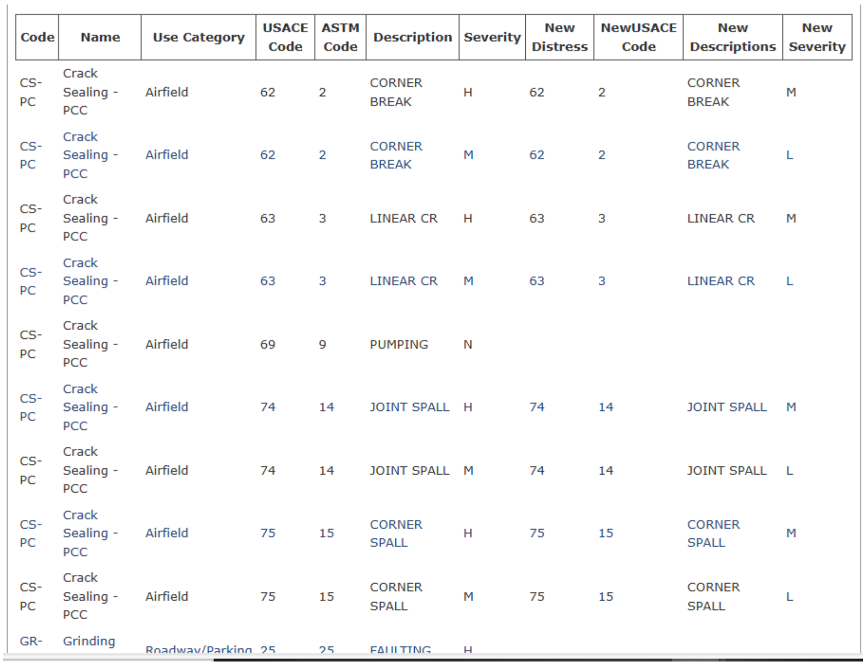
To generate accurate budget estimates for preservation activities, the study employed the standard Localized Preventive for Airfields policy within FAA PAVEAIR. This module functions as a deterministic matrix that links specific pavement distresses observed during inspection to standardized repair activities. The software automatically assigns a Work Code based on the distress type and severity level, as illustrated in Figure 3.17. For instance, high-severity block cracking (Distress 3, Severity H) is mapped to the work code CS-AC (Crack Sealing - Asphalt), while structural failures like rutting (Distress 13) trigger PA-AD (Patching - AC Deep).



Distress	Severity	Descriptions	Work Code	Work Type	Work Unit	Material
2	N	BLEEDING	PA-AD	Patching - AC Deep	m²	0
3	H	BLOCK CR	CS-AC	Crack Sealing - AC	m	0
3	M	BLOCK CR	CS-AC	Crack Sealing - AC	m	0
5	H	DEPRESSION	PA-AD	Patching - AC Deep	m²	0
5	M	DEPRESSION	PA-AD	Patching - AC Deep	m²	0
7	H	JT REF. CR	CS-AC	Crack Sealing - AC	m	0
7	M	JT REF. CR	CS-AC	Crack Sealing - AC	m	0
8	H	L & T CR	CS-AC	Crack Sealing - AC	m	0
8	M	L & T CR	CS-AC	Crack Sealing - AC	m	0
9	N	OIL SPILLAGE	PA-AS	Patching - AC Shallow	m²	0
10	H	PATCHING	PA-AD	Patching - AC Deep	m²	0
10	M	PATCHING	PA-AD	Patching - AC Deep	m²	0
13	H	RUTTING	PA-AD	Patching - AC Deep	m²	0
13	M	RUTTING	PA-AD	Patching - AC Deep	m²	0
14	H	SHOVING	PA-AS	Patching - AC Shallow	m²	0
14	M	SHOVING	PA-AS	Patching - AC Shallow	m²	0
15	N	SLIPPAGE CR	PA-AS	Patching - AC Shallow	m²	0
16	H	SWELLING	PA-AD	Patching - AC Deep	m²	0
16	M	SWELLING	PA-AD	Patching - AC Deep	m²	0
1	H	BLOW-UP	PA-PF	Patching - PCC Full Depth	m²	0

Figure 3.17 Localized work code based on the distress type and severity level

Financial projections for these interventions are derived from the Default Cost by Work Type library, which assigns a specific unit rate to each work code. To simulate the functional benefit of these repairs, PAVEAIR utilizes a Work Consequence algorithm that mathematically reduces distress severity rather than eliminating it. As demonstrated in the default consequence table Figure 3.18, applying a seal to a high-severity distress typically downgrades its classification to medium or low severity. This severity reduction recalculates the deduct values, resulting in an incremental improvement in the section's PCI that reflects the extended service life provided by the repair.

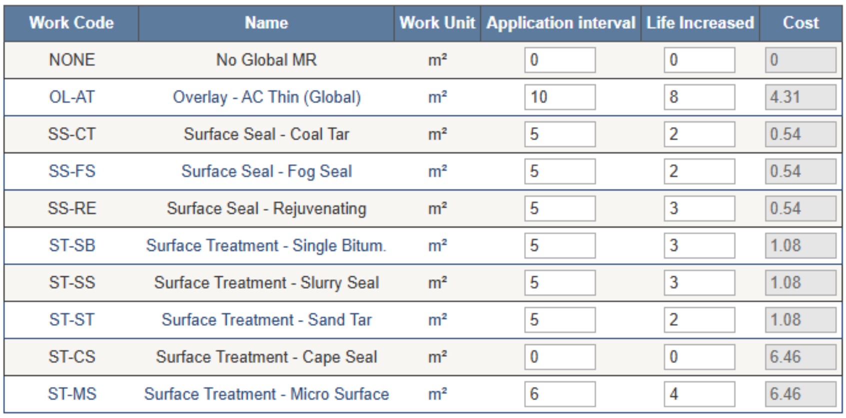


Code	Name	Use Category	USACE Code	ASTM Code	Description	Severity	New Distress	NewUSACE Code	New Descriptions	New Severity
CS-PC	Crack Sealing - PCC	Airfield	62	2	CORNER BREAK	H	62	2	CORNER BREAK	M
CS-PC	Crack Sealing - PCC	Airfield	62	2	CORNER BREAK	M	62	2	CORNER BREAK	L
CS-PC	Crack Sealing - PCC	Airfield	63	3	LINEAR CR	H	63	3	LINEAR CR	M
CS-PC	Crack Sealing - PCC	Airfield	63	3	LINEAR CR	M	63	3	LINEAR CR	L
CS-PC	Crack Sealing - PCC	Airfield	69	9	PUMPING	N				
CS-PC	Crack Sealing - PCC	Airfield	74	14	JOINT SPALL	H	74	14	JOINT SPALL	M
CS-PC	Crack Sealing - PCC	Airfield	74	14	JOINT SPALL	M	74	14	JOINT SPALL	L
CS-PC	Crack Sealing - PCC	Airfield	75	15	CORNER SPALL	H	75	15	CORNER SPALL	M
CS-PC	Crack Sealing - PCC	Airfield	75	15	CORNER SPALL	M	75	15	CORNER SPALL	L
GR-	Grinding	Roadway/Parking	25	25	FAULTING	H				

Figure 3.18 FAA PAVEAIR work consequence algorithm

Global Maintenance Policy and Cost Configuration

FAA PAVEAIR utilizes a Global Maintenance module designed to address surface-wide deterioration that cannot be rectified by spot repairs alone. Global is applied to the entire pavement section area to retard oxidation, improve friction, and extend the functional service life of the asset. The economic and technical parameters for these interventions are defined in the Global Cost Table. This library Figure 3.19 establishes a cost-benefit relationship for each treatment type, quantifying the trade-off between the unit cost and the resulting extension in service life.



Work Code	Name	Work Unit	Application interval	Life Increased	Cost
NONE	No Global MR	m²	0	0	0
OL-AT	Overlay - AC Thin (Global)	m²	10	8	4.31
SS-CT	Surface Seal - Coal Tar	m²	5	2	0.54
SS-FS	Surface Seal - Fog Seal	m²	5	2	0.54
SS-RE	Surface Seal - Rejuvenating	m²	5	3	0.54
ST-SB	Surface Treatment - Single Bitum.	m²	5	3	1.08
ST-SS	Surface Treatment - Slurry Seal	m²	5	3	1.08
ST-ST	Surface Treatment - Sand Tar	m²	5	2	1.08
ST-CS	Surface Treatment - Cape Seal	m²	0	0	6.46
ST-MS	Surface Treatment - Micro Surface	m²	6	4	6.46

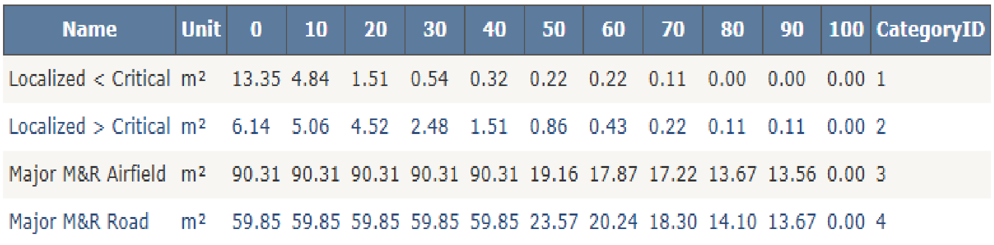
Figure 3.19 FAA Global surface treatment costs

The application of these treatments is governed by the Global Policy interface, which categorizes triggers into three performance tiers: Minimal/No distress, Climate-related, and Skid-causing. This structure allows the analyst to assign specific global treatments to these conditions.

Major M&R Policy and Cost Configuration

The final tier of the maintenance hierarchy is major maintenance and rehabilitation (M&R), which addresses pavements that have deteriorated beyond the capacity of localized repairs or global preservation. This category encompasses capital-intensive structural interventions, specifically major overlays and full-depth reconstruction, designed to restore the pavement to a new condition (PCI 100).

Unlike localized maintenance, which is driven by specific distress types, Major M&R is governed exclusively by a condition-based policy. FAA PAVEAIR employs a cost matrix that correlates specific PCI ranges with generic reconstruction costs per square meter Figure 3.20. In this simulation, the software evaluates the section’s PCI at the start of each analysis year; if the condition falls within a critical band, the system triggers the corresponding major intervention cost rather than summing individual repair costs. This approach ensures that budget estimates for failing pavements reflect the reality of full structural renewal.



Name	Unit	0	10	20	30	40	50	60	70	80	90	100	CategoryID
Localized < Critical	m²	13.35	4.84	1.51	0.54	0.32	0.22	0.22	0.11	0.00	0.00	0.00	1
Localized > Critical	m²	6.14	5.06	4.52	2.48	1.51	0.86	0.43	0.22	0.11	0.11	0.00	2
Major M&R Airfield	m²	90.31	90.31	90.31	90.31	90.31	19.16	17.87	17.22	13.67	13.56	0.00	3
Major M&R Road	m²	59.85	59.85	59.85	59.85	59.85	23.57	20.24	18.30	14.10	13.67	0.00	4

Figure 3.20 PCI ranges with generic reconstruction costs per square meter for Major M&R

3.2.6.4 M&R Analysis Period

This subsection defines the temporal horizon used to simulate and compare the efficacy of different M&R strategies. Industry guidelines vary regarding the optimal duration for pavement management planning. The ACRP (2011) notes that while a five-year horizon is typical for standard airport planning, larger facilities often extend this to 15 years to encompass broader lifecycle trends. Similarly, for Life Cycle Cost Analysis (LCCA), the AAPTP (2011) recommends a window of 10 to 30 years, and FAA AC 150/5320-6D specifically advises 20 years for evaluating major rehabilitation alternatives. However, these theoretical recommendations must be reconciled with the operational constraints of the analysis tool. The FAA PAVEAIR M&R module is computationally limited to a maximum simulation range of 10 years.

To balance these requirements, this study adopted a 10-year analysis period; this timeframe fulfills the definition of long-term planning to ensure that the analysis captures the generation of future distresses and the lifecycle benefits of interventions. Simultaneously, it maximizes the software’s capability, utilizing the longest duration allowed by FAA PAVEAIR to provide the most reliable projection possible.

Furthermore, Phillips et al. (1981) argue that a 10-year analysis period is essential for the comparative effectiveness of maintenance strategies. Because major rehabilitation activities (such as overlays) have significantly longer service lives than minor treatments (such as seal coats), a shorter analysis window would bias the results against durable interventions. A 10-year horizon ensures that the survival rates of major rehabilitation methods are fully captured, allowing for a fair economic and performance comparison against short-term maintenance options.

This 10-year duration is further supported by recent methodological frameworks in transportation infrastructure management. For instance, Dong et al. (2025) explicitly defined a 10-year M&R planning cycle in their multi-objective optimization model, demonstrating that this timeframe effectively captures the trade-offs between agency costs, user costs, and environmental impacts without introducing the excessive uncertainty associated with longer projection windows.

The Federal Highway Administration (2020) stated that a 10-year analysis period is justified by the natural performance cycle of asphalt. As demonstrated by the New Jersey Department of Transportation (NJDOT), life-cycle data establishes that pavements typically function for one decade before requiring preservation overlays. Therefore, a 10-year horizon provides the optimal technical window to capture the pavement's complete first life, ensuring that M&R strategies are evaluated against a full operational cycle rather than a partial fragment

3.2.6.5 Selected M&R Scenarios for This Study

The central objective of this study is to develop a strategic M&R plan that balances optimal engineering performance with financial prudence. To achieve this, the study conducts a comparative analysis of four distinct Maintenance and Rehabilitation (M&R) scenarios, specifically designed to address the current poor condition of the KIA network while accounting for the budgetary constraints typical of a developing economy.

These scenarios function as alternative management strategies, ranging from unconstrained restoration to safety-driven preservation. All analyses are simulated over the established 10-year analysis period (2025-2035), utilizing the decision-support logic of the FAA PAVEAIR M&R module. A critical parameter in this modeling is the economic basis of the interventions; due to the unavailability of standardized local unit cost data for airfield construction in Rwanda, all financial estimates are derived strictly from the FAA PAVEAIR default cost library. This ensures a consistent, scientifically validated baseline for comparing the relative economic efficiency of the selected strategies.

- Unlimited Budget
- Minimum Condition
- Consequences of the Local Repair
- Limited Budget Plan

3.2.6.6 Comparative Analysis Methodology

Following the simulation of the distinct Maintenance and Rehabilitation (M&R) strategies, a comparative analysis will be conducted to determine the optimal M&R strategy for Kigali International Airport. To ensure a balanced evaluation that accounts for both engineering performance and economic reality, the strategies will be assessed against four critical performance metrics:

- **Initial cost requirement (Year 1):** This metric evaluates the immediate financial burden of each strategy by isolating the upfront investment required in the first year (2025) to launch the program, distinguishing between strategies that front-load costs versus those that defer spending.
- **Total 10-Year lifecycle cost:** This metric assesses long-term economic efficiency by summing the total expenditures over the full analysis period (2025-2035).

- **Performance evaluation in terms of PCI (Before vs. Terminal PCI):** To measure technical effectiveness, the study compares the initial PCI condition immediately before the repairs against the **terminal PCI**. This reveals the status of the pavement at the end of the analysis period.
- **Implementation Feasibility:** Finally, the quantitative results are contextualized within the financial constraints of a developing economy. This qualitative assessment judges the viability of each strategy based on the typical funding capabilities of Rwanda, discarding theoretically optimal solutions that are financially unattainable in favor of practical, sustainable alternatives.

3.2.7 Development of Maintenance and Rehabilitation (M&R) Framework for KIA

This section focuses on the development of a systematic maintenance and rehabilitation (M&R) framework tailored to the specific operational context of Kigali International Airport (KIA). The objective is to synthesize the analytical procedures conducted in this study, from data collection to different maintenance strategies simulation into a standardized workflow that airport authorities can adopt for future asset management.

The framework is constructed by structuring the methodology into five chronological and interdependent operational phases. This design is intended to guide the transition from reactive repair practices to a predictive Pavement Management System (PMS). The formulation of the framework follows this logical sequence:

- **Network inventory and database establishment:** Defining the protocol for digitizing physical pavement infrastructure into a manageable database.
- **Condition assessment and evaluation:** Establishing standard procedures for periodic inspection and PCI calculation.

- **Multi-scenario M&R simulation:** Integrating prediction models to forecast future performance under various constraints.
- **Comparative analysis and M&R strategy selection:** Developing a decision matrix to evaluate strategies based on performance and financial feasibility.
- **Implementation of preventive maintenance:** Outlining the execution guidelines for selected preservation treatments.

CHAPTER 4

RESULTS AND DISCUSSION

This chapter presents a comprehensive analysis and findings from the pavement study for Kigali International Airport (KIA), using the FAA PAVEAIR software as the primary analytical engine. The analysis begins by processing inventory and distress data to establish the current functional condition of the pavement network, then develops predictive models to forecast future pavement performance trends. A central focus of the study is the simulation and comparative evaluation of distinct maintenance and rehabilitation (M&R) scenarios to quantify the KIA pavement network's immediate capital recovery needs versus long-term preservation costs. Synthesizing these quantitative results, the chapter concludes by selecting the most viable M&R strategy and developing a tailored, transferable M&R framework to guide KIA and similar developing countries in transitioning from reactive failure management to proactive pavement preservation.

4.1 KIA Pavement Condition Index (PCI)

This section reports the results of the functional condition assessment for the Kigali International Airport (KIA) pavement network. The 2024 assessment, performed by the consultant, utilized MicroPAVER software. The pavement was re-evaluated using 2024 distress survey data, including distress type, severity, and quantity, and processed in the FAA PAVEAIR platform. The resulting Pavement Condition Index (PCI) reflects the current operational health of the airfield. A primary objective of this analysis is to compare the FAA PAVEAIR results with those of the MicroPAVER analysis. This comparison validates the accuracy of the database developed for this thesis and ensures that subsequent deterioration modeling relies on verified condition data.

4.1.1 PCI from FAA PAVEAIR Analysis

Following the comprehensive development of the KIA pavement inventory in the FAA PAVEAIR system within the created KIA01PROJECT database, a detailed condition assessment was performed at the sample-unit level of pavement distress from the 2024 inspection report. For analytical purposes, a standardized recording process was used for each sample unit to capture detailed information on distress categories, their severity levels, and the total volume of degradation. The software computed the Pavement Condition Index (PCI) for each sample unit and aggregated these values to determine the overall PCI for each pavement section. This procedure strictly follows the ASTM D5340 methodology and the calculation logic presented in Figure 3.6, as well as the custom rating scale used for condition classification in Figure 3.7. Table 4.1 presents the PCI for each pavement section, providing a critical baseline for the deterioration modeling conducted in this study.

Table 4.1 FAA PAVEAIR computed PCI for each pavement section

Runway	
Section	**FAA PAVEAIR Generated PCI**
Runway End10	40
Runway End 28	38
Runway Touchdown	42
Aprons	
Apron Alpha General Aviation	50
Apron Alpha Main	35
Apron Bravo	40
Apron Charlie	38
Taxiways	
Taxiway Alpha	38
Taxiway Bravo	41
Taxiway Charlie	47

To estimate the overall condition of the Kigali International Airport (KIA) network in terms of PCI, FAA PAVEAIR utilizes the weighted average (PCI), which is a metric that considers the surface area to ensure that larger and more critical sections proportionally influence the final score. For each branch, the network PCI is estimated using the area-weighted Equation 4.1, which is then aggregated to determine the definitive network-level condition, as demonstrated in the summary Table 4.2.

$$Weighted\ PCI_{branch} = \frac{\sum(PCI_i \times Area_i)}{\sum Area_{total}} \tag{4.1}$$

Where i stands for the individual section of a branch

Table 4.2 Estimation of KIA pavement network overall weighted average PCI

Runway			
Sections	PCI	Area	PCI * Area
Runway End10	40	105,525	4,221,000.00
Runway End 28	38	11,475.85	436,082.30
Runway Touchdown	42	40,500	1,701,000.00
Total		157,501	6,358,082.30
Weighted Runway PCI	**40.37**		
Aprons			
Apron Alpha General Aviation	50	10,500.00	525,000.00
Apron Alpha Main	35	45,375.00	1,588,125.00
Apron Bravo	40	28,757.00	1,150,280.00
Apron Charlie	38	42,002.00	1,596,076.00
Total		126,634.00	4,859,481.00
Weighted Aprons PCI	**38.4**		
Taxiways			
Taxiway Alpha	38	11,042.00	419,596.00
Taxiway Bravo	41	3,681.85	150,955.85
Taxiway Charlie	47	8,810.85	414,109.95
Total		23,534.70	984,661.80
Weighted Taxiways PCI	41.8		
Overall	**39.7**	307,669.55	12,202,225.10

4.1.2 Comparison of PCI Results from MicroPAVER by Inspection Report and FAA PAVEAIR Results

To verify the accuracy of the developed PAVEAIR database, the calculated PCI values were cross-referenced with the 2024 assessment report generated using MicroPAVER software. Since both platforms utilize the identical ASTM D5340 standard algorithms for distress deduction, their analytical outputs are expected to exhibit high concordance. As presented in Table 4.3, the results demonstrate a strong correlation between the two software environments. The overall network PCI differs by a marginal margin of -0.71 points (39.7 in PAVEAIR versus 40.41 in MicroPAVER), confirming the reliability of the digitized inventory. These minor positive variances are likely attributable to differences in how each platform handles internal rounding or sample unit aggregation. Ultimately, this validation confirms that the FAA PAVEAIR model is statistically robust and serves as a trustworthy baseline for subsequent deterioration modeling and maintenance planning.

Table 4.3 PCI Results from two different analysis platforms

Pavement use	MicroPaver PCI	FAAPAVEAIR PCI	Difference in PCI
Runway	38.45	40.37	+1.92
Apron	42.10	38.40	-3.7
Taxiway	40.70	41.80	+1.1
Overall	40.41	39.70	-0.71

4.1.3 Classifying KIA Pavement According to PCI Rating

The KIA pavement network was evaluated using the FAA PAVEAIR analysis and the ASTM D5340 rating scale, which the FAA uses for airport pavement strength reports. Table 4.4 shows that all pavement sections have a critical level of deterioration, with PCI values ranging from 38 to 42. These scores place the entire network in the “Poor” category. Because of this, preventive maintenance alone is insufficient, and the network is structurally compromised. Major rehabilitation is needed right away to restore serviceability and safety (FAA, 2014).

Table 4.4 KIA pavement PCI condition rating

Pavement use	FAAPAVEAIR PCI	ASTM PCI ranges	Pavement rating
Runway	40.37	40-55	Poor
Apron	38.4	25-40	Very poor
Taxiway	41.8	40-55	Poor
Overall	39.7	40-55	Poor

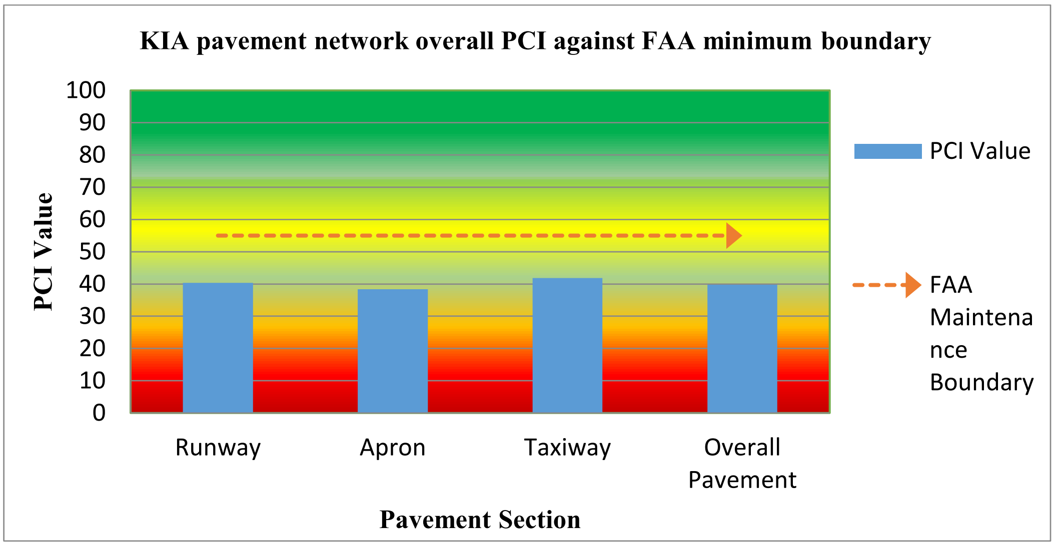


Figure 4.1 KIA pavement network PCI against the FAA minimum requirement

As illustrated in Figure 4.1, all pavements exhibit PCI values significantly below the established critical threshold of PCI 55, below which major M&R is the restoration treatment (Hajek et al., 2011). This threshold, designated by the FAA and other sources, such as Wesołowski & Iwanowski (2020), as the lower bound for preventive maintenance effectiveness, signifies a transition into accelerated structural deterioration. The fact that the overall pavement network (PCI 39.7) is nearly 15 points below this safety margin indicates that the window for cost-effective preservation has closed, given the maintenance triggers and treatments shown in Table 3.7 of section 3.2.5. Consequently, these results confirm that the current pavement condition poses a substantial operational risk and necessitates an immediate shift in strategy from routine maintenance to comprehensive rehabilitation to restore the network to a serviceable standard above the PCI 55 baseline.

4.2 KIA Pavement Structural Evaluation

This section presents a structural evaluation of the Kigali International Airport (KIA) pavement network, assessing its load-bearing capacity against current operational demands, given the current traffic mix. The analysis uses geotechnical and material data derived from the 2024 inspection report, including the coring survey, Dynamic Cone Penetrometer (DCP) tests, and Heavy Falling Weight Deflectometer (HFWD) test. Utilizing the FAA's FAARFIELD design software, thickness analysis was conducted for each pavement section across the Runway, Taxiway, and Apron to calculate the theoretical layer thickness required to support the current aircraft fleet. Although asphalt airport pavements are conventionally designed for a 20-year service life, as noted also from the Applied Research Associates, Inc. (2011), this study adopts a 10-year analysis period for all the analysis including thickness design to evaluate the immediate impact of the current aircraft mix on the pavement and to provide a more precise diagnosis of the current structural deficits identified. These design outputs were later compared against the existing pavement profiles documented in the 2024 inspection report. This comparative analysis quantifies the network's structural adequacy and identifies specific deficits in which the current pavement thickness is insufficient to sustain future traffic loads without accelerated failure.

4.2.1 Runway structural analysis

The structural capacity of the KIA Runway was evaluated using the FAA's design software, FAARFIELD 2.1.1. This evaluation involved modeling pavement layer configurations to match the airport's operational requirements. The specific KIA traffic fleet mix, including annual departure frequencies, drove the required structural profile shown in Figure 4.2. The results show that the pavement requires a cross-section comprising a 102 mm Hot Mix Asphalt (HMA) surface course, a 127 mm HMA-stabilized base, and a 351 mm crushed aggregate base to limit the Cumulative Damage Factor (CDF) to 1.0. The resulting profile represents the theoretical structural baseline required to support the current traffic volume and was subsequently compared with the existing in-situ pavement structure to quantify the magnitude of the structural deficit.

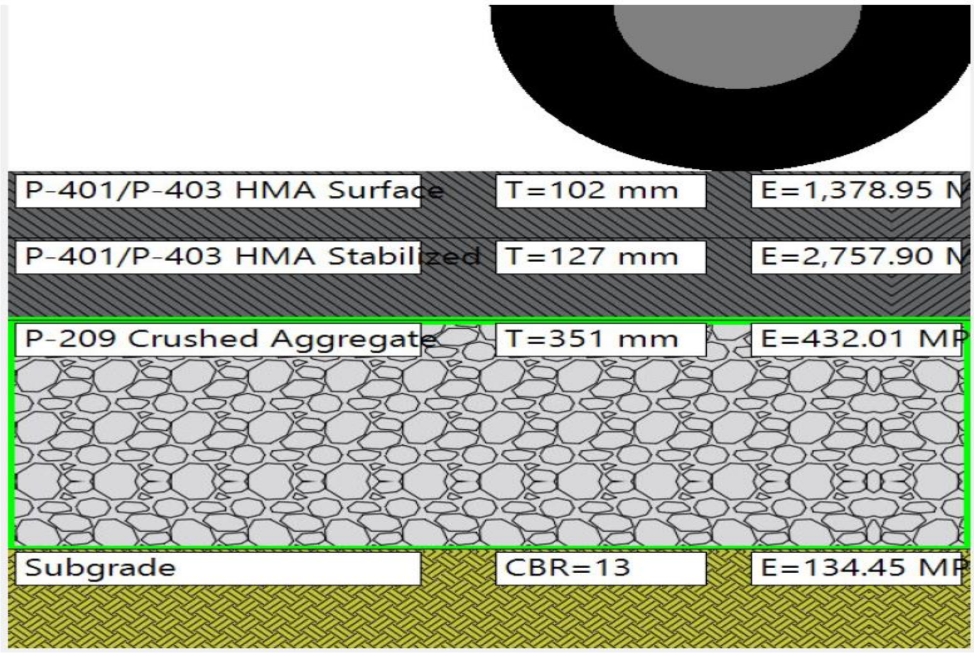


Figure 4.2 Required Runway pavement thickness to support the current traffic

Cumulative Damage Factor (CDF) Analysis was used to identify the critical loading patterns across the runway width. As illustrated in Figure 4.3, the CDF follows a standard bell-shaped distribution, peaked at the pavement centerline, with a value of 1.0, indicating that the pavement's entire structural fatigue life is consumed over the design period.

The CDF analysis Figure 4.3, reveals that the A330-900 (light blue curve) is the critical aircraft for the KIA runway, contributing the most significant magnitude of fatigue damage per pass. Other wide-body aircraft, such as the B787-9 (red curve) and B777-9 (green curve), also contribute significantly to the cumulative damage profile. This dominance of heavy, wide-body traffic confirms that the structural design must be governed by the load characteristics of these specific aircraft rather than the frequency of smaller regional jets.

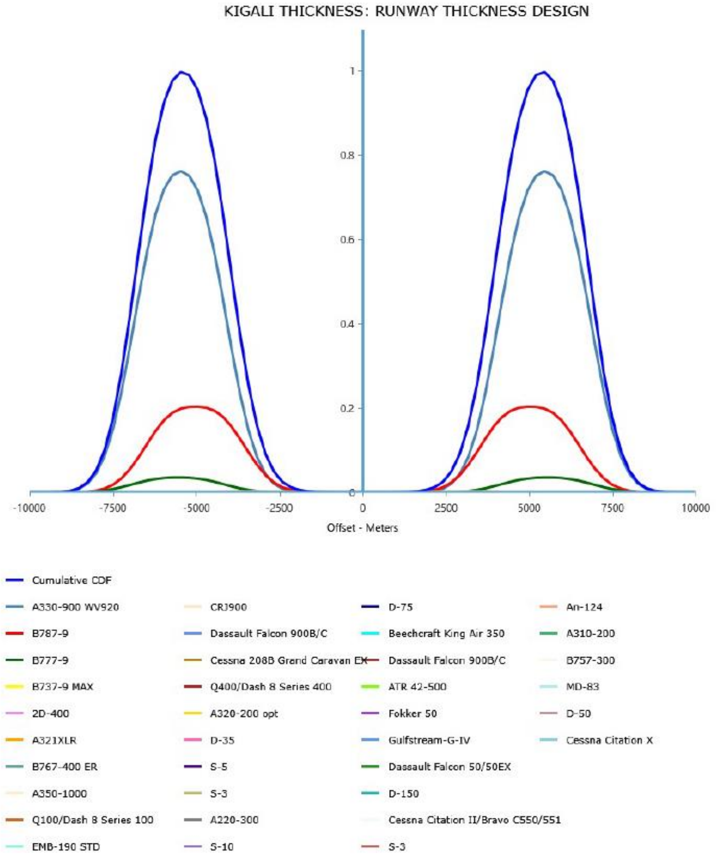


Figure 4.3 Runway Cumulative Damage Factor (CDF) showing the most damaging aircraft from the traffic mix

To quantify runway structural adequacy, the existing pavement profile was compared with the FAARFIELD-computed design thickness presented in Table 4.5.

The comparative analysis reveals a total structural shortfall of 90 mm in the overall pavement thickness, and the pavement profile is inadequate to protect the subgrade (CBR 13%) from vertical compressive strains throughout the pavement system.

Table 4.5 Runway structural deficiency analysis (10-Year design horizon)

Pavement layer	**Existing Thickness(mm)**	**FAARFIELD required Thickness(mm)**	**Structural deficit(mm)**
P-401 HMA Surface	70	102	-32
P-401 Stabilized Base	120	127	-7
P-209 Crushed Aggregate	300	351	-51
Total Structure	490	580	-90

The most critical issues are observed in the Crushed Aggregate Base layer, which is under-designed by 51 mm, and in the HMA Surface layer, which is under-designed by 32 mm. The current 70 mm asphalt surface is significantly thinner than the 102 mm needed to withstand the tire pressures and shear forces imposed by the critical A330-900 aircraft. This deficiency directly relates to the functional distress identified in the 2024 condition survey.

4.2.2 Apron Alpha Structural Analysis

The analysis indicates that while the existing Crushed Aggregate Base (450 mm) significantly exceeds the structural requirement (340 mm), the upper bituminous layers are under-designed. Specifically, the existing 90 mm HMA surface falls short of the required 102 mm, and the 110 mm HMA stabilized base is below the required 127 mm Figure 4.4.

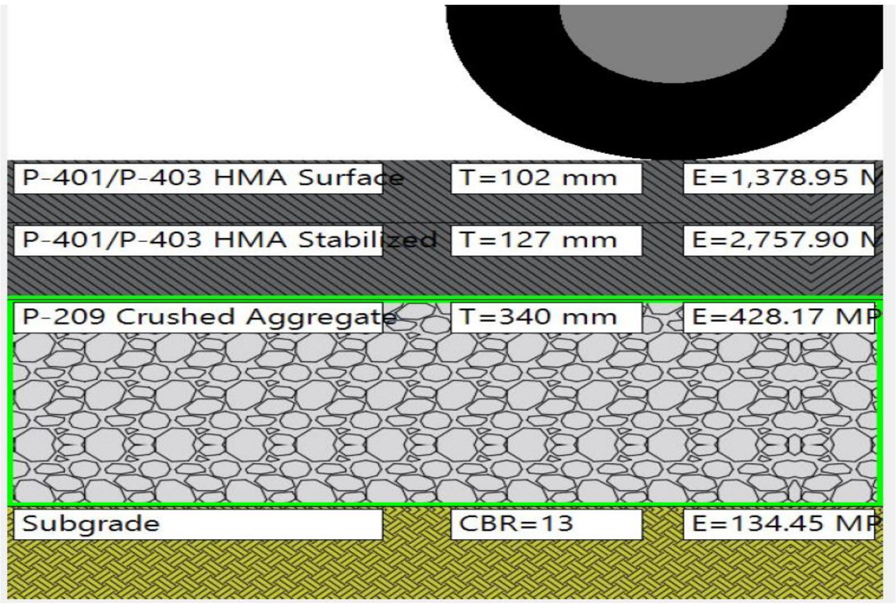


Figure 4.4 Required Alpha Apron pavement thickness to support the current traffic

The analysis of the Cumulative Damage Factor (CDF) distribution from Figure 4.5 indicates that structural demand is primarily driven by heavy wide-body aircraft, specifically the A330-900, B787-9, and B777-9, which serve as the critical load vehicles contributing to pavement fatigue.

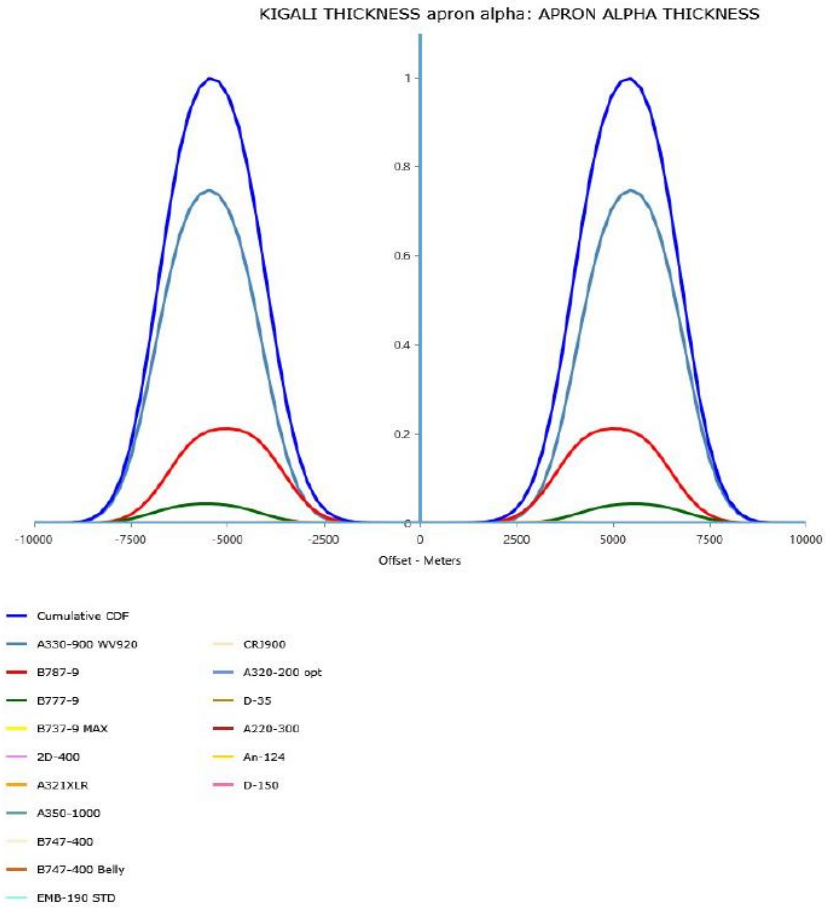


Figure 4.5 Alpha Apron Cumulative Damage Factor (CDF) showing the most damaging aircraft from the traffic mix

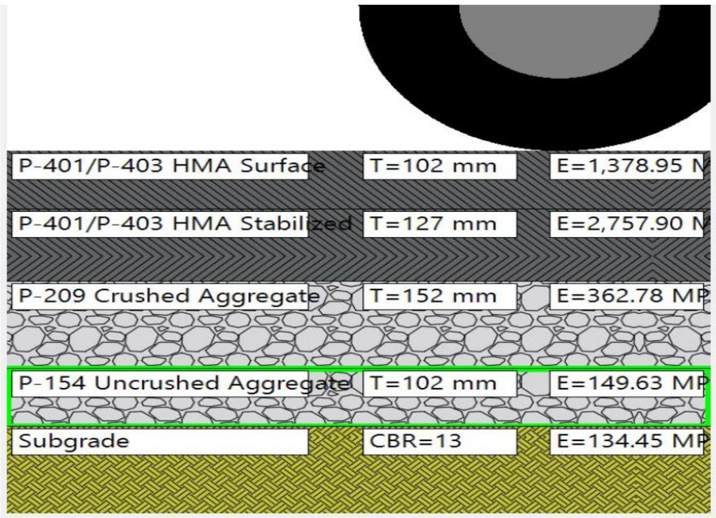
A comparative analysis of the existing profile and the theoretically required design structure in Table 4.6, highlights a critical deficiency in the asphalt pavement layers. Although the total pavement thickness (650 mm) exceeds the computed requirement (569 mm), the thickness of its asphalt layers compromises the pavement's structural capacity. The combined 29 mm deficit in the HMA and Stabilized Base layers indicates that the upper pavement structure lacks sufficient stiffness to resist the high tire pressures and shear stresses from parked heavy aircraft, likely accelerating surface fatigue and cracking observed in the condition survey.

Table 4.6 Alpha Apron structural deficiency analysis (10-Year design horizon)

Pavement layer	Existing Thickness(mm)	FAARFIELD required Thickness(mm)	Structural deficit(mm)
P-401 HMA Surface	90	102	-12
P-401 Stabilized Base	110	127	-17
P-209 Crushed Aggregate	450	340	110
Total Structure	650	569	81

4.2.3 Apron Bravo and Charlie Structural Analysis

A comparative analysis of the layer profile from **Table 4.7** shows that the existing bituminous layers (AC: 200 mm) exhibit a slight deficit relative to the designed (AC: 229 mm) value, totaling 29 mm. This is heavily compensated by the massive Uncrushed Aggregate Subbase, where the existing 400 mm thickness exceeds the design requirement of 102 mm by nearly 300 mm, as illustrated in Figure 4.6.



P-401/P-403 HMA Surface T=102 mm E=1,378.95 M
P-401/P-403 HMA Stabilized T=127 mm E=2,757.90 M
P-209 Crushed Aggregate T=152 mm E=362.78 MP
P-154 Uncrushed Aggregate T=102 mm E=149.63 MP
Subgrade CBR=13 E=134.45 MP

Figure 4.6 Required Bravo & Charlie Apron pavement thickness to support the current traffic

Table 4.7 Bravo & Charlie Apron structural deficiency analysis (10-Year design horizon)

Pavement layer	**Existing Bravo Thickness(mm)**	**Existing Charlie Thickness (mm)**	**FAARFIELD required Thickness(mm)**	**Structural deficit(mm)**
P-401 HMA Surface	100	100	102	-2
P-401 Stabilized Base	100	100	127	-27
P-209 Crushed Aggregate	150	150	152	-2
P- 154 Uncrushed Aggregate	400	400	102	298
Total Structure	615	615	483	132

The analysis of the Cumulative Damage Factor (CDF) distribution provides critical visual evidence of the strong pavement's bearing capacity, where in the CDF graph, the damage profile is exceptionally low, peaking at a maximum value of 0.25, Figure 4.7. Unlike the runway and apron Alpha where heavy wide-body aircraft created distinct spikes in fatigue consumption, this graph reveals that no individual aircraft type in the current mix generates considerable structural damage. This confirms that the existing pavement structure effectively distributes loads from the entire fleet without approaching failure.

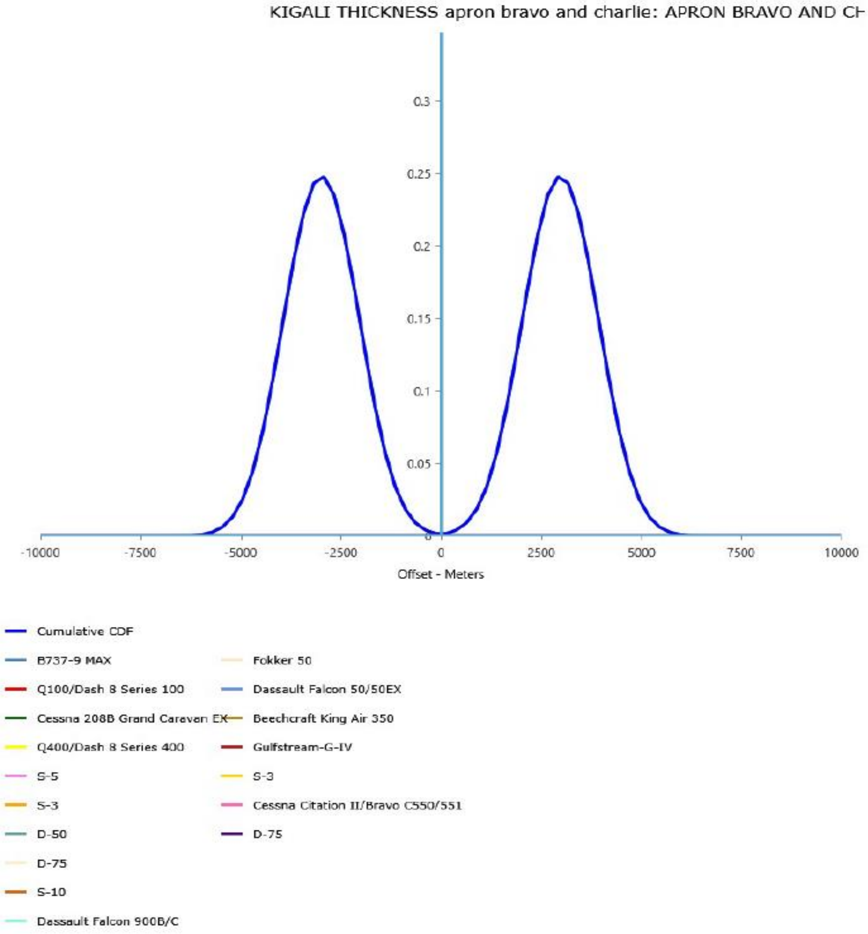


Figure 4.7 Bravo & Charlie Apron Cumulative Damage Factor (CDF) showing the most damaging aircraft from the traffic mix

This graphical evidence of a 0.25 computed CDF indicates that the traffic will consume only 25% of the pavement’s fatigue life over the next decade, leaving a substantial 75% reserve capacity. This concludes that the apron pavement is structurally adequate, indicating that the rapid deterioration observed in the condition analysis is attributable to non-structural factors, such as material durability or construction quality, rather than traffic-induced fatigue.

4.3 KIA Pavement Prediction Modelling

Following the establishment of the pavement inventory and the computation of PCI values within FAA PAVEAIR, this section presents the development of the pavement deterioration models. Applying the family curve methodology outlined in Section 3.2.3.2. Different prediction models were generated for the Runway, Taxiway, and Apron branches by performing regression analysis on historical construction and inspection data, yielding mathematical equations that define the performance trajectories of each pavement group. The following subsections outline the specific processes for generating model parameters that quantify the unique deterioration rates of each functional area within the KIA network.

For all the models developed, the blue dots represent valid inspection data collected from 2001 and 2024 inspections and used to generate the curves. Red triangles denote data points identified as outliers excluded to maintain prediction accuracy. The black-dashed lines indicate the upper and lower outlier thresholds set by the software filter. The solid red line shows the second-order polynomial model that best fits the runway's deterioration over time.

4.3.1 Runway Prediction Modelling

The pavement performance model for the KIA Runway **Figure 4.8** was developed through regression analysis in FAA PAVEAIR, using a historical dataset spanning over 40 years. Model development focused on four key data points: the initial construction in 1983, the 2001 inspection, the 2005 major rehabilitation, and the 2024 inspection. The model was generated using data from two primary sections: Runway End 10 and Runway End 28, both of which share an identical construction and maintenance timeline. In contrast, the Touchdown Zone section was excluded from the initial model generation process because its maintenance history diverged significantly from the rest of the runway following a localized patching intervention in 2019.

The model indicates a gradual decline in pavement condition, as the runway is currently 19 years old (since the 2005 rehabilitation) and has a weighted average PCI of 40.37. The model indicates that the pavement has already exceeded its critical service life, which has been below the crucial threshold for almost 4 years, and is now undergoing accelerated structural deterioration, underscoring the urgent need for major rehabilitation.

Figure 4.8 KIA Runway prediction model between the initial construction period (1983-2001, 18 years) and the post-rehabilitation period (2005-2024, 19 years).

4.3.2 Taxiways Prediction Modelling

To predict pavement performance across the KIA taxiway network Figure 4.9, a single deterioration curve was created and applied to Taxiways Alpha, Bravo, and Charlie. Because FAA PAVEAIR needs at least two past inspection points to build a valid model, Taxiway Bravo was chosen as the primary data source. Bravo was constructed in 1983, renovated in 2005, and inspected in 2001 and 2024, providing the necessary historical data. In contrast, Alpha and Charlie, both built in 2016 and not yet maintained, lacked sufficient inspection data to support the development of independent models. As a result, the Bravo model was applied to Alpha and Charlie, yielding a consistent performance trend across all three taxiways.

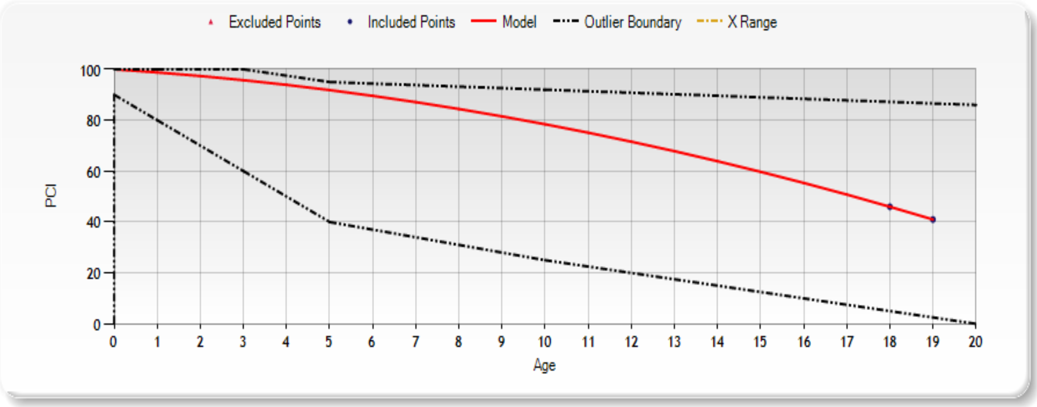


Figure 4.9 KIA Taxiway Prediction Model between the initial construction period (1983-2001, 18 years) and the post-rehabilitation period (2005-2024, 19 years).

The data demonstrate a consistent decline in pavement condition. Taxiway Bravo, now 19 years old after its 2005 rehabilitation, exhibits a PCI of 41, which corresponds to the model's classification of "Poor" condition. In comparison, the newer Taxiways Alpha and Charlie, each 8 years old, have PCIs of 38 and 47, respectively. All three values fall significantly below the established Critical PCI threshold of 55 determined in this study. This threshold marks the economic inflection point at which pavement deterioration accelerates, and the potential for cost-effective preventive maintenance is lost. To restore the structural integrity and operational safety of the airfield, a comprehensive rehabilitation program for the Taxiway Alpha, Bravo, and Charlie is recommended rather than continued routine maintenance.

4.3.3 Apron Prediction Modelling

To assess the apron network's predictive performance, a representative deterioration model was developed using historical data from the Main Apron Alpha section in Figure 4.10. This section was selected as the modeling baseline due to its structural and operational similarity to the broader network, sharing identical Asphalt Concrete (AC) layer thickness with Aprons Bravo and Charlie in addition to its comprehensive data availability. Unlike Aprons Bravo (constructed in 2016) and Charlie (constructed in 2020), which had only a single inspection data point from 2024, Apron Alpha provided a robust chronological profile spanning from its initial construction in 1983 through a major rehabilitation in 2005, with valid inspection points in 2001 and 2024.

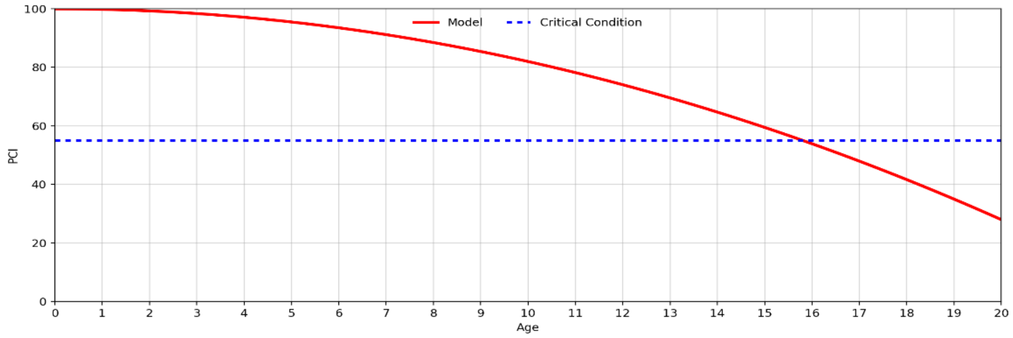


Figure 4.10 KIA Apron prediction model spanning between the initial construction period (1983–2001, 18 years) and the post-rehabilitation period (2005–2024, 19 years).

This performance curve, shown in Figure 4.10, was generated using a manual second-order polynomial equation: $y=100-0.18x^2$, where y is the PCI and x are pavement age in years, respectively. This approach was adopted to address regression instability, in which the automated solver failed to reconcile the steep drop in condition between the first inspection at age 18 (PCI 49) and the second inspection at age 19 (PCI 35) without violating the downward-only constraint's curve logic. The developed model FAA PAVEAIR strictly adheres to the mathematical regression framework defined in the FAA PAVEAIR documentation, which uses the general polynomial form of $y= \beta_0+\beta_1 x+\beta 2x^2$. By explicitly defining the coefficients (β_0=100, β_1=0 and β_2=-0.18), the model bypasses the solver error while maintaining the standard mathematical structure required by the software.

The apron model reveals a non-linear degradation pattern, with the pavement maintaining relatively stable performance for approximately 15 years before entering a phase of accelerated structural decay that has rapidly depressed the condition to its current PCI of 35. This indicates that the window for cost-effective preventive maintenance has been closed, and the asset now requires major rehabilitation to address deep-seated structural fatigue.

4.4 KIA Pavement Condition Analysis

This section presents a detailed performance evaluation of the entire KIA pavement network, including the Runway, Taxiway, and Apron branches. Using the branch-specific deterioration models from Section 4.3, the analysis reconstructs each pavement section's full lifecycle by applying predicted performance curves to its construction and maintenance histories. The graphs assess the effectiveness of past maintenance practices and quantify the current rate of structural degradation. By pinpointing the exact timing of critical failure points, these condition profiles create a data-driven baseline for predicting and prioritizing the Maintenance and Rehabilitation (M&R) interventions needed to maintain airport operations over the next 10 years.

4.4.1 Runway Condition Analysis

The functional integrity of the KIA runway was evaluated through a comprehensive condition analysis, tracing the pavement's performance from its original commissioning in 1983 through the 2024 inspection cycle. By applying the validated deterioration models to the specific maintenance timelines for the Runway End 10, End 28, and Touchdown Zone sections, this assessment calculates historical rates of decay and visually quantifies the impact of past interventions, such as the 2005 major rehabilitation and the localized 2019 repairs. These conditions serve as a vital diagnostic tool, revealing specific periods during which maintenance was delayed and establishing a data-driven baseline to justify the critical rehabilitation measures required to restore the airfield's condition. The condition analysis graph uses color-coded lines to represent distinct performance as follows:

- **The red line**: Depicts the actual, modeled deterioration of the pavement PCI over time. The vertical jump in the red line (around 2005) signifies the restoration of pavement condition to PCI 100 following the major rehabilitation.
- **The solid green horizontal line**: Represents the established critical PCI threshold of 55.
- **The yellow arrow**: Marks the intersection of the deterioration curve with this green line (Critical threshold) and identifies the exact point in time when the pavement structurally failed or is predicted to fail.

4.4.1.1 Runway End10 Section Condition Analysis (1983-2024)

The condition history of the Runway End 10 section was assessed using the runway-validated deterioration model based on the section's construction and maintenance timeline. The analysis, shown across two distinct operational phases in Figure 4.11, highlights a repeating pattern of pavement deterioration and delayed intervention. Pavement performance between 1983 and 2005, covering the initial lifecycle after the 1983 construction, indicates a consistent rate of decline. As seen in the historical graph, the condition dropped below the critical PCI threshold of 55 around 14 years into service (1997). Despite crossing this safety threshold, major rehabilitation was postponed for another eight years. During this time, the PCI fell to a critical low of 35 by 2005, showing that the section was allowed to deteriorate into severe structural failure before the major rehabilitation in 2005 restored the PCI to 100.

The observed rapid initial decline in PCI from 100 to 95 following the 2005 rehabilitation is attributed to the aggressive operational environment at Runway End 10, which functions as the primary turnaround zone for the network. Unlike linear runway sections, this area is subjected to intense near-surface shear forces generated by aircraft executing turning maneuvers and braking (You et al., 2019). As defined in FAA AC 150/5380-6B, these lateral stresses can cause slippage cracking a form of surface deformation that occurs when turning wheels shear the pavement surface, often exposing deficiencies in layer bonding or asphalt mixture strength

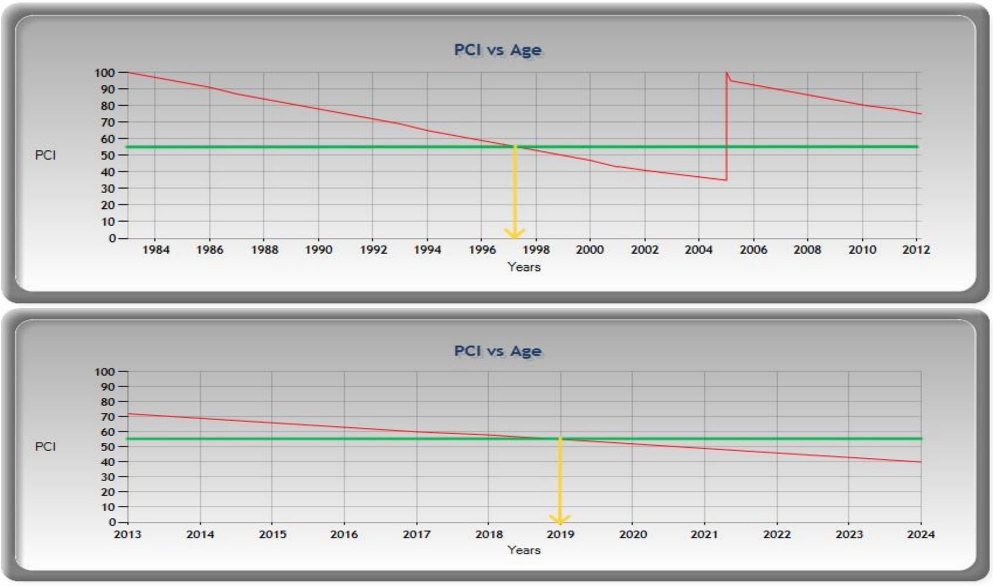


Figure 4.11 Runway End10 section condition analysis (1983-2024)

Current performance (2005-2024) of the post-rehabilitation lifecycle shows a recurring deterioration trend. Analysis of the past decade reveals that pavement performance again dropped below the critical PCI 55 threshold around 2019. Since then, the condition has continued to deteriorate to the current 2024 PCI value of 40. This confirms that Runway End 10 has been in poor condition for about 5 years, emphasizing the urgent need for a second major rehabilitation to address the increasing damage.

4.4.1.2 Runway End28 Section Condition Analysis (1983-2024)

The condition analysis for the Runway End 28 section was conducted at the section level within FAA PAVEAIR by superimposing the runway-validated prediction model onto its specific maintenance timeline, spanning from initial construction in 1983 to the present.

The analysis reveals two distinct deterioration cycles. In the first cycle (1983-2005), the runway reached the critical PCI 55 threshold approximately 10 years after construction (around 1993). The sharp PCI decline observed between 2001 and 2005 illustrates how deterioration accelerates rapidly once pavement integrity falls below the 55 thresholds. In addition to that, it proves the effects of a delayed maintenance where major rehabilitation was delayed until 2005, forcing the airport to operate on significantly degraded pavement for nearly 8 years. In the current cycle (post-2005), the model indicates the runway End28 section again crossed the critical threshold mid-2018 as shown in Figure 4.12.

Figure 4.12 Runway End28 section condition analysis (1983-2024)

This confirms that the runway End28 section is currently operating in a poor condition state (PCI 38) and has been structurally compromised for approximately 5 years. The steep slope of the red line in the final years highlights an accelerated rate of deterioration, underscoring the urgent necessity for major rehabilitation rather than superficial repairs to restore operational standards.

4.4.1.3 Runway Touchdown Section Condition Analysis (1983-2024)

The condition analysis of the Runway Touchdown Zone, using the validated runway deterioration model, monitors the pavement's structural health from its initial construction in 1983 through various lifecycle stages. Like other runway sections, the Touchdown Zone showed a steady decline after its initial construction. The analysis reveals that the pavement crossed the critical PCI threshold of 55 around 1997, remaining structurally deficient for nearly 8 years until a major rehabilitation in 2005 restored the PCI to 100, Figure 4.13.

Figure 4.13 Runway Touchdown zone condition analysis (1983-2024)

The post-2005 lifecycle highlights the impact of targeted maintenance. As the section deteriorated over time, it approached the critical PCI 55 threshold again in 2019. At this crucial stage, a localized patching maintenance intervention was executed as shown in the condition graph. This 2019 intervention created a vertical jump in the condition curve, effectively boosting the PCI back above the critical line and extending the section's service life. However, this relief was temporary; the deterioration trend continued, and the section crossed the critical threshold again at the end of 2020.

With the current 2024 inspection recording a PCI well below 55, the analysis confirms that while the 2019 patching provided a short-term life extension, the pavement section has now returned to a poor condition, necessitating comprehensive rehabilitation alongside the rest of the runway.

4.4.2 Apron Condition Analysis

This section details the functional performance evaluation of the KIA apron branch, including the Main Apron Alpha, Apron Bravo, and Apron Charlie. By applying the validated deterioration model derived from the long-term behavior of Apron Alpha to each section's construction timeline, condition profile graphs were generated to map the pavement from initial construction through the 2024 inspection. These graphical analyses serve as a critical diagnostic tool, revealing distinct deterioration patterns ranging from long-term fatigue in aging infrastructure to premature structural failure in recently constructed expansions. These findings quantify current operational risks and provide a data-driven baseline to define the scope of urgent rehabilitation required to restore network serviceability.

4.4.2.1 Apron Alpha Condition Analysis (1983-2024)

The condition history of Apron Alpha was evaluated using the validated manual deterioration model, as visualized in the performance graphs in Figure 4.14. The analysis reveals a clear pattern of structural decline across two distinct life cycles separated by the major rehabilitation in 2005. Following the 1983 construction, the pavement exhibited accelerating deterioration crossing the critical PCI threshold of 55 approximately 16 years into service, around 1999. Despite exceeding this safety margin, major rehabilitation was not undertaken until 2005, which kept the apron in a structurally deficient state; PCI declined to a low of 20 before the 2005 intervention restored it to 100. The quick drop in PCI observed between 2001 and 2005 visually confirms the Critical Condition theory, where the rate of deterioration accelerates so fast once the pavement integrity falls below the critical threshold of 55. Hence, the graph demonstrates how missing the window for preventive maintenance around 1999 allowed the pavement to collapse into a failed condition.

Figure 4.14 Apron alpha condition analysis (1983-2024)

The condition graph indicates that the pavement maintained serviceable performance for approximately 13 years before crossing the critical PCI 55 threshold again around 2018. After that, the condition continued to decline sharply, reaching the 2024 level of PCI 35. This indicates that Apron Alpha has been in poor to very poor condition for approximately six years, underscoring that the pavement section is well beyond the scope of preventive maintenance and requires immediate, major rehabilitation to address severe structural fatigue.

4.4.2.2 Apron Bravo Condition Analysis (2016-2024)

The condition analysis of Apron Bravo evaluates pavement performance using the assigned deterioration model. As illustrated in Figure 4.15, the analysis reveals a quick decline in pavement functional performance over a relatively short operational period. From the initial PCI value of 100 in 2016, the deterioration curve (red line) trends sharply downward, intersecting the critical PCI threshold of 55 (solid green line) in late 2021. This intersection, highlighted by the yellow vertical arrow, indicates that the pavement had a serviceable life of only six years before transitioning to a structurally deficient condition.

Figure 4.15 Apron Bravo condition analysis (2016-2024)

The analysis confirms that Apron Bravo has been in poor condition for about two years. This fast deterioration, happening much sooner than the typical 15-20 years lifespan of airfield asphalt pavement, indicates early structural fatigue, making preventive maintenance ineffective and requiring urgent, extensive rehabilitation to restore operational capability.

4.4.2.3 Apron Charlie Condition Analysis (2020-2024)

The condition analysis of Apron Charlie tracks the performance of the newest pavement section in the network, spanning from its construction in 2020 to the 2024 inspection. The condition graph in Figure 4.16 shows a severe rate of deterioration that deviates significantly from standard pavement lifecycle expectations. The performance curve (red line) depicts a steep decline, falling from a PCI of 100 in 2020 to a poor rating in less than three years. The intersection with the critical PCI threshold of 55 (solid green line), marked by the yellow vertical arrow, occurred in late 2022. This indicates that the pavement provided a serviceable life of fewer than three years before becoming structurally deficient.

Figure 4.16 Apron Charlie condition analysis (2020-2024)

With the trendline continuing to drop well below the critical threshold by 2024, severe premature failure is likely due to construction quality issues or structural underdesign relative to actual traffic loads, necessitating urgent intervention.

4.4.3 Taxiway Condition Analysis

This section provides a detailed assessment of the functional performance of the KIA taxiway branch, including Taxiways Alpha, Bravo, and Charlie. Using the validated deterioration model calibrated from the historical performance of Taxiway Bravo and applied to the entire branch, condition graphs were created to illustrate the structural behavior of each pavement section from its initial construction through the 2024 inspection. These graphical analyses offer a comprehensive diagnostic tool for visualizing the current condition of the pavement and assessing the timing and effectiveness of past maintenance practices. By identifying the specific timeline of structural failure, these findings establish the essential baseline needed to justify the immediate rehabilitation interventions proposed later in this study.

4.4.3.1 Taxiway Alpha Condition Analysis (2016-2024)

The condition analysis of Taxiway Alpha assesses the pavement performance from its construction in 2016 to the present, using the assigned deterioration model. As shown in Figure 4.17, the analysis graph indicates a rapid decline in pavement functional capabilities. Starting with a theoretical PCI of 100 in 2016, the deterioration curve (red line) drops steeply, crossing the critical PCI threshold of 55 (green line) in late 2021, as marked by the yellow vertical arrow.

Figure 4.17 Taxiway Alpha condition analysis (2016-2024)

This crossing point suggests that the pavement provided a serviceable life of only approximately 6 years before becoming functionally deficient. With the curve continuing to trend downward into 2024 (current PCI 38), the analysis confirms that

Taxiway Alpha has failed prematurely and has been in poor condition for nearly two years, necessitating urgent rehabilitation despite its relatively recent construction.

4.4.3.2 Taxiway Bravo Condition Analysis (1983-2024)

As visualized in the condition performance graphs of its operational timeline, the Bravo taxiway pavement exhibits two distinct life cycles, each characterized by a period of steady decline followed by deferred intervention. In the first life cycle, the taxiway performance deteriorated at a predictable rate. The analysis indicates that the pavement crossed the Critical PCI threshold of 55 at 15 years (1998), as shown in Figure 4.18. Despite entering this critical state, major rehabilitation was not executed until 2005. This delay forced the taxiway to operate in a structurally deficient condition for nearly 7 years before the 2005 intervention, which restored the PCI to 100.

Figure 4.18 Taxiway Bravo condition analysis (1983-2024)

The second lifecycle after the 2005 rehabilitation, as shown in the condition graph, indicates that the taxiway remained serviceable for about 14 years before crossing the Critical PCI 55 threshold again in late 2019. Since reaching this critical point, the condition has continued to deteriorate until 2024 inspection, with PCI 41. This demonstrates that Taxiway Bravo has been in poor condition for roughly five years, highlighting the need for immediate major rehabilitation to address the accumulated deterioration.

4.4.3.3 Taxiway Charlie Condition Analysis (2016-2024)

The condition analysis of Taxiway Charlie assesses the pavement's performance from its construction in 2016 through the 2024 inspection, based on the assigned deterioration model. As shown in the condition history graph in Figure 4.19, the analysis indicates a steady structural decline over its eight-year service life. The red deterioration curve shows a sharp downward trend from the initial PCI of 100. The point where it intersects the critical PCI threshold of 55 (solid green line) is marked by the yellow vertical arrow, indicating that the pavement entered a critical condition around late 2022, approximately 7 years after construction.

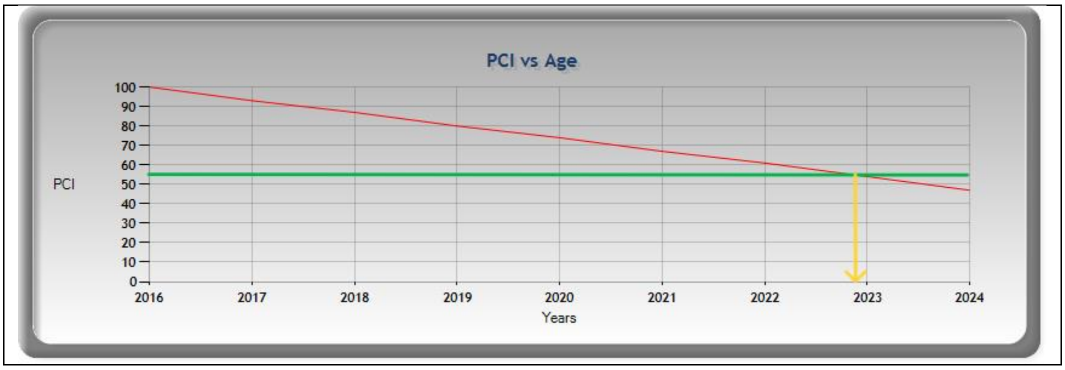


Figure 4.19 Taxiway Charlie condition analysis (2016-2024)

This crossing point shows that the taxiway operated at an acceptable standard for about 7 years, with the latest 2024 inspection recording a PCI of 47. The analysis confirms that Taxiway Charlie is now in poor condition and has been experiencing a functional deficiency for over a year. This rapid deterioration indicates a premature surface failure, requiring immediate major rehabilitation to prevent further rapid degradation.

4.4.4 KIA Past Maintenance Practice from Pavement Condition Analysis

The comprehensive condition analysis of the KIA pavement network indicates a historically reactive, rather than proactive, maintenance approach, characterized by major interventions only after structural or functional failure occurs. Standard pavement management principles recommend a cyclical intervention strategy to keep pavements in serviceable condition in a cost-effective way. Typically, preventive maintenance should be performed every 3 to 5 years to address early environmental wear, while minor rehabilitation is usually scheduled between 10 to 12 years to restore surface friction and ride quality before structural damage develops (Smith et al., 2024). This proactive cycle aims to keep the PCI well above the critical threshold, extend the pavement's lifespan, and maximize return on investment.

However, the historical performance curves for KIA show that these critical maintenance windows were mostly missed. For example, the analysis of Apron Alpha provides clear evidence where the pre-2005 performance curve shows a steady decline over 18 years (1983-2001). The lack of intermediate interventions allowed the pavement to deteriorate well below the Critical PCI, forcing the airport to operate on failed pavement for nearly 8 years before the 2005 rehabilitation was initiated.

In conclusion, the overall network condition analysis confirms that the historical reliance on a "run-to-failure" strategy has caused faster deterioration, leading to costly repairs that could have been avoided with timely, lower-cost preservation treatments.

4.5 Application of Different M&R Scenarios Using FAA PAVEAIR

This section presents a detailed analysis of four distinct maintenance and rehabilitation (M&R) scenarios using FAA PAVEAIR, which has been selected to align with Rwanda's economic realities as a developing nation, where optimizing limited resources is critical. The simulations range from the Unlimited Budget, which establishes the unconstrained funding baselines required for maximum performance, to the Minimum Condition strategy, which sets a rigid performance floor to prevent structural degradation. These are contrasted against strictly constrained strategies such as the Limited Budget ($1M Annually), representing a minimal survival expenditure cap, and the Consequence of Local Repair (CLR), a safety-centric strategy designed to secure operational continuity at the lowest feasible cost. Over a 10-year analysis period (2025-2035) for analysis conducted in 2025 and (2026-2036) for analysis conducted in 2026, each scenario is evaluated to forecast the required budget, define specific maintenance and rehabilitation (M&R) treatments, and quantify the resulting improvement in the Pavement Condition Index (PCI).

Table 4.8 presents the Pavement Condition Index (PCI) for each section from 2024 to 2026, derived from condition analysis. Due to FAA PAVEAIR restrictions requiring analysis to begin on the current date, the ten-year analysis windows vary slightly. Projections cover either 2025-2035 or 2026-2036, depending on whether the specific section was analyzed in late 2025 or early 2026.

Table 4.8 PCI for 2024 to 2026 from the condition analysis of each pavement section

Pavement sections	PCI 2024	PCI 2025	PCI 2026
Runway END10	40	38	36
Runway END28	38	36	34
Runway TDZ	42	39	37
Apron Alpha	35	28	21
Apron Bravo	40	33	26
Apron Charlie	38	31	24
Taxiway Alpha	38	36	34
Taxiway Bravo	41	39	37
Taxiway Charlie	47	42	40

It is noted that despite recent construction in 2016 and 2020, Aprons Bravo and Charlie show abnormally rapid deterioration, having already declined to poor condition (PCI 38-40) in 2024 and dropping 7 PCI each year. FAARFIELD analysis confirmed that the pavement thickness is structurally adequate for current aircraft, explicitly ruling out under-design or overloading as causes. Consequently, this premature failure is attributed to poor construction practices and low-quality materials, which have severely compromised the pavement's durability compared to standard lifecycle expectations.

4.5.1 Unlimited Budget M&R Scenario

In this scenario, the entire KIA pavement network is evaluated under an unconstrained funding model for the 10-year analysis period (2025-2035). The PAVEAIR policy configuration in this scenario requires that all required maintenance activities be triggered immediately, without financial constraints. The Unlimited Budget scenario functions as an unconstrained needs assessment, estimating the total capital required to address all network deficiencies immediately. Its calculation engine relies on the determine budget consequences framework within FAA PAVEAIR, which is configured through two primary features: Plan Mode and Policy & Costs.

In plan mode, the strategy is set to trigger the full spectrum of interventions:

- Localized maintenance (both above and below critical PCI)
- Global Maintenance (surface treatments), and
- Major M&R (rehabilitation/reconstruction).

To estimate the required budget and treatments for these interventions, the software utilizes the policy and cost settings in the following manner:

- **Distress-based calculation (M&R Families)**: This policy is applied to localized maintenance (safety and preventive). For every section, PAVEAIR identifies existing distresses (e.g., High-Severity Alligator Cracking) and maps them directly to a specific work code (e.g., PA-AD: Patching - AC Deep) and unit cost. This generates the stopgap and preventive budget needs based on actual field defects.
- **Condition-based calculation (Default cost by PCI):** For structural interventions, the software utilizes the default cost by PCI matrix as shown in Table 4.9. This feature assigns a unit cost ($\$/\text{m}^2$) to pavement sections based on their PCI range rather than specific distresses. For example, a section with a PCI between 0-40 falls into the major M&R airfield category, triggering a reconstruction cost of $\$90.31/\text{m}^2$.

Table 4.9 Cost by PCI default values used by Unlimited Budget M&R strategy for Major M&R (FAA PAVEAIR, 2021)

Name	**Unit**	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
Localized < Critical	m^2	13.35	4.84	1.51	0.54	0.32	0.22	0.22	0.11	0	0	0
Localized > Critical	m^2	6.14	5.06	4.52	2.48	1.51	0.86	0.43	0.22	0.11	0.11	0
Major M&R Airfield	m^2	90.31	90.31	90.31	90.31	90.31	19.16	17.87	17.22	13.67	13.56	0

- **Immediate implementation**: By activating the apply policy in the first-year option, the algorithm forces all triggered treatments, whether distress-based repairs or PCI-based reconstructions, to be scheduled immediately in the first year (Year 1).

- **Default work consequences (The mechanism of PCI estimation):** The default work consequence matrix serves as the fundamental engineering logic that enables PAVEAIR to accurately estimate the post-intervention Pavement Condition Index (PCI). This feature operates by mapping specific repair codes to quantifiable reductions in distress severity, specifically downgrading defects from high to medium or medium to low severity. Crucially, this stepwise reduction in severity lowers the associated deduct values, which provides the necessary data for the software to recalculate the pavement's structural rating and generate the new PCI following the intervention.

4.5.1.1 Runway End10 Unlimited Budget M&R Scenario

Under the Unlimited Budget scenario, the Runway End 10 section with the area of (105,525.85 m²) was evaluated starting from a failed condition with a PCI of 38 in 2025. Given the unconstrained funding parameters, the PAVEAIR simulation immediately triggered a Major Rehabilitation event totaling $9.53 million, as shown in Figure 4.20, effectively overriding minor localized repair policies to reconstruct the structurally deficient pavement. Major rehabilitation is generally described as a pavement construction that removes and replaces the pavement surface, thus resetting the PCI value to 100 and the pavement age to 0. Typical policies include full- and partial-depth reconstruction and mill and overlay (Florida Department of Transportation, 2022).

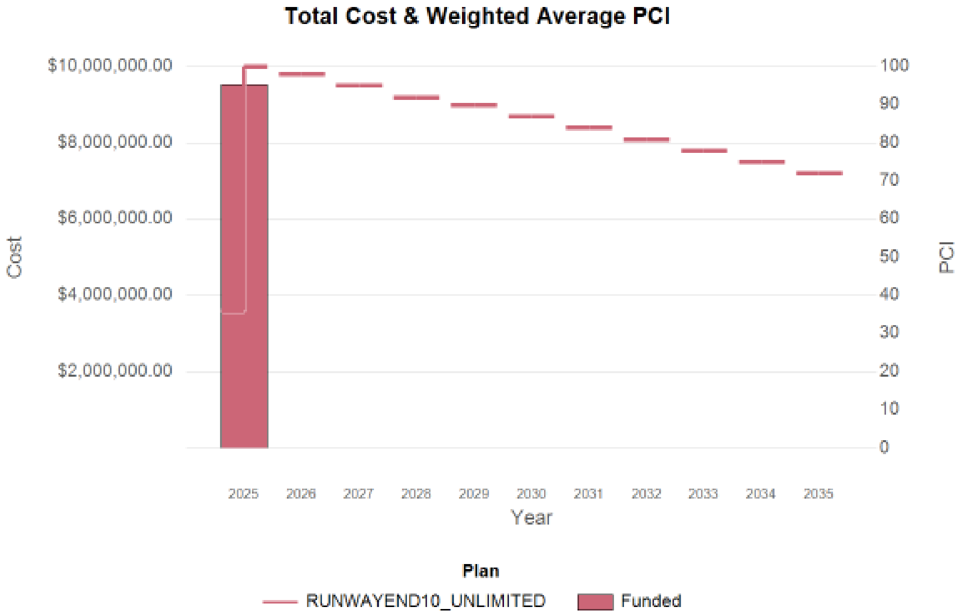


Figure 4.20 Runway End10 section maintenance Cost and PCI gained under an unlimited budget M&R scenario.

This vital intervention reset the pavement lifecycle, increasing the PCI to 100 and clearing the maintenance backlog within the first year. During the subsequent analysis period, the pavement followed a natural deterioration pattern, ending the cycle at a PCI of 71, a condition that requires no further capital investment.

4.5.1.2 Runway End28 Section Unlimited Budget M&R Scenario

Runway End 28 enters the analysis period in a structurally failed state with a PCI of 36 in 2025. Under the Unlimited Budget parameters, this critical deficiency triggers an immediate Major Rehabilitation event in 2025, requiring a capital investment of $1,036,384 as shown in Figure 4.21. This intervention effectively resets the pavement lifecycle, raising the PCI to 100 and ensuring a satisfactory terminal condition of 72 by 2035.

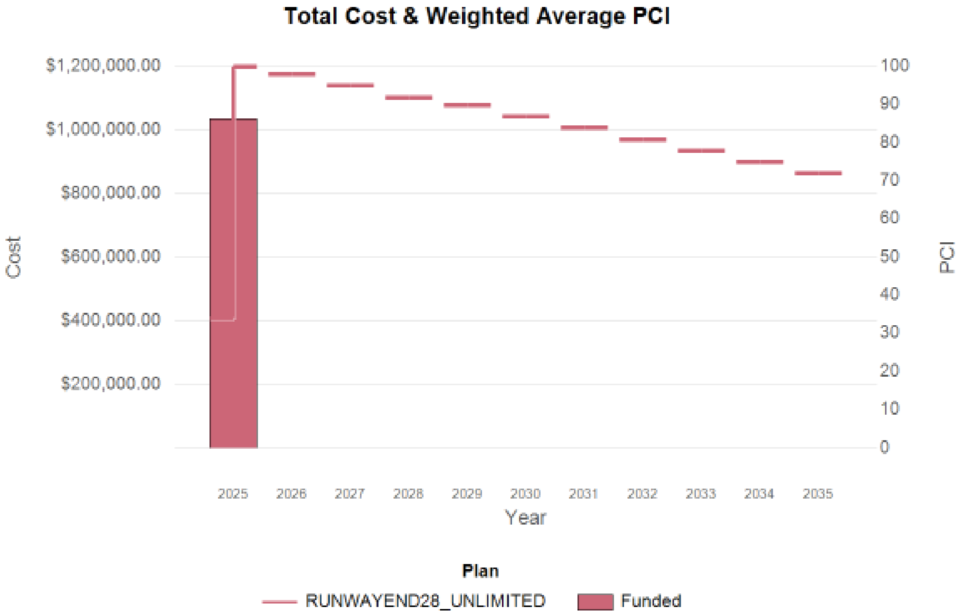


Figure 4.21 Runway End28 section maintenance Cost and PCI gained under an unlimited budget M&R scenario.

Note that while the failure mode and treatment strategy are similar to those for Runway End 10, the required budget is roughly nine times lower ($1.04 million vs. $9.53 million). This significant cost difference is solely due to the geometric differences between the sections: Runway End 28 has a much smaller surface area (11,475.85 m²) compared to Runway End 10 (105,525.85 m²).

4.5.1.3 Runway Touchdown Zone Unlimited Budget M&R Scenario

Based on analysis of the Runway Touchdown Zone (40,500.85 m²) under the Unlimited Budget scenario, the simulation indicates a critical structural deficiency at the start of the planning period, with a PCI of 39 in 2025. This suggests that, despite documented repairs in 2019, the section deteriorated to be in very poor condition within five years, necessitating major rehabilitation rather than minor preservation. As a result, the unconstrained model allocates a total capital investment of $3,657,631.75 in the first year to rebuild the section, Figure 4.22. This substantial intervention immediately restores the PCI to 100, effectively removing the structural backlog and creating a durable deterioration curve that preserves a satisfactory terminal PCI of 72 by 2035.

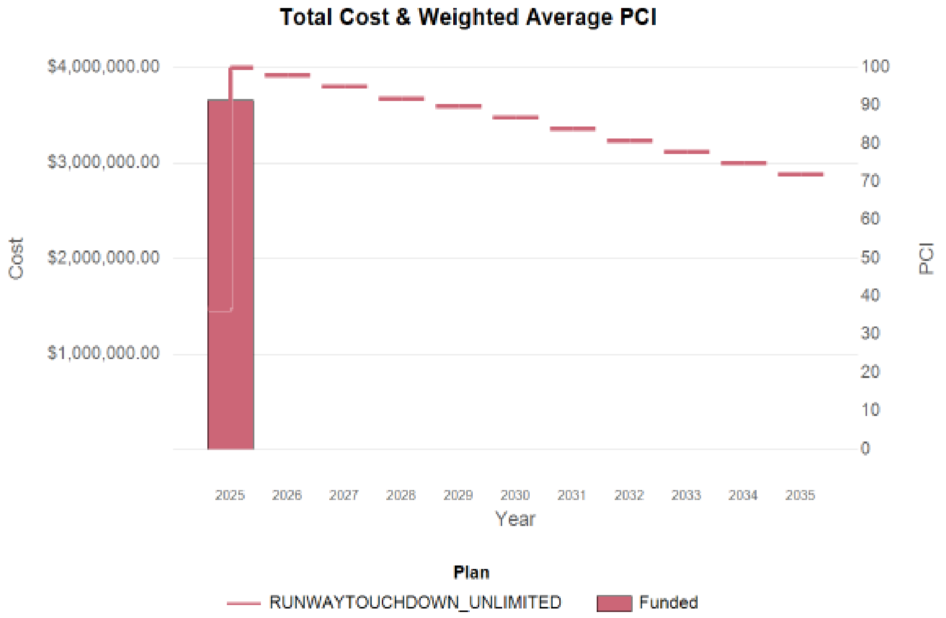


Figure 4.22 Runway Touchdown Zone section maintenance Cost and PCI gains under an unlimited-budget M&R scenario.

4.5.1.4 Apron Alpha Unlimited Budget M&R Scenario

Based on the analysis of Apron Alpha Main (45,376.00 m²) under the Unlimited Budget scenario, the simulation identifies this section as the highest priority in the network, starting the 2025 analysis period in a serious condition with a PCI of 28. This severe deterioration, well below the structural failure threshold, necessitates an immediate Major Rehabilitation, leading to a substantial capital investment of $4,097,906.50 in the first year as shown in Figure 4.23.

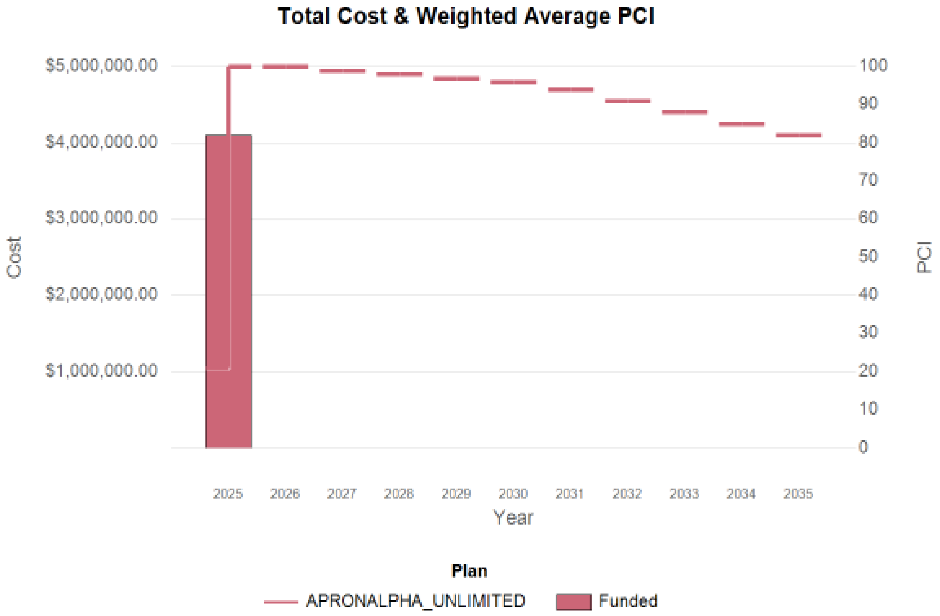


Figure 4.23 Apron Alpha maintenance Cost and PCI gains under an unlimited-budget M&R scenario.

This intervention effectively restores the pavement, raising the PCI to 100 and creating a strong performance curve that gradually declines to 82 by 2035.

4.5.1.5 Apron Bravo Unlimited Budget M&R Scenario

The evaluation of Apron Bravo indicates severe structural distress, with the 28,756 m² section entering the 2025 planning cycle in a debilitated state at PCI 33. To reverse this condition, the unlimited budget model mandates a decisive front-end capital of $2,596,954.25 for major rehabilitation in the first year, as shown in Figure 4.24. This investment serves as a complete system reset, instantly elevating PCI to 100 and maintaining high operational performance, sustaining a PCI rating of 82 through the end of the decade without requiring further expenditures.

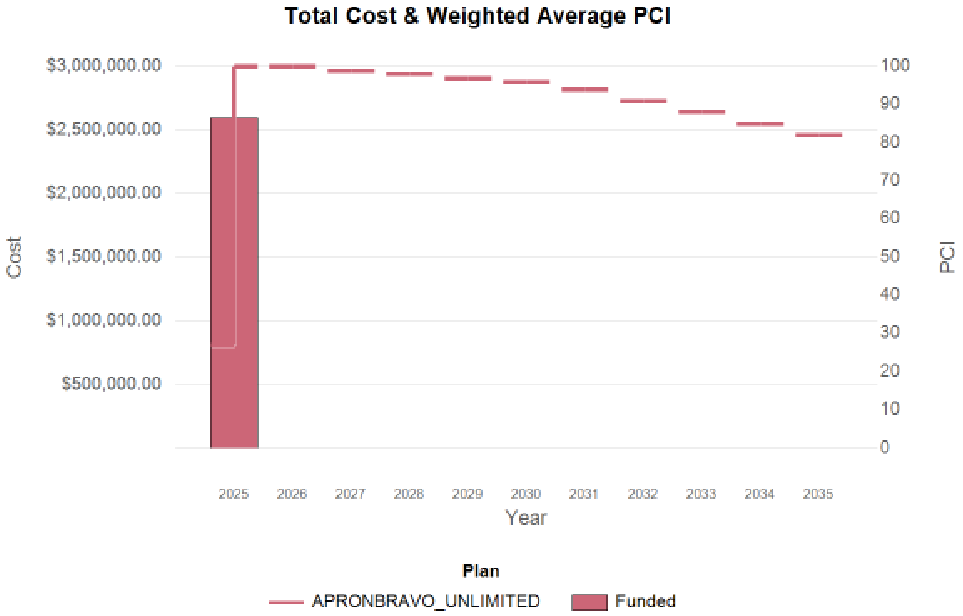


Figure 4.24 Apron Bravo maintenance Cost and PCI gains under an unlimited-budget M&R scenario.

4.5.1.6 Apron Charlie Unlimited Budget M&R Scenario

Based on the analysis of Apron Charlie (42,001.00 m²) under the Unlimited Budget scenario, the simulation indicates a severe structural deficiency at the start, with the section rated in serious condition, with a PCI of 31, in 2025, triggering an immediate requirement for Major Rehabilitation. The unconstrained model consequently allocates $3,793,110.25 in capital investment in the first year to reconstruct the pavement as shown in Figure 4.25. This intervention resets the asset to a PCI of 100, establishing a durable performance curve that degrades gradually to the terminal condition of 82 by 2035, requiring no further significant expenditure during the analysis decade.

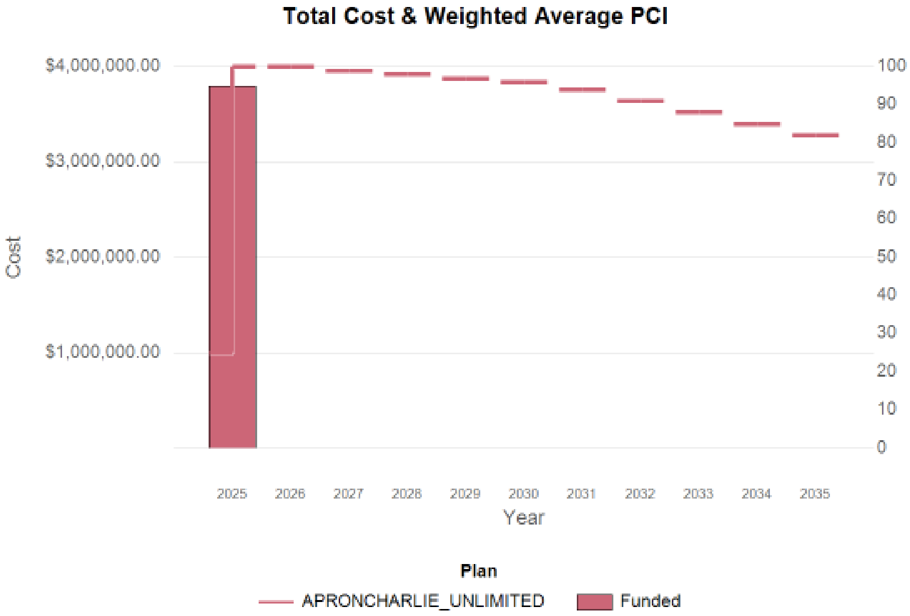


Figure 4.25 Apron Charlie maintenance Cost and PCI gains under an unlimited-budget M&R scenario.

4.5.1.7 Taxiway Alpha Unlimited Budget M&R Scenario

The evaluation of Taxiway Alpha reveals a critical structural failure, with the section showing a PCI of 36 in 2025. Consistent with the network-wide trend, the unconstrained model triggers an immediate Major Rehabilitation to rectify this deficiency, restoring the pavement to a perfect PCI of 100 and maintaining a condition of 78 through 2035. This intervention requires the lowest capital investment of any previous runway and apron section, totaling $997,112.69, as shown in Figure 4.26. This cost is driven by the section’s geometric area of (11,041 m^2).

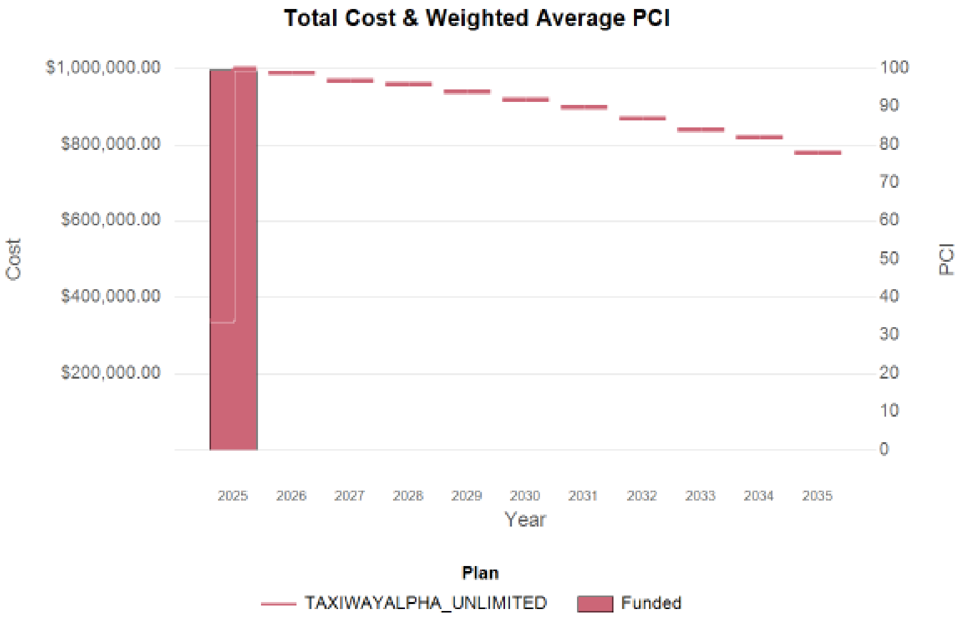


Figure 4.26 Taxiway Alpha maintenance Cost and PCI gains under an unlimited-budget M&R scenario.

4.5.1.8 Taxiway Bravo Unlimited Budget M&R Scenario

The evaluation of Taxiway Bravo, the smallest section in the network (3,680.85 m²), mirrors the systemic failure observed elsewhere and begins the 2025 cycle with a PCI of 39. To address this, the unlimited-budget scenario requires a single Major Rehabilitation event in the first year, with a capital investment of $332,417.56 as shown in Figure 4.27. This intervention effectively resets the pavement to a PCI of 100, establishing a stable deterioration trajectory that concludes the analysis period at a rating of 78. While the treatment strategy is identical to that in larger sections, the total expenditure is lowest in the network, directly proportional to its limited surface area.

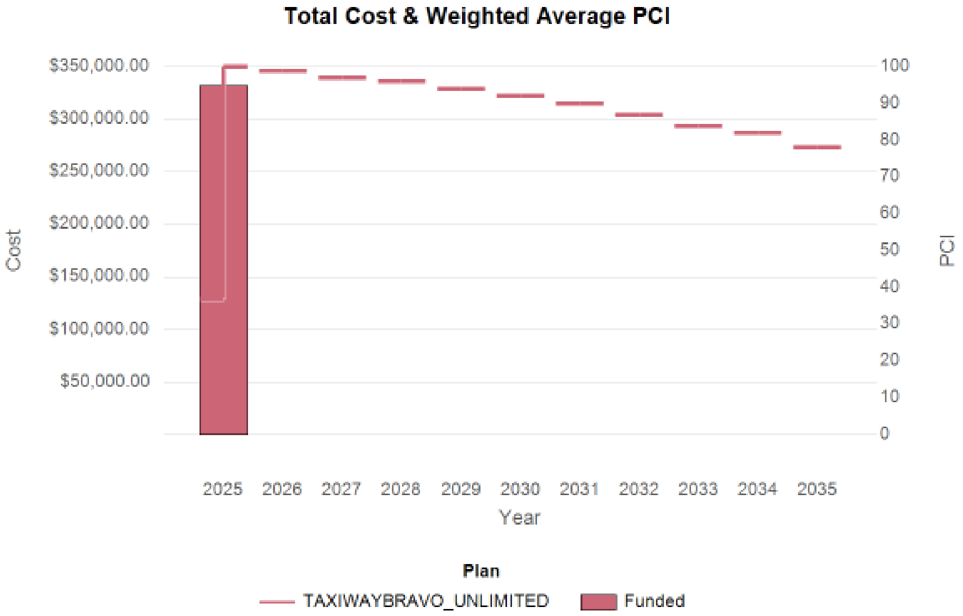


Figure 4.27 Taxiway Bravo maintenance Cost and PCI gains under an unlimited-budget M&R scenario.

4.5.1.9 Taxiway Charlie Unlimited Budget M&R Scenario

The evaluation of Taxiway Charlie (8,809.85 m²) indicates a similar pattern of structural deficiency, entering the 2025 planning period with a PCI of 42. Although this rating is slightly higher than that of the other taxiways, it remains firmly in the very poor category, triggering an unlimited budget for immediate Major Rehabilitation, with a capital investment of $795,617.56 in the first year to reconstruct the section. This intervention resets the pavement condition to a perfect PCI of 100, ensuring a robust performance trajectory that degrades to a satisfactory level of 78 by the end of the 2035 analysis period as shown in Figure 4.28.

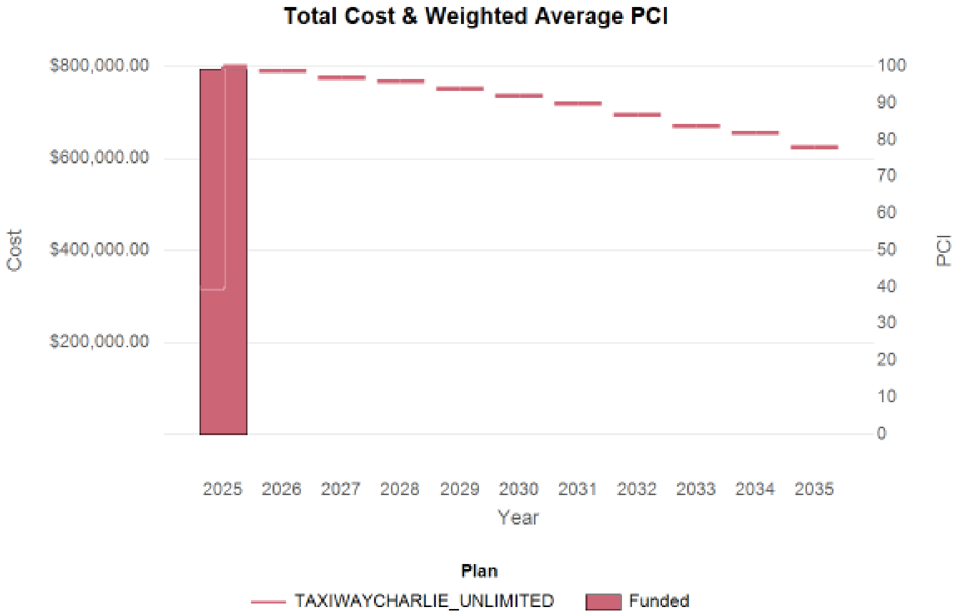


Figure 4.28 Taxiway Charlie maintenance Cost and PCI gains under an unlimited-budget M&R scenario.

After a comprehensive analysis under the Unlimited Budget baseline, the total capital investment needed to eliminate the maintenance backlog and fully restore the KIA network is approximately $26.84 million, as shown in Table 4.10. In each section, the simulation prompted an immediate Major Rehabilitation in 2025, which reset the PCI to 100. The terminal PCI (2035) indicates that, even after 10 years of natural aging following this significant investment, all sections remain within the range of 72-82, requiring no further major interventions during this period.

Table 4.10 Summary of Unlimited Budget scenario analysis results (2025-2035)

Pavement Section	Surface Area (m²)	Initial PCI (2025)	Treatment Type	Budget Required ($)	Terminal PCI (2035)
Runway End 10	105,525.85	38	Major Rehabilitation	$9,530,040.00	72
Runway End 28	11,475.85	36	Major Rehabilitation	$1,036,384.00	72
Runway TD Zone	40,500.85	39	Major Rehabilitation	$3,657,631.75	72
Apron Alpha	45,376.00	28	Major Rehabilitation	$4,097,906.50	82
Apron Bravo	28,756.00	33	Major Rehabilitation	$2,596,954.25	82
Apron Charlie	42,001.00	31	Major Rehabilitation	$3,793,110.25	82
Taxiway Alpha	11,041.00	36	Major Rehabilitation	$997,112.69	78
Taxiway Bravo	3,680.85	39	Major Rehabilitation	$332,417.56	78
Taxiway Charlie	8,809.85	42	Major Rehabilitation	$795,617.56	78
TOTAL	**297,166.40**		**Network Reconstruction**	**$26,837,174.56**	

4.5.2 Consequence of Local Repair M&R Scenario

The Consequence of Local Repair (CLR) strategy is technically defined by FAA PAVEAIR as a diagnostic tool that calculates the costs and resulting condition of immediate implementation of local M&R for the most recent inspection years. Unlike long-term forecasting models, this strategy evaluates the specific distresses recorded in the latest field survey to generate an actionable, immediate work plan.

The CLR M&R strategy functions strictly as an immediate diagnostic tool rather than a predictive model, anchoring its analysis to the most recent inspection rather than a projected future date. Because the strategy calculates repairs based on specific distresses recorded in the latest field survey, it effectively forces the starting Pavement Condition Index (PCI) to match the last known physical condition (the 2024 inspection value for this study), regardless of the analysis year selected.

Operationally, the simulation is initialized by setting a start date and configuring the plan mode to bypass global and major maintenance triggers. Instead, the logic relies exclusively on localized maintenance policies driven by two conditional parameters:

- **Policy < Critical:** For sections below the critical threshold, the software applies a localized safety policy (Stopgap), targeting only high-severity distresses to restore operational safety.
- **Policy > Critical:** For sections above the threshold, it applies a localized preventive policy to address minor defects.

The budget estimation does not use generic square-meter averages, which are mostly applied to reconstruction and overlays; it utilizes the default cost by work type database. The algorithm calculates the precise quantity of each distress (e.g., linear meters of cracking) and multiplies it by the specific unit cost (e.g., \$30.68/m for crack sealing) as shown in Table 4.11. Simultaneously, the localized policy consequences feature simulates the reduction in distress severity (e.g., downgrading high severity to medium, thereby calculating the exact PCI improvement resulting from this immediate investment.

Table 4.11 Localized maintenance unit costs (FAA PAVEAIR, 2021)

Work Code	Name	Work Unit	Cost (USD)
PA-SP	Spall Repair	m²	112.05
NONE	No Localized MR	m²	0
CS-AC	Crack Sealing - AC	m	30.68
JS-SI	Joint Seal - Silicon	m	38.32
PA-AD	Patching - AC Deep	m²	149.62
PA-AL	Patching - AC Leveling	m²	74.16
PA-AS	Patching - AC Shallow	m²	138.42
SH-LE	Shoulder leveling	m	52.64

The divergence in total budget requirements between the two localized maintenance policies is not driven by variable pricing, but rather by the scope of eligible work:

the safety policy (< Critical) restricts quantities by targeting only high-severity distresses, whereas the preventive policy (> Critical) accumulates higher costs by addressing a broader spectrum of low, medium, and high-severity defects at the same unit rate.

4.5.2.1 Runway Consequence of Local Repair M&R

The analysis for the runway branch evaluates the immediate maintenance needs to address safety-critical distresses across its three defined sections: Runway End 10, Runway End 28, and the Touchdown Zone (TDZ). The total capital required to stabilize the runway branch in the first year, as shown in Figure 4.29, is \$3,464,091.43. The majority of this investment is directed toward Runway End 10, which requires \$1,938,389.66 due to its extensive area of 105,525m2 and poor condition. Runway End 28 follows with a requirement of \$1,255,244.49, while the TDZ requires a comparatively lower investment of \$270,457.28.

Figure 4.29 Runway sections CLR M&R cost for Year 1

The CLR strategy for the runway successfully mitigates immediate safety risks but fails to restore the asset to a standard condition of a PCI score greater than 55 as shown in Table 4.12. For example, at Runway End 10, despite the nearly $2 million investment, the PCI improves only moderately from 40 to 52, remaining in the poor-fair category. On the other hand, Runway End 28, the condition sees negligible improvement, moving from a PCI of 38 to 40. This indicates that the $1.25 million spent is almost entirely consumed by Stopgap repairs to prevent FOD, without adding structural capacity. Similarly, the Touchdown Zone improves marginally from PCI 42 to 46.

Table 4.12 Summarized 1year 1 CLR M&R budget for the Runway

Plan info	**Beginning of the plan**	**End of plan**
Plan: CLR_Runway_END10		
Year	2024	2025
PCI	40	52
Plan: CLR_Runway_END28		
Year	2024	2025
PCI	38	40
Plan: CLR_Runway_TDZ		
Year	2024	2025
PCI	42	46
Budget Allocation		
Plan Parameter	**Cost ($)**	**Area (m^2)**
Plan: CLR_Runway_END10		
Major	1,938,389.66	105,525.85
Total	1,938,389.66	105,525.85
Plan: CLR_Runway_END28		
Major	1,255,244.49	11,475.85
Total	1,255,244.49	11,475.85
Plan: CLR_Runway_TDZ		
Major	270,457.28	40,500.85
Total	270,457.28	40,500.85

4.5.2.2 Aprons Consequence of Local Repair M&R

The Consequence of Local Repair analysis for the Apron branch reveals a total immediate funding requirement of $893,063.54 to mitigate safety hazards and stabilize the pavement surface. From Figure 4.30, the Apron Alpha accounts for the majority of the investment ($675,620.72), resulting in a noticeable condition improvement from PCI 35 to 49, which indicates a high volume of repairable surface defects. Conversely, Apron Bravo ($159,642.36) and Apron Charlie ($57,800.46).

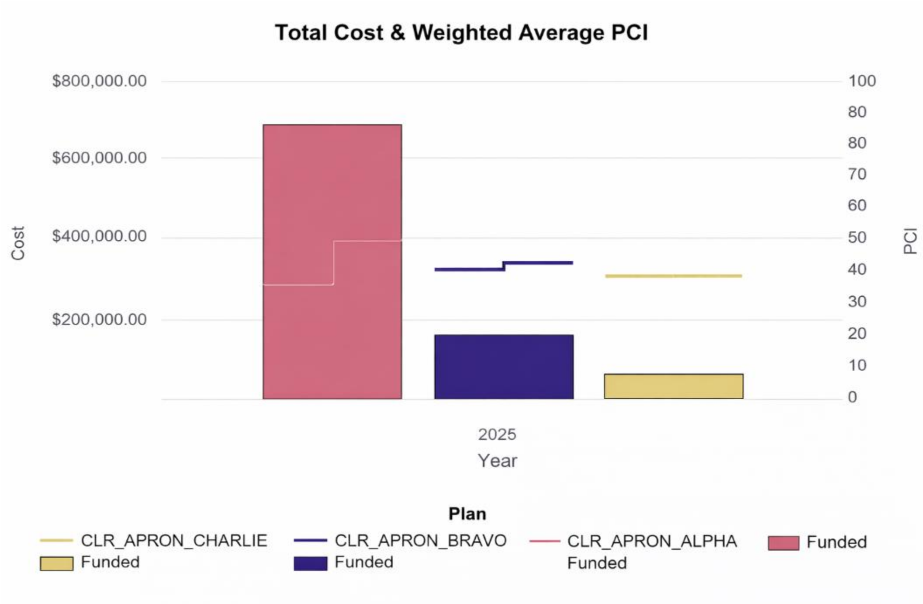


Figure 4.30 Aprons CLR year 1 M&R cost

Apron Bravo sees only a marginal increase from PCI 40 to 42, as shown in Table 4.13, while Apron Charlie's condition remains stagnant at PCI 38 despite the investment. This zero-gain result for Apron Charlie serves as definitive evidence that the branch suffers from deep structural failure rather than superficial wear; while the allocated funds successfully address immediate safety risks (Stop-Gap), they are insufficient to correct the underlying structural deficiencies causing the low PCI.

Table 4.13 Summarized year 1 CLR M&R budget for the Aprons

Plan info	**Beginning of the plan**	**End of plan**
Plan: CLR_Apron_ALPHA		
Year	2024	2025
PCI	35	49
Plan: CLR_Apron_BRAVO		
Year	2024	2025
PCI	40	42
Plan: CLR_Apron_CHARLIE		
Year	2024	2025
PCI	38	38
Budget Allocation		
Plan Parameter	**Cost ($)**	**Area (m^2)**
Plan: CLR_Apron_ALPHA		
Major	675,620.72	45,376.00
Total	675,620.72	45,376.00
Plan: CLR_Apron_BRAVO		
Major	159,642.36	28,756.00
Total	159,642.36	28,756.00
Plan: CLR_Apron_CHARLIE		
Major	57,800.46	42,001.00
Total	57,800.46	42,001.00

4.5.2.3 Taxiways Consequence of Local Repair M&R

The Consequence of Local Repair analysis for the Taxiway branch presents the most financially efficient stabilization opportunity within the KIA network, requiring a total investment of $275,502.60. Unlike the Runway and Apron branches, which showed limited condition improvements, the Taxiway sections exhibit a higher responsiveness to local maintenance. Specifically, Taxiway Bravo and Taxiway Charlie demonstrate significant recoverability; an investment of $63,489.47 in Bravo raises its PCI from 41 to 56, while $104,456.06 allocated to Charlie improves its condition from 47 to 55, as shown in Figure 4.31.

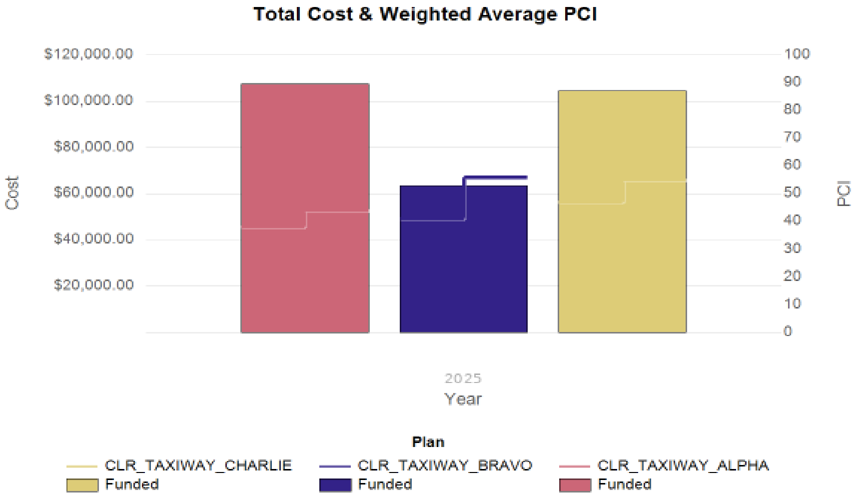


Figure 4.31 Taxiways CLR year1 M&R cost

These results also indicate that surface-level repairs are sufficient to restore these sections to a fair operational state. However, Taxiway Alpha remains the critical outlier; despite receiving the highest individual allocation of $107,557.07, its condition only improves marginally from PCI 38 to 44, as illustrated in Table 4.14. This identifies Taxiway Alpha as structurally compromised, confirming that while the CLR strategy is a sustainable solution for the majority of the taxiway network, Alpha will require more substantial rehabilitation in the near future.

Table 4.14 Summarized the year 1 CLR M&R budget for the Taxiways

Plan info	**Beginning of the plan**	**End of plan**
Plan: CLR_Taxiway_ALPHA		
Year	2024	2025
PCI	38	44
Plan: CLR_Taxiway_BRAVO		
Year	2024	2025
PCI	41	56
Plan: CLR_Taxiway_CHARLIE		
Year	2024	2025
PCI	47	55
Budget Allocation		
Plan Parameter	**Cost ($)**	**Area (m²)**
Plan: CLR_Taxiway_ALPHA		
Major	107,557.07	11,041.00
Total	107,557.07	11,041.00
Plan: CLR_Taxiway_BRAVO		
Major	63,489.47	3,681.00
Total	63,489.47	3,681.00
Plan: CLR_Taxiway_CHARLIE		
Major	104,456.06	8,810.00
Total	104,456.06	8,810.00

The analysis of the Consequence of Local Repair (CLR) strategy establishes a financially practical stopgap alternative for the immediate stabilization of the KIA network. The results from summary Table 4.15 demonstrate that operational safety can be secured with a total initial capital investment of $4.63 million in the first year, a figure that is dramatically lower than the $26.8 million benchmark required for the Unlimited Budget reconstruction scenario. While this strategy is not designed to achieve full structural restoration, its primary value lies in its ability to immediately stabilize the network for continued operation. Although the absolute gains in Pavement Condition Index (PCI) are modest, the intervention successfully elevates critical sections within the manageable safety range (PCI 40-55). By arresting rapid degradation, the CLR strategy ensures that the airport remains fully operational and compliant with safety standards and provides airport management time to mobilize the substantial capital reserves required for future major rehabilitation.

The distribution of this budget reveals a significant imbalance driven by the vast difference in total surface area between the branches. The Runway branch, which encompasses the largest footprint at 157,500 m², consumes approximately 75% of the total required budget ($3.46 million). This disproportionate cost is a direct function of scale; the extensive surface area amplifies the absolute volume of localized distresses, necessitating a massive quantity of stopgap repairs on heavily deteriorated sections of Runway. On the other hand, the Taxiway branch involves a much smaller surface area of only 23,530 m². Consequently, it requires the least capital investment ($0.28 million**)** yet yields the highest relative condition improvement, with sections like Taxiway Bravo gaining 15 PCI points due to the concentrated impact of repairs on a smaller, more manageable area.

Table 4.15 Summary of CLR M&R strategy findings

Branch	**Section**	**Area (m²)**	**Initial capital cost (2026)**	**PCI (Before) 2024**	**PCI (After)**	**PCI gain**
Runway	End 10	105,525	$1,938,389.66	40	52	12
	End 28	11,475	$1,255,244.49	38	40	2
	TDZ	40,500	$270,457.28	42	46	4
Sub-Total		**157,500**	**$3,464,091.43**			
Apron	Alpha	45,376	$675,620.72	35	49	14
	Bravo	28,756	$159,642.36	40	42	2
	Charlie	42,001	$57,800.46	38	38	0
Sub-Total		**116,133**	**$893,063.54**			
Taxiway	Alpha	11,041	$107,557.07	38	44	6
	Bravo	3,680	$63,489.47	41	56	15
	Charlie	8,809	$104,456.06	47	55	8
Sub-Total		**23,530**	**$275,502.60**			
NETWORK TOTAL		**297,163 m²**	**$4,632,657.57**			

4.5.3 Minimum Condition M&R Scenario

The Minimum Condition M&R strategy serves as a threshold-based planning tool designed to calculate the budget strictly required to keep pavement sections above a specific performance level. By defining a minimum acceptable PCI set in this study at PCI in the range of 55 to 70, so-called PCI 60 in this thesis, the strategy automatically triggers major M&R interventions (such as overlays or reconstruction) whenever a section deteriorates below these critical values. To validate the selection of PCI 60 as the optimal target for the Minimum Condition strategy at KIA, a sensitivity analysis was conducted on the runway sections (Runway End 10, End 28, and TDZ) using thresholds of PCI 55, 70, and 80. The simulation results revealed a different structural intervention between PCI 55 and PCI 70 than that of PCI 80.

As demonstrated in the simulation summaries in Figure 4.32, the capital requirements for PCI 50 and PCI 70 were identical, \$14.2 million for 10 years analysis. This phenomenon occurs because the current network condition represents a structural failure. Whether the target is set to 55 or 70, the PAVEAIR algorithm is forced to trigger the same major reconstruction activity in Year 1 to restore the asset with a terminal PCI of 75 at the end of the analysis period.

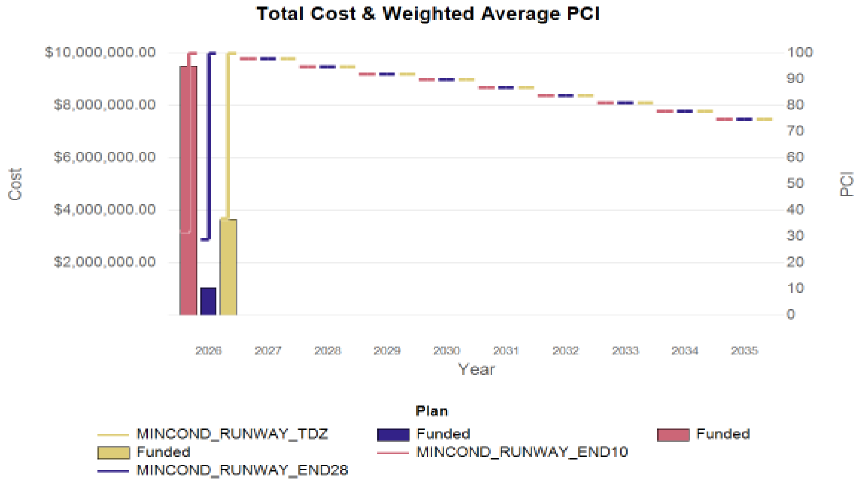


Figure 4.32 Illustration of the same effect of the Minimum Condition M&R strategy for lower threshold PCI of 55 and 75 in FAA PAVEAIR

On the other hand, setting the threshold to PCI 80 resulted in a significant cost escalation to $17.05 Million (a 20% increase) in the same analytical period. The lifecycle graph, Figure 4.33, indicates that this aggressive target forces a secondary major capital injection in 2034. As the reconstructed pavement naturally degrades to PCI 78 by year 9, it breaches the strict 80 threshold, forcing the software to program an early overlay solely to meet the numerical target.

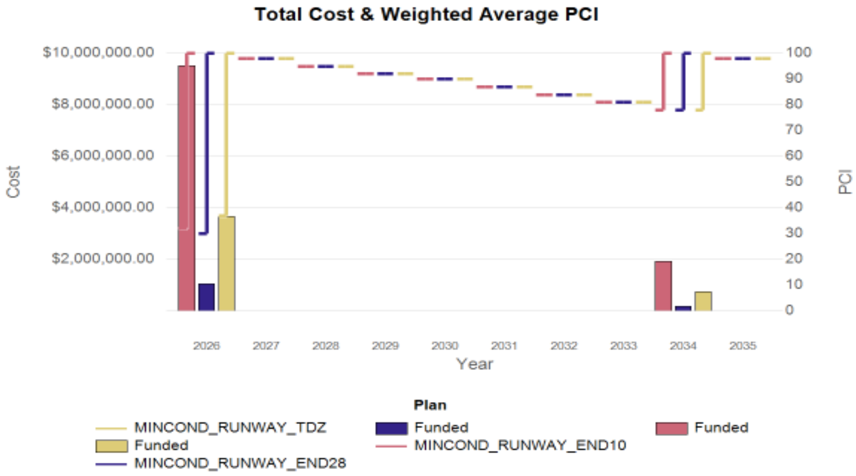


Figure 4.33 Illustration of the effect of higher PCI thresholds of PCI 80 using the Minimum Condition M&R strategy.

Furthermore, the study observed that the PAVEAIR analytical module enforces a hard input constraint, restricting the Minimum Condition threshold to a range of PCI between 30 and 80. This algorithmic boundary dictates that the software is designed to manage operational and maintenance zones only; it cannot simulate scenarios for perfect standards with PCI above 80 or stopgap strategies where PCI is below 30, forcing the user to optimize within the realistic window of active pavement management.

The threshold of PCI 60 was selected as the optimal equilibrium. It lies within the stable cost ranges, avoiding the high expenditure associated with PCI 80 while adhering to standard FAA guidelines, where PCI 60 typically demarcates the transition from preventative maintenance (PCI 55- 70) to structural rehabilitation. The analysis with this strategy functions in a way that, when a pavement section goes below the defined PCI threshold, the software does not program a minor repair but triggers a major rehabilitation.

4.5.3.1 Runway Minimum Condition M&R

The Minimum Condition analysis for the Runway branch demonstrates that enforcing a minimum performance threshold on the currently deteriorated network necessitates an immediate, massive capital injection of $14,224,055 in the first year, as demonstrated by Figure 4.34. Because all three sections, Runway End 10 (PCI 36), End 28 (PCI 34), and the Touchdown Zone (PCI 37), are currently below the acceptable safety standard, the strategy triggers full-scale rehabilitation rather than simple maintenance.

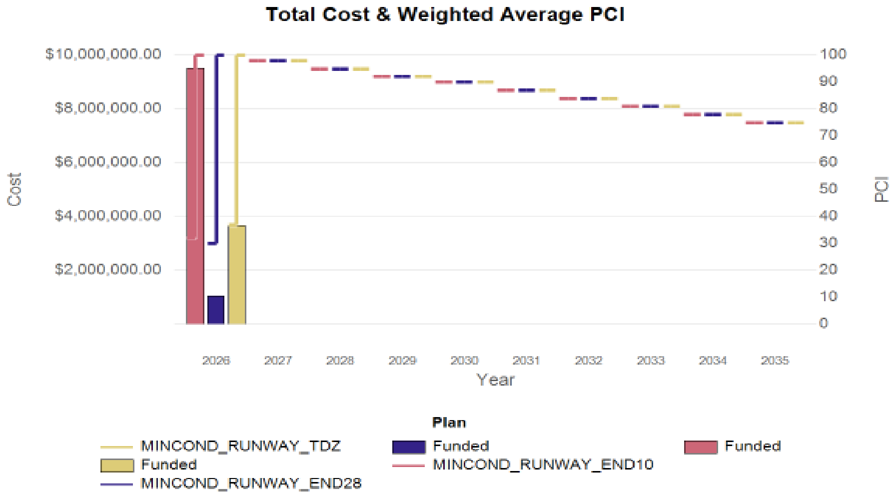


Figure 4.34 Runway Minimum Condition 10 years M&R cost

Runway End 10 alone absorbs the majority of this budget ($9.53 Million) as illustrated in Table 4.16, confirming that meeting minimum conditions actually requires correcting the deep structural failure of the entire primary landing surface. While this investment successfully raises the branch PCI to a sustainable level of 75 by the end of the analysis period, the prohibitive upfront cost proves that, for the runway, a minimum condition policy is financially indistinguishable from total reconstruction.

Table 4.16 Summarized 10 years Minimum Condition M&R budget for the Runway sections

Plan info	**Beginning of the plan**	**End of plan**
Plan: Minimum Condition_Runway_END10		
Year	2026	2035
PCI	36	75
Plan: Minimum Condition_Runway_END28		
Year	2026	2035
PCI	34	75
Plan: Minimum Condition_Runway_TDZ		
Year	2026	2035
PCI	37	75
Budget Allocation		
Plan Parameter	**Cost ($)**	**Area (m²)**
Plan: Minimum Condition_Runway_END10		
Major	9,530,039.51	105,526.00
Total	9,530,039.51	105,526.00
Plan: Minimum Condition_Runway_END28		
Major	1,036,384.01	11,476.00
Total	1,036,384.01	11,476.00
Plan: Minimum Condition_Runway_TDZ		
Major	3,657,631.76	40,501.00
Total	42,001.00	42,001.00

4.5.3.2 Aprons Minimum Condition M&R

The application of the Minimum Condition strategy to the Apron branch reveals a critical funding imperative, requiring a total initial capital investment of $10,487,971 in the first year to meet the established performance standards. As shown in Figure 4.35, Apron Alpha necessitates the largest single allocation of $4.10 Million, while Apron Charlie and Apron Bravo require $3.79 Million and $2.60 Million, respectively.

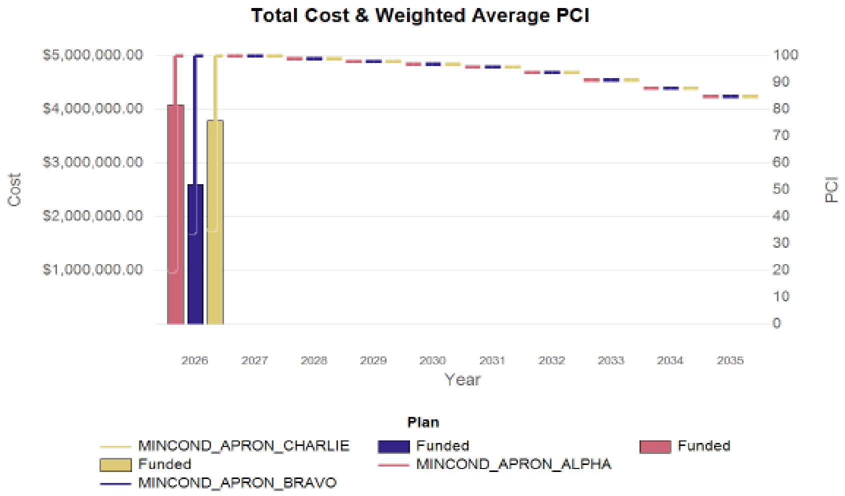


Figure 4.35 Aprons Minimum Condition 10 years M&R cost

The result of this substantial investment is a dramatic restoration of the branch to excellent condition, with all sections reaching a PCI of 85 by the end of the planning period Table 4.17. However, this confirms that for the Apron branch, the Minimum Condition strategy effectively mandates full reconstruction, as there are no intermediate repair options capable of lifting such low PCI values to the target threshold.

Table 4.17 Summarized 10 years Minimum Condition M&R budget for Aprons

Plan info	**Beginning of the plan**	**End of plan**
Plan: Minimum Condition_Apron_ALPHA		
Year	2026	2035
PCI	21	85
Plan: Minimum Condition_Apron_BRAVO		
Year	2026	2035
PCI	26	85
Plan: Minimum Condition_Apron_CHARLIE		
Year	2026	2035
PCI	24	85
Budget Allocation		
Plan Parameter	**Cost ($)**	**Area (m²)**
Plan: Minimum Condition_Apron_ALPHA		
Major	4,097,906.56	45,376.00
Total	4,097,906.56	45,376.00
Plan: Minimum Condition_Apron_BRAVO		
Major	2,596,954.36	28,756.00
Total	2,596,954.36	28,756.00
Plan: Minimum Condition_Apron_CHARLIE		
Major	3,793,110.21	42,001.00
Total	42,001.00	42,001.00

4.5.3.3 Taxiways Minimum Condition M&R

The Minimum Condition analysis for the Taxiway branch reinforces the pattern observed across the wider network, where the current deterioration levels are too severe to be managed by low-cost maintenance, necessitating a total initial capital investment of $2,062,465. Taxiway Alpha requires the most significant individual investment of $997,112.71 to address its structural failure, while Taxiways Charlie and Bravo require $732,935.47 and $332,417.56, respectively, as shown by Figure 4.36.

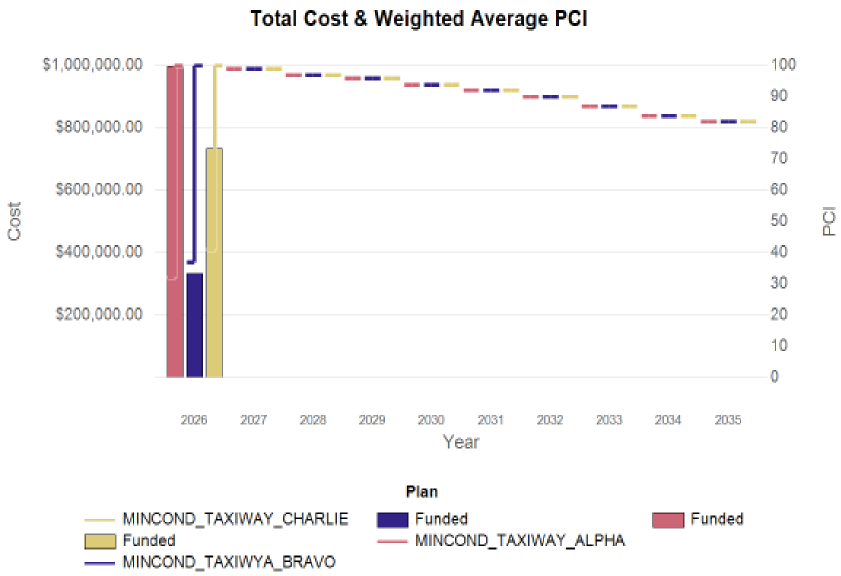


Figure 4.36 Taxiways Minimum Condition 10 years M&R cost

The analysis shows that all three taxiway sections, Alpha (PCI 34), Bravo (PCI 37), and Charlie (PCI 40), currently fall well below the standard serviceability threshold. As a result, the strategy automatically triggers major rehabilitation for every section rather than selective repair. While this heavy investment successfully restores the entire branch to an excellent state with a uniform PCI of 82 by the end of the plan as illustrated by Table 4.18, it further proves that the Minimum Condition strategy offers no immediate financial relief for KIA, as it demands 7 times increase in spending compared to the safety-focused Local Repair strategy ($0.27M).

Table 4.18 Summarized 10 years Minimum Condition M&R budget for Taxiways

Plan info	**Beginning of the plan**	**End of plan**
Plan: Minimum Condition_Taxiway_ALPHA		
Year	2026	2035
PCI	34	82
Plan: Minimum Condition_Taxiway_BRAVO		
Year	2026	2035
PCI	37	82
Plan: Minimum Condition_Taxiway_CHARLIE		
Year	2026	2035
PCI	40	82
Budget Allocation		
Plan Parameter	**Cost ($)**	**Area (m²)**
Plan: Minimum Condition_Taxiway_ALPHA		
Major	997,112.71	11,041.00
Total	997,112.71	11,041.00
Plan: Minimum Condition_Taxiway_BRAVO		
Major	332,417.56	3,681.00
Total	332,417.56	3,681.00
Plan: Minimum Condition_Taxiway_CHARLIE		
Major	732,935.47	8,810.00
Total	732,935.47	8,810.00

For the KIA network, the analysis of this strategy revealed a decisive financial reality: the current state of the pavement is too far deteriorated to benefit from threshold management. The simulation generated a total capital requirement of $26,774,492. This figure is statistically identical to the $26.84 Million required for the aggressive Unlimited budget. The consolidated analysis of the Minimum Condition strategy aims only to maintain a minimum standard; the severe structural failure of the current network triggers immediate, full-scale reconstruction for every major section. Consequently, the total initial capital required for this strategy is $26,774,492, as shown in Table 4.19, statistically identical to the aggressive Unlimited budget and Backlog Elimination strategies.

Table 4.19 Summary of Minimum Condition M&R strategy findings

Branch	**Section**	**Area (m²)**	**Initial Capital Cost (2026)**	**PCI (Start)**	**PCI (End 2035)**
Runway	End 10	105,526	$9,530,039.51	36	75
	End 28	11,476	$1,036,384.01	34	75
	TDZ	40,501	$3,657,631.76	37	75
Sub-Total		**157,503**	**$14,224,055.28**		
Apron	Alpha	45,376	$4,097,906.56	21	85
	Bravo	28,756	$2,596,954.36	26	85
	Charlie	42,001	$3,793,110.31	24	85
Sub-Total		**116,133**	**$10,487,971.23**		
Taxiway	Alpha	11,041	$997,112.71	34	82
	Bravo	3,681	$332,417.56	37	82
	Charlie	8,810	$732,935.47	40	82
Sub-Total		**23,532**	**$2,062,465.74**		
NETWORK TOTAL		**297,168 m²**	**$26,774,492.25**		

4.5.4 Limited Budget ($1Million) Per Year M&R Scenario

The Limited Budget M&R Strategy operates within FAA PAVEAIR as a constrained optimization simulation, designed to prioritize maintenance activities when capital resources are insufficient to meet the total network’s needs. The configuration process begins by defining the analysis period, where the user establishes the simulation start date and specifies the duration, strictly limited to a range of 1 to 10 years. Unlike the Unlimited assessment, the operational core of this strategy lies in the plan mode configuration, specifically within the budget consequences settings. The user can select the fixed amount per year option and input the specific monetary cap ($1,000,000/year) used for this study, effectively forcing the software to transition from a needs-based calculation to a resource-based allocation.

Once the financial constraint is set, the strategy utilizes the policy and costs framework to generate the work plan. The system activates the full spectrum of intervention types from localized maintenance (Safety and Preventive), global maintenance (Surface Treatments), and major M&R. For the specific purpose of this study, the global maintenance and major M&R categories were deliberately unchecked (disabled) in the configuration. This exclusion was mandatory due to the current critical state of the pavement network. If enabled, the software's internal logic would have immediately triggered reconstruction or structural overlay work types, which would have instantly exceeded the $1 million annual capital and rendered the simulation non-functional. By restricting the scope exclusively to localized maintenance (Safety and Preventive), the strategy forces the algorithm to bypass unaffordable structural resets and instead identify the maximum quantity of high-priority surface repairs that can be executed within the available funds, effectively modeling a holding strategy rather than a restoration plan, deferring the remaining unfunded work to subsequent years as backlog.

For the constrained budget analysis ($1 million/year), funds were allocated based on the scale in terms of surface coverage and severity level of distress. The Runway branch received the primary allocation of $500,000 (50%) due to its status as the main airport operational pavement and its dominance of the network area covering 51.2% with 157,501 m². The Apron branch followed with $260,000 (26%), prioritizing its massive volume of 126,634 m² and critical degradation with the lowest PCI of 38.4. Finally, the Taxiway branch was assigned $240,000 (24%), as it has a significantly smaller footprint (7.6%) of surface area and relatively superior condition compared to others, with a PCI of 41.8.

4.5.4.1 Runway Limited Budget ($500,000) Per Year M&R Strategy

Within the Runway branch, the $500,000 annual budget was distributed based on sectional scale and distress intensity. Runway End 10 received the majority share of $250,000 (50%) to address routine maintenance across its massive 105,525 m² footprint, which constitutes 67% of the runway area. In contrast, Runway End 28 was allocated $150,000 (30%); despite its small size of 11,476 m², its critical condition with the lowest PCI of 38 demands capital-intensive structural intervention. Finally, the Touchdown Zone (TDZ) received $100,000 (20%); its superior structural health with PCI 42 allows for a lower-cost preservation strategy despite covering a substantial 40,500 m² area.

The simulation data indicate that despite the allocation of funds, the total funded budget executed was $0.00 across all three sections. The chart visually confirms a massive accumulation of Backlog (Unfunded liability) in the first year, of $1,938,390 allocated to Runway End 10, approximately $1.26 million for Runway End 28, and $270,457 for the Touchdown Zone, as illustrated by Figure 4.37.

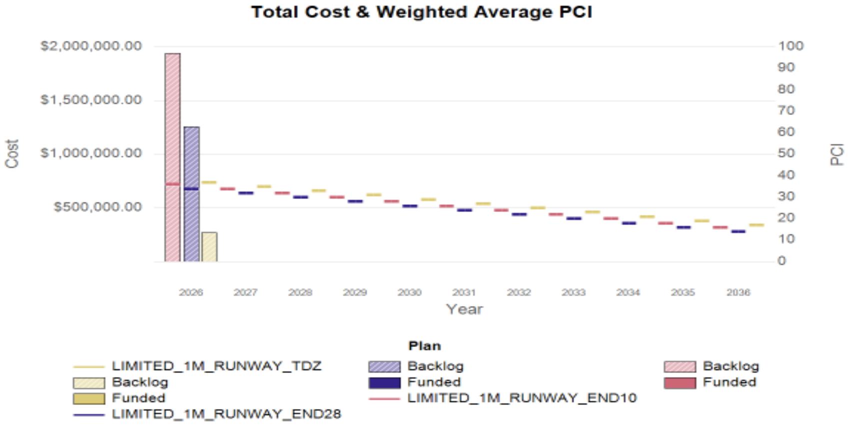


Figure 4.37 Runway limited budget ($500/year) 10 years M&R cost

This outcome confirms a funding threshold failure, where the allocated amounts were insufficient to cover even the minimum stopgap safety interventions required, causing FAA PAVEAIR management logic to defer the entire workload as backlog rather than execute partial repairs as shown in Table 4.20. Consequently, the strategy functioned effectively as a Do-Nothing plan, leading to catastrophic asset loss with the structural condition of the network collapsing over the 10 years, with Runway End 28 degrading to a PCI of 14, Runway End 10 with PCI 16, and the TDZ falling to a PCI of 17 (Failed).

Table 4.20 Summarized 10-years limited budget M&R budget plan for runway sections

Plan info	**Beginning of the plan**	**End of plan**
Plan: Limited_1M_Runway_END10		
Year	2026	2036
PCI	36	16
Plan: Limited_1M_Runway_END28		
Year	2026	2036
PCI	34	14
Plan: Limited_1M_Runway_TDZ		
Year	2026	2036
PCI	37	17
Budget Allocation		
Plan Parameter	**Cost ($)**	**Area (m²)**
Plan: Limited_1M_Runway_END10		
Stop Gap Funded	0.00	0.00
Preventive Funded	0.00	0.00
Global Funded	0.00	0.00
Major Funded	0.00	0.00
Total Funded	0.00	0.00
Last Year Unfunded	0.00	0.00
Plan: Limited_1M_Runway_END28		
Stop Gap Funded	0.00	0.00
Preventive Funded	0.00	0.00
Global Funded	0.00	0.00
Major Funded	0.00	0.00
Total Funded	0.00	0.00
Last Year Unfunded	0.00	0.00
Plan: Limited_1M_Runway_TDZ		
Stop Gap Funded	0.00	0.00
Preventive Funded	0.00	0.00
Global Funded	0.00	0.00
Major Funded	0.00	0.00
Total Funded	0.00	0.00
Last Year Unfunded	0.00	0.00

4.5.4.2 Aprons Limited Budget ($260,000) Per Year M&R Strategy

The simulation results of the Apron branch under a highly constrained annual budget of $260,000 distributed as $100,000 for Alpha, $80,000 for Bravo, and $80,000 for

Charlie. The Apron branch, the $260,000 annual budget was distributed to sections in such a way that apron Alpha received the highest allocation of $100,000 (38%), a necessity driven by its critical status as both the largest and most deteriorated section; covering 45,375 m² with a critical PCI of 35, it represents the highest volume of distress in the entire network. The remaining funds were split evenly between Apron Bravo and Apron Charlie $80,000 each. This distribution acknowledges the heavy distress on Apron Charlie with PCI 38, and 42,002 m² surface area, while ensuring that Apron Bravo (PCI 40, 28,757 m²) receives adequate funding to maintain its relatively stable condition before it degrades to the critical levels observed in Alpha.

Despite receiving the largest allocation, Apron Alpha, with a $100,000 cap, and Apron Bravo, with an $80,000 cap, received zero funding ($0.00) in the execution phase. This occurred because the cost of immediate, mandatory stopgap safety repairs exceeded the assigned budget. The FAA PAVEAIR logic dictates that if the minimum required safety work costs more than the available funds, the software cannot execute a partial safety repair; instead, it defers the entire project. Consequently, the system registered an immediate unfunded backlog of $675,620 for Alpha and $159,642 for Bravo in the first year alone as shown in Figure 4.38.

In contrast, Apron Charlie was the only section to consume on allocated funds, utilizing $57,800.46 of its $80,000 allocation. This success was not due to better conditions, but rather mathematical feasibility, where the calculated cost of safety repairs for Charlie fell within its budget limit, which allowed the system to execute the work, effectively clearing its immediate safety backlog while leaving a surplus of approximately $22,000 as deferred work.

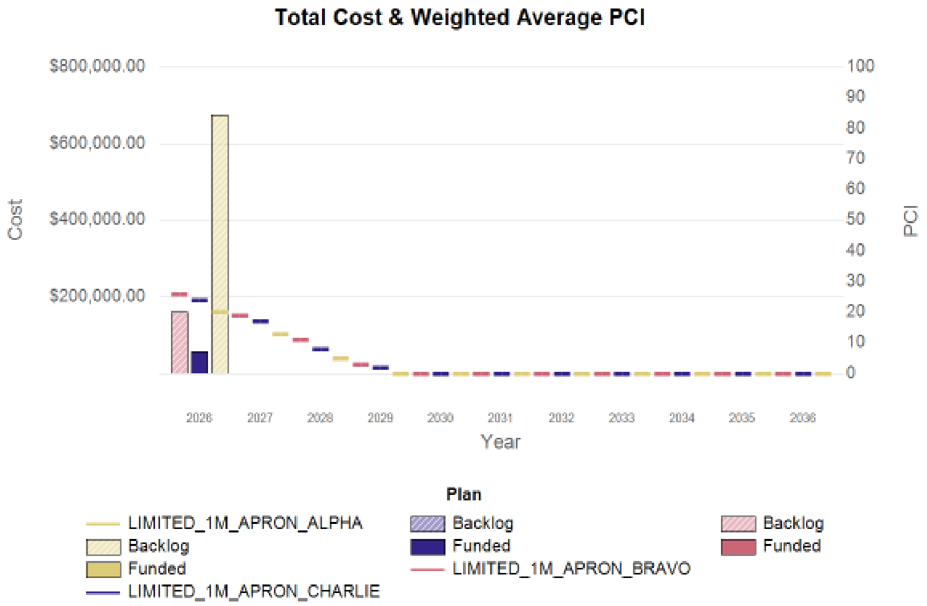


Figure 4.38 Aprons limited budget ($260,00/year) 10 years M&R cost

Finally, this strategy proved catastrophic for the branch's longevity. While the stopgap repairs on apron Charlie addressed immediate safety risks repairs, the lack of capital for structural rehabilitation (Major M&R) meant that underlying deterioration continued unchecked. As illustrated in the lifecycle projection Table 4.21, the 2024 condition of all three sections, Alpha (PCI 21), Bravo (PCI 26), and Charlie (PCI 24), rapidly degraded, reaching a terminal PCI of 0 (Total failure) by the end of the analysis period in 2036.

Table 4.21 Summarized 10-years limited budget M&R budget plan for Aprons

Plan info	**Beginning of the plan**	**End of plan**
Plan: Limited_1M_Apron_ALPHA		
Year	2026	2036
PCI	21	0
Plan: Limited_1M_Apron_BRAVO		
Year	2026	2036
PCI	26	0
Plan: Limited_1M_Apron_CHARLIE		
Year	2026	2036
PCI	24	0
Budget Allocation		
Plan Parameter	**Cost ($)**	**Area (m^2)**
Plan: Limited_1M_Apron_ALPHA		
Stop Gap Funded	0.00	0.00
Preventive Funded	0.00	0.00
Global Funded	0.00	0.00
Major Funded	0.00	0.00
Total Funded	0.00	0.00
Last Year Unfunded	0.00	0.00
Plan: Limited_1M_Apron_BRAVO		
Stop Gap Funded	0.00	0.00
Preventive Funded	0.00	0.00
Global Funded	0.00	0.00
Major Funded	0.00	0.00
Total Funded	0.00	0.00
Last Year Unfunded	0.00	0.00
Plan: Limited_1M_Apron_CHARLIE		
Stop Gap Funded	57,800.46	42,001.00
Preventive Funded	0.00	0.00
Global Funded	0.00	0.00
Major Funded	0.00	0.00
Total Funded	57,800.46	42,001.00
Last Year Unfunded	0.00	0.00

4.5.4.3 Taxiways Limited Budget ($240,000) Per Year M&R Strategy

Within the Taxiway branch, the $240,000 annual budget was distributed to prioritize sections exhibiting the highest structural vulnerability. Taxiway Alpha was assigned the largest share of $100,000, approximately 42%, a decision necessitated based on both the largest section with 11,042 m² (47%) of the branch area and the most deteriorated with (PCI 38). The remaining funds were split evenly between Taxiway Bravo and Taxiway Charlie ($70,000 each), where Taxiway Bravo received a high-intensity investment relative to its small size 3,681 m² to aggressively arrest its rapid decline of PCI 41. In contrast, Taxiway Charlie, which is more than double the size of Bravo 8,810 m², received the same funding amount because its superior condition of PCI 47 allows for lower-cost preventive maintenance rather than expensive structural repairs.

The simulation reveals a funding gap where the cost of mandatory safety repairs exceeded the allocated limits. Specifically, Taxiway Alpha required approximately $108,000, and Taxiway Charlie required $105,000 to seal cracks and patch hazardous defects. Because these amounts surpassed their respective caps of $100,000 and $70,000, the management system of FAA PAVEAIR could not execute partial repairs. Consequently, it deferred the entire workload, resulting in $0.00 funded for both sections and triggering an immediate accumulation of unfunded backlog (deferred maintenance) in the first year.

In contrast, Taxiway Bravo was the only section to receive funding, utilizing just $1,406.96 of its $70,000 allocation illustrated in Figure 4.39. This was not due to strategic prioritization, but rather because its minor safety requirements fell comfortably within the budget limit. While this successfully eliminated immediate safety risks on Bravo, it left nearly $68,000 of the branch's budget unspent while the larger sections (Alpha and Charlie) continued to deteriorate without funds.

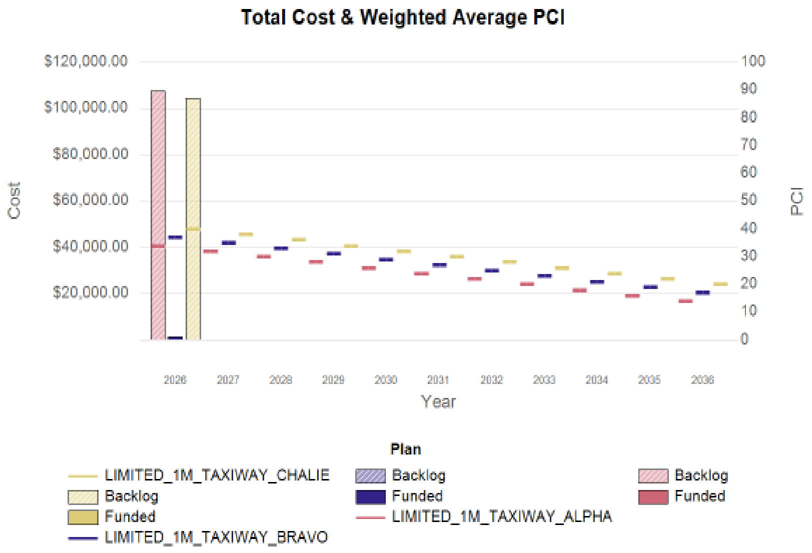


Figure 4.39 Taxiways limited budget ($260,00/year) 10 years M&R cost

In the end, this approach failed to arrest the structural decline of the branch where the pavement degraded rapidly. By the end of the analysis period (2036), the entire taxiway system collapsed into very poor to serious condition, with Taxiway Alpha falling to PCI 14, Taxiway Bravo to PCI 17, and Taxiway Charlie to PCI 20 as demonstrated in Table 4.22. This confirms that the $240,000 budget is insufficient to sustain the taxiway network's structural integrity.

Table 4.22 Summarized 10-years limited budget M&R budget plan for Taxiways

Plan info	**Beginning of the plan**	**End of plan**
Plan: Limited_1M_Taxiway_ALPHA		
Year	2026	2036
PCI	34	14
Plan: Limited_1M_Taxiway_BRAVO		
Year	2026	2036
PCI	37	17
Plan: Limited_1M_Taxiway_CHARLIE		
Year	2026	2036
PCI	40	20
Budget Allocation		
Plan Parameter	**Cost ($)**	**Area (m²)**
Plan: Limited_1M_Taxiway_ALPHA		
Stop Gap Funded	0.00	0.00
Preventive Funded	0.00	0.00
Global Funded	0.00	0.00
Major Funded	0.00	0.00
Total Funded	0.00	0.00
Last Year Unfunded	0.00	0.00
Plan: Limited_1M_Taxiway_BRAVO		
Stop Gap Funded	1,406.96	3,680.85
Preventive Funded	0.00	0.00
Global Funded	0.00	0.00
Major Funded	0.00	0.00
Total Funded	1,406.96	3,680.85
Last Year Unfunded	0.00	0.00
Plan: Limited_1M_Taxiway_CHARLIE		
Stop Gap Funded	57,800.46	42,001.00
Preventive Funded	0.00	0.00
Global Funded	0.00	0.00
Major Funded	0.00	0.00
Total Funded	57,800.46	42,001.00
Last Year Unfunded	0.00	0.00

Conclusively, the analysis confirms a systemic failure of the $1 Million constrained budget strategy to address the network’s most critical maintenance liabilities. For the majority of the pavement such as Runway End 10, Runway End 28, Apron Alpha, and Taxiway Alpha, the allocated annual caps proved insufficient to cover even the minimum execution threshold for stopgap safety repairs. Because the cost of immediate mandatory work exceeded these rigid financial limits, the pavement management logic was forced to defer the entire workload for these sections rather than executing partial repairs. As a result, the system utilized only $59,207 approximately 6% of the available $1 Million in the first year, leaving the vast majority of the capital unspent while the most critical assets continued to deteriorate without intervention where by the end of the analysis period (2036), the entire network degraded to a failed state with PCI ranging between 0 and 20 as shown in Table 4.23.

Table 4.23 Summarized Limited Budget M&R strategy analysis

Branch	**Section**	**PCI (Start)**	**Annual Allocation**	**Actual Funded (Year 1)**	**Unfunded Backlog (Year 1)**	**End PCI (2036)**
Runway	End 10	36	$250,000	$0.00	$1,938,390	16 (Failed)
	End 28	34	$150,000	$0.00	$1,260,000	14 (Failed)
	TDZ	37	$100,000	$0.00	$270,457	17 (Failed)
Sub-total	**Runway**		**$500,000**	**$0.00**	**$3,468,847**	
Apron	Alpha	21	$100,000	$0.00	$675,621	0 (Failed)
	Bravo	26	$70,000	$0.00	$159,642	0 (Failed)
	Charlie	24	$70,000	$57,800	$0	0 (Failed)
Sub-total	**Apron**		**$240,000**	**$57,800**	**$835,263**	
Taxiway	Alpha	34	$100,000	$0.00	$108,000	14 (Failed)
	Bravo	37	$80,000	$1,407	$0	17 (Failed)
	Charlie	40	$80,000	$0.00	$105,000	20 (Failed)
Sub-total	**Taxiway**		**$260,000**	**$1,407**	**$213,000**	
TOTAL	**NETWORK**		**$1,000,000**	**~$59,207**	**$4.5 Million**	**FAILED**

4.5.5 Comparative Analysis of Five Different M&R Strategies for KIA

The simulation of maintenance and rehabilitation (M&R) interventions for the Kigali International Airport (KIA) pavement network reveals a critical contrast between theoretical engineering idealism and practical financial feasibility. The comparative analysis of the four selected strategies, including Unlimited Budget, Consequence of Local Repair (CLR), Minimum Condition (PCI 60), and Limited Budget ($1M/year), as illustrated in Table 4.24, shows that traditional worst-first or structural reset approaches are economically non-viable within the context of a developing economy such as that of Rwanda. The analysis identifies three distinct performance clusters:

- The structural reset model
- Consequences of the micro-funding
- Stabilization of the pavement condition within the operational safety window

Table 4.24 Comparative summary of M&R Strategies analysis results

Parameter	**Unlimited Budget**	**Consequence of Local Repair (CLR)**	**Min. Condition (PCI 60)**	**Limited Budget ($1M/Year)**
Strategy philosophy	Unconstrained optimization	Risk-based safety sustainment	Rigid performance floor	Capped expenditure
Initial PCI 2026 (Weighted Average PCI)	39.7 (Poor)	39.7 (Poor)	39.7 (Poor)	39.7 (Poor)
Year 1 capital required	$26,837,175	$4,632,658	$26,774,492	$59,207 (Funded)
Year 1 Unfunded backlog	$0.00	$0.00 (Safety met)	$0.00	$4.5 million
Total 10-year cost	$26.837,175 Million	$13,897,974 (Explained in section 4.5.5.3)	$26,774,492 Million	$10 Million
Accumulated Backlog (Year 10)	$0.00	~$26.8 million (Deferred Liability)	$0.00	$31.5 million
Terminal PCI (2036)	72-82	40-55	75-85	0-20
Network Outcome	Excellent condition	Operational safety secured	Excellent condition	Catastrophic failure
Feasibility Verdict	**Unaffordable**	**OPTIMAL and RECOMMENDED**	**Unaffordable**	**Rejected (Unsafe)**

4.5.5.1 Structural Reset M&R Strategies

The first cluster, comprising the Unlimited Budget and Minimum Condition (PCI 60) strategies, represents the structural reset model. These scenarios yield nearly identical outcomes by successfully restoring the network to a very good state of PCI > 75 at the end of 10 years analysis period by eliminating all distress immediately. However, this technical success is predicated on an overwhelming upfront capital injection of between \$26.7 and \$27.8 million in the first year, resetting the PCI to 100. While these strategies effectively reset the asset's lifecycle, they ignore the budgetary constraints typical of developing countries, rendering them functionally unimplementable.

Shahin and Walther's (1990) analysis validates the rejection of the structural reset strategies, although their study confirmed that an unlimited budget yields the lowest total lifecycle cost (\$10.6M), it also revealed that such strategies require an unattainable upfront capital injection of \$6 million, nearly 60% of the total 10-year cost. This extreme front-loading of expenditure makes the strategy practically impossible to implement, proving that theoretical efficiency does not equate to operational feasibility. Furthermore, Onyango et al. (2017) provide further validation for rejecting these strategies. Although their study confirmed that the Unlimited models are technically superior for eliminating backlogs, they found the associated upfront costs to be prohibitive. Specifically, they noted that the \$6 million-year 1 capital requirement for the unlimited scenario was impossible for many cities to acquire, effectively ruling out such front-loaded strategies as viable management solutions for resource-constrained administrations.

For developing nations like Rwanda, where pavement networks are in critical condition yet faced with severe financial constraints, the structural reset strategies are fundamentally unimplementable; they can serve only as theoretical benchmarks rather than actionable solutions, offering no viable path to address the urgent rehabilitation needs within the existing fiscal limitations.

4.5.5.2 Consequences of Micro-Funding

The second cluster is represented by the Limited Budget ($1M annually) strategy, which illustrates the catastrophic consequences of the micro-funding trap. The analysis confirms that an annual allocation of $1 million is insufficient to trigger even the most critical safety repairs, resulting in an immediate unfunded backlog of $4.5 million and a terminal network collapse to a failed state with PCI < 20 by 2036. This finding aligns with established literature (Shahin, 2005; Synovec, 2020), which suggests that funding levels below a critical threshold accelerate asset deterioration rather than preserving it.

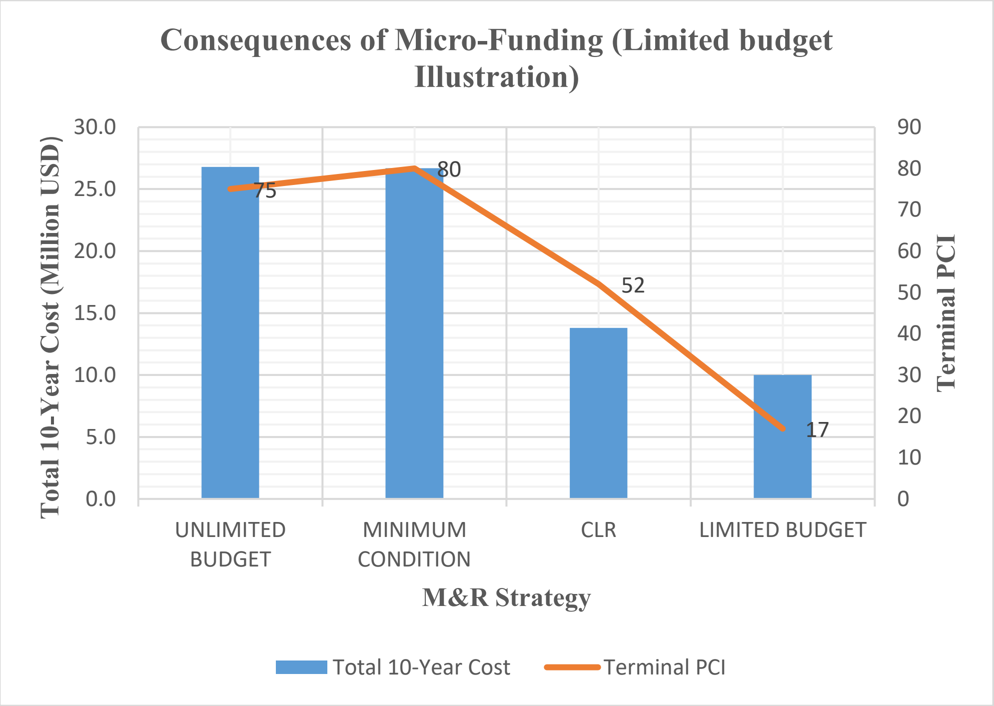


Figure 4.40 Lowest terminal PCI for 10 years analysis by a limited budget M&R strategy

As shown in Figure 4.40, the first three strategies maintain the network in a functional state with terminal PCI between 52 and 80 (shown by the orange line). In contrast, the Limited Budget scenario leads to a sharp decline in pavement quality, dropping to a failing PCI of 17. Although the strategy theoretically allocates $10 Million over the decade, the rigid annual cap of $1 million prevents the execution of necessary structural interventions in Year 1, which are valued at $31.5 million (Backlog) at the end of the analysis period. Because the required repair costs exceed the available micro-funding threshold, the PAVEAIR algorithm is forced to defer critical maintenance. This deferral triggers a structural failure where untreated distresses accelerate deterioration, ultimately resulting in a terminal PCI below 20 by 2036. This finding proves that funding levels below a critical threshold do not preserve the asset partially; rather, they result in the total loss of infrastructure value.

The pavement failure observed in the KIA Limited Budget scenario is corroborated by the findings of Onyango et al. (2017) in their optimization analysis of Chattanooga’s arterial roads. Their study defined a micro-funding scenario ($132,000/year) that mirrored the structural paralysis observed at KIA. Under this strictly constrained budget, Onyango et al. (2017) reported a systemic inability to address network needs, resulting in a backlog accumulation of $9 million and a steady decline in PCI from 73.64 to 69.14 over five years. Crucially, the study identified the specific mechanism of this failure: the budget constraint forced a Do-Nothing policy on approximately 74% of the pavement sections, as it was impossible to allocate the budget to necessary repairs. This effectively validates the KIA simulation results, where the $1 million capital is insufficient to cover the $4.5 million structural requirement and forced the PAVEAIR algorithm to defer essential maintenance, driving the network into a failed terminal PCI. Both cases confirm that funding levels below a specific survival threshold do not result in partial preservation, but rather in accelerated backlog accumulation and eventual asset forfeiture.

4.5.5.3 Stabilization of the Pavement Condition Within the Operational Safety Window

The third and optimal cluster is the Consequence of Local Repair (CLR) strategy. Positioned as a sustainment approach, the CLR strategy rejects the two choices between unaffordable reconstruction and inevitable failure. By targeting a safety threshold investment of $4.63 million for the first year, it stabilizes the pavement condition within the operational safety window with PCI ranging between 40 and 55. Although it does not achieve the high superficial standards of the unlimited scenarios, it is the only strategy that satisfies safety requirements while reducing the initial capital burden by approximately 83% compared to reconstruction.

This study suggested that the implementation of the Consequence of Local Repair (CLR) M&R strategy follows a phased capitalization model designed to reconcile immediate safety needs with long-term fiscal constraints. As illustrated in Table 4.25, the trajectory of the CLR strategy diverges from traditional reconstruction models by prioritizing operational continuity over structural perfection. Specifically, following the initial stabilization in Year 1, the strategy accounts for the rapid deterioration trends identified in the condition analysis, which predict that pavements in a fair state are prone to deteriorate below the critical safety threshold rapidly. To counteract this, the strategy adopts a cyclical reinvestment every three years (2026, 2029, and 2032), injecting the same capital amount to arrest this decline and rigorously maintain the pavement within the safety zone.

Table 4.25 Prioritizing operational continuity by CLR M&R strategy implementation

Year	Condition before intervention (PCI)	Condition after intervention (PCI)	Required budget	Operational Status
2026	**39.7 (Critical)**	**52 (Fair)**	**$4.6 Million**	**Safety Restored**
2027	48	48	$0	Operational
2028	44	44	$0	Operational
2029	**38 (Critical)**	**50 (Fair)**	**$4.6 Million**	**Cycle 1 Intervention**
2030	46	46	$0	Operational
2031	42	42	$0	Operational
2032	**38 (Critical)**	**48 (Fair)**	**$4.6 Million**	**Cycle 2 Intervention**
2033	44	44	$0	Operational
2034	40	40	$0	Operational
2035	36	36	$0	Operational
2036	32	32	$0	End of Period (Operational) Major M&R implementation
Total (10 years)			**$13.8 Million**	

The strategy mandates a targeted initial capital injection of $4.6 million within the first three years. This investment is strictly allocated to stopgap maintenance (localized safety repairs) to address high-severity distresses that pose immediate Foreign Object Debris (FOD) risks to aircraft engines and tires. This surgical approach effectively raises the weighted average PCI from a critical 39.7 to a stable operational zone of 50 to 55, as shown in Figure 4.41.

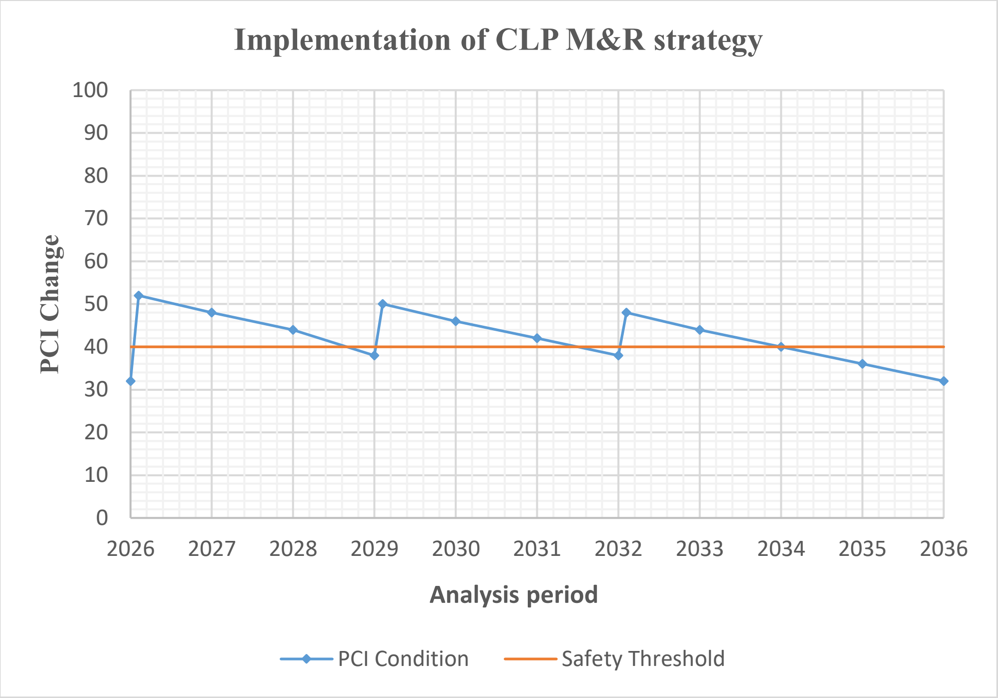


Figure 4.41 Implementation of CLR M&R strategy

By maintaining the pavement in a fair but safe condition, the administration avoids the massive capital outlay of full reconstruction. This stabilization secures a decade of uninterrupted flight operations, protecting the airport's revenue stream. Crucially, this period functions as a financial bridge; the deferral of major works allows the administration to mobilize funds gradually through operational profits.

By the end of the 10-year analysis period, the total cumulative expenditure reaches $13.8 Million, approximately 50% of the cost of immediate reconstruction. By this stage, the airport will have successfully secured ten years of operation, allowing for the strategic accumulation of reserves to fund the inevitable Major M&R projects required post-2036, without having jeopardized safety.

4.5.6 Adopted M&R Strategy for Restoration of KIA Pavement Network

Based on the comparative analysis of technical performance and financial feasibility, this study adopts the Consequence of Local Repair (CLR) maintenance strategy as the optimal restoration framework for the Kigali International Airport (KIA) pavement network. The CLR strategy offers a practical safety-first alternative, securing operational certification for an initial investment of just $4.6 Million (approximately 17% of the reconstruction cost) by prioritizing targeted stopgap interventions to eliminate high-severity distresses and stabilize the network within the operational safety zone (PCI > 40). This approach not only aligns with the fiscal realities of Rwanda but also serves as a scalable model for other developing nations, demonstrating that operational continuity can be sustained through phased capitalization rather than unaffordable total reconstruction.

The adoption of the Consequence of Local Repair (CLR) strategy for Kigali International Airport is directly validated by the 2022 Florida Department of Transportation (FDOT) District 2 Airfield Pavement Evaluation Report. Adhering to FAA Advisory Circulars 150/5380-6C and 7B, the FDOT report validates the rejection of Unlimited models and confirms the technical validity of the CLR approach through three critical dimensions:

- **Infeasibility of unlimited models**: The FDOT report explicitly classifies unconstrained budget scenarios as financially impractical due to the year 1 spike phenomenon, where all major rehabilitation needs are front-loaded into the first planning year. This industry observation validates the rejection of the KIA Unlimited Budget scenario, where 99% of the $26.8 Million requirement appeared immediately in 2026, rendering it unimplementable for a developing economy.
- **Validity of stopgap as an operational protocol**: The FDOT defines localized stopgap maintenance as a formal protocol required to keep a pavement in a safe and operational condition. This definition elevates the CLR strategy from a minimum-repair approach to a recognized safety and operational preservation standard for managing high-severity distress without full reconstruction.

- **Economic efficiency**: The FDOT data confirms that localized safety maintenance provides extreme value for money, representing less than 5% of the cost of major rehabilitation ($8.7M vs. $271M in District 2). This supports the KIA findings, where the CLR strategy achieves operational safety at roughly 17% of the cost of full reconstruction ($4.6M vs. $26.8M), representing a highly efficient use of scarce capital.

The proposed Consequence of Local Repair (CLR) maintenance strategy for Kigali International Airport (KIA) is strongly supported by Synovec's (2020) findings, which examine U.S. Air Force airfield pavements and address the exact dilemma facing KIA: how to manage a deteriorating portfolio under severe fiscal constraints without compromising operational capability. Synovec's dissertation validates the CLR approach through three key arguments:

The single-runway constraint necessitates safety interventions. Synovec (2020) highlights a critical limitation in traditional preventive maintenance models for single-runway airfields, arguing that the failure to address failing sections without compromising continuity of operations is a significant issue. He claims that, unlike multi-runway airports, where closure is an option, single-runway assets impose a hard constraint that forces investment into failing pavements to prevent total airfield shutdown. This directly validates the CLR strategy for KIA, confirming that for a single-runway asset with critical pavement conditions (PCI 39.7), mandatory safety interventions are required.

Rejection of worst-first maintenance models: Synovec (2020) explicitly advises against worst-first maintenance strategies, warning that directing limited resources toward immediate reconstruction is inefficient and traps organizations in a glide slope of long-term infrastructure degradation. The CLR strategy aligns with this finding by rejecting the capital-intensive reconstruction model (Cluster 1) in favor of distributed safety investments, thereby prioritizing network-wide resource efficiency over isolated structural perfection.

Targeting durability distress to prevent structural failure: Synovec (2020) provides technical validation for the CLR strategy by establishing that the majority of airfield distresses are climate and durability-related, which only evolve into structural failures when maintenance is deferred. This finding underpins the CLR approach of prioritizing targeted interventions (\$4.6M) to address these surface defects early, thereby preventing their propagation into deep structural failures that would necessitate a \$26.8 million reconstruction.

4.6 Inflation Sensitivity Analysis of M&R Strategy Costs

The financial results discussed earlier are reported assuming 0% inflation, using the default unit costs embedded in FAA PAVEAIR. However, over a 10-year planning horizon, cost escalation is unavoidable and can significantly affect the affordability and feasibility of maintenance and rehabilitation (M&R) strategies, particularly in developing economies, where inflation can be more volatile. To test the effectiveness of the recommended Consequence of Local Repair (CLR) strategy under realistic economic conditions, an inflation-based sensitivity analysis was performed. Three annual inflation scenarios were considered as shown in Figure 4.42 referring to current 2026 International Monitory Fund (IMF) publication: USA (2.2%), reflecting the cost environment underlying FAA PAVEAIR's default unit prices; Rwanda (4.1%), representing the context of the Kigali International Airport (KIA) case study; and Nigeria (18%) as a high-inflation developing-country scenario to illustrate the potential upper bound of inflation impacts on long-term M&R budgeting. The future value (FV) of the required M&R budgets was then computed using the following compound inflation escalation model:

$$FV = PV(1+i)^n \qquad (4.2)$$

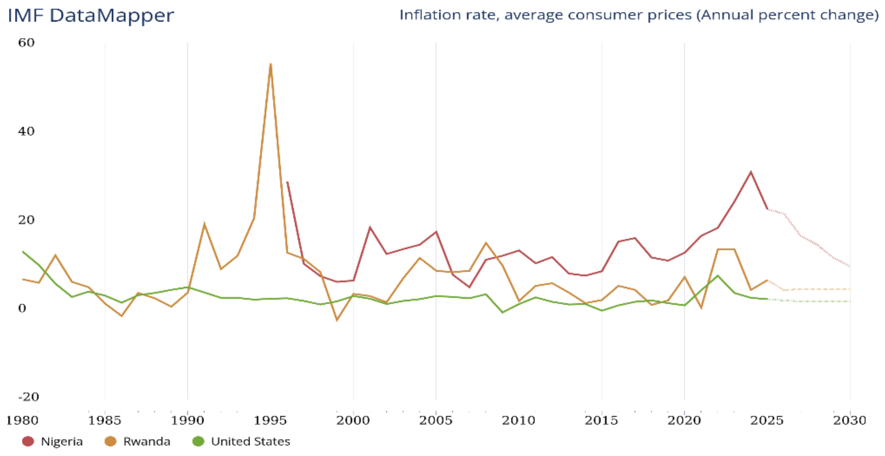
Where:

FV: Future value

PV: Present/base cost in 2026 dollars (FAA PAVEAIR unit-cost basis)

i: Annual inflation rate

n: Number of years from base year



©IMF, 2025, Source: World Economic Outlook (October 2025)

Figure 4.42 International Monetary Fund (IMF) 2026 annual inflation rate for the USA, Rwanda, and Nigeria

In this sensitivity analysis, inflation is applied only to the years in which expenditures occur. Because the Unlimited Budget and Minimum Condition M&R strategies require full funding in 2026, these approaches are characterized by a front-loaded capital investment, with approximately \$26.8 million fully consumed in the first year (Year 0) to achieve immediate network restoration. Mathematically, this insensitivity to inflation is verified by the Future Value (FV), Equation (4.2). Since the entire budget is executed immediately at the start of the analysis period, the time variable (n) is equal to zero. Consequently, the inflation multiplier $(1+i)^0 = 1$ becomes unity, resulting in FV = PV. This means the Future Value of the expenditure is identical to the Present Value, regardless of whether the inflation rate (i) is 2.2% (USA), 18% (Nigeria), or 4.1 (Rwanda).

In contrast to the front-loaded expenditure models, the Consequence of Local Repair strategy, the initial capital expenditure scheduled for Year 1 (2026) was treated as a present-day obligation; therefore, no inflation factor was applied to this specific outlay, preserving its base value across all scenarios. Instead, the analysis exclusively applied compounded inflation rates to the deferred intervention cycles scheduled for Year 3 (2029) and Year 6 (2032). By projecting these specific future liabilities under the three defined economic scenarios (USA, Rwanda, and Nigeria), the study quantified the total fiscal variance, measuring exactly how much the operational cost deviates from the original, non-inflated PAVEAIR base budget due to economic volatility, as illustrated in Table 4.26.

Table 4.26 Inflation sensitivity analysis for CLR strategy implementation (Cost in USD Million)

Inflation Sensitivity Analysis for CLR Strategy Implementation (Cost in USD Million)				
Intervention Cycle	**Base Cost (2026 Value)**	**Scenario A: USA (2.2%)**	**Scenario B: Rwanda (4.1%)**	**Scenario C: Nigeria (18.0%)**
Cycle 1 (2026) Initial year	$4.63	$4.63	$4.63	$4.63
Cycle 2 (2029)	$4.63	$4.94	$5.22	$7.61
Cycle 3 (2032)	$4.63	$5.28	$5.89	$12.50
TOTAL 10-Year Cost	**$13.89**	**$14.85**	**$15.75**	**$24.74**
Variance from Baseline	–	6.9%	13.4%	78.1%

The sensitivity analysis quantifies the financial risks associated with the phased expenditure model of the Consequence of Local Repair (CLR) strategy. As detailed in the results, the impact of inflation varies significantly across the three economic scenarios:

Scenario A (USA 2.2% inflation): Under stable economic conditions, the CLR strategy shows high fiscal resilience. The total 10-year nominal cost increases marginally from the $13.89 million base to $14.85 million. This 6.9% variance represents a negligible budgetary impact, confirming that in stable economies, the cost of deferring maintenance is minimal.

Scenario B (Rwanda 4.1% inflation): In the specific context of Kigali International Airport, the strategy remains fiscally sound. The total cost rises to $15.75 million, representing a 13.4% variance from the base estimate. While this requires an additional of $1.86 million in nominal appropriation over the decade, it remains well within manageable limits for national infrastructure planning.

Scenario C (Nigeria 18.0% inflation): The high-volatility scenario exposes the strategy's primary vulnerability. The compounding effect of 18% annual inflation drives the cost of the final intervention cycle (2032) to $12.50 million, nearly tripling its base value. Consequently, the total 10-year cost surges to $24.74 million, a substantial 78.1% variance.

The inflation sensitivity analysis shows that cost escalation is driven mainly by when expenditures occur. Because the CLR strategy defers major interventions to later years, its nominal 10-year cost increases with inflation as demonstrated moderately under the USA rate (+6.9%) and Rwanda rate (+13.4%), but sharply under a high-inflation developing-country stress case (+78.1%). In contrast, Unlimited Budget and Minimum Condition are effectively inflation-insensitive under the study assumption that the required capital is expended in the base year (2026). Overall, the comparison confirms that CLR remains the most financially feasible option, but its implementation in high-inflation contexts requires contingency provisions to prevent underfunding of later intervention cycles.

4.7 Development of M&R Framework for KIA Pavement

The conclusion of this study is the development of a comprehensive maintenance and rehabilitation (M&R) framework tailored to Kigali International Airport and adaptable to other developing countries worldwide. As discussed in the literature, many airports in the region currently operate under a reactive maintenance model, addressing pavement distress only after structural failure has occurred. This is primarily due to a lack of historical maintenance data and budget constraints, which force airport authorities to experience the maximum possible cost of major rehabilitation while risking operational safety. The proposed framework establishes a systematic, data-driven cycle to transition the airport from a high-cost, reactive state to a cost-effective, preventive management culture.

The developed framework, Figure 4.43, aims to optimize limited resources, enhance operational safety, and contribute to the region’s broader economic stability. To achieve this transition, the proposed framework is organized into five chronological and interdependent phases that mirror the methodology of this research:

- Network inventory and database establishment
- Condition assessment and evaluation
- Multi-scenario M&R simulation
- M&R scenario comparative analysis and strategy selection
- Implementation of preventive maintenance

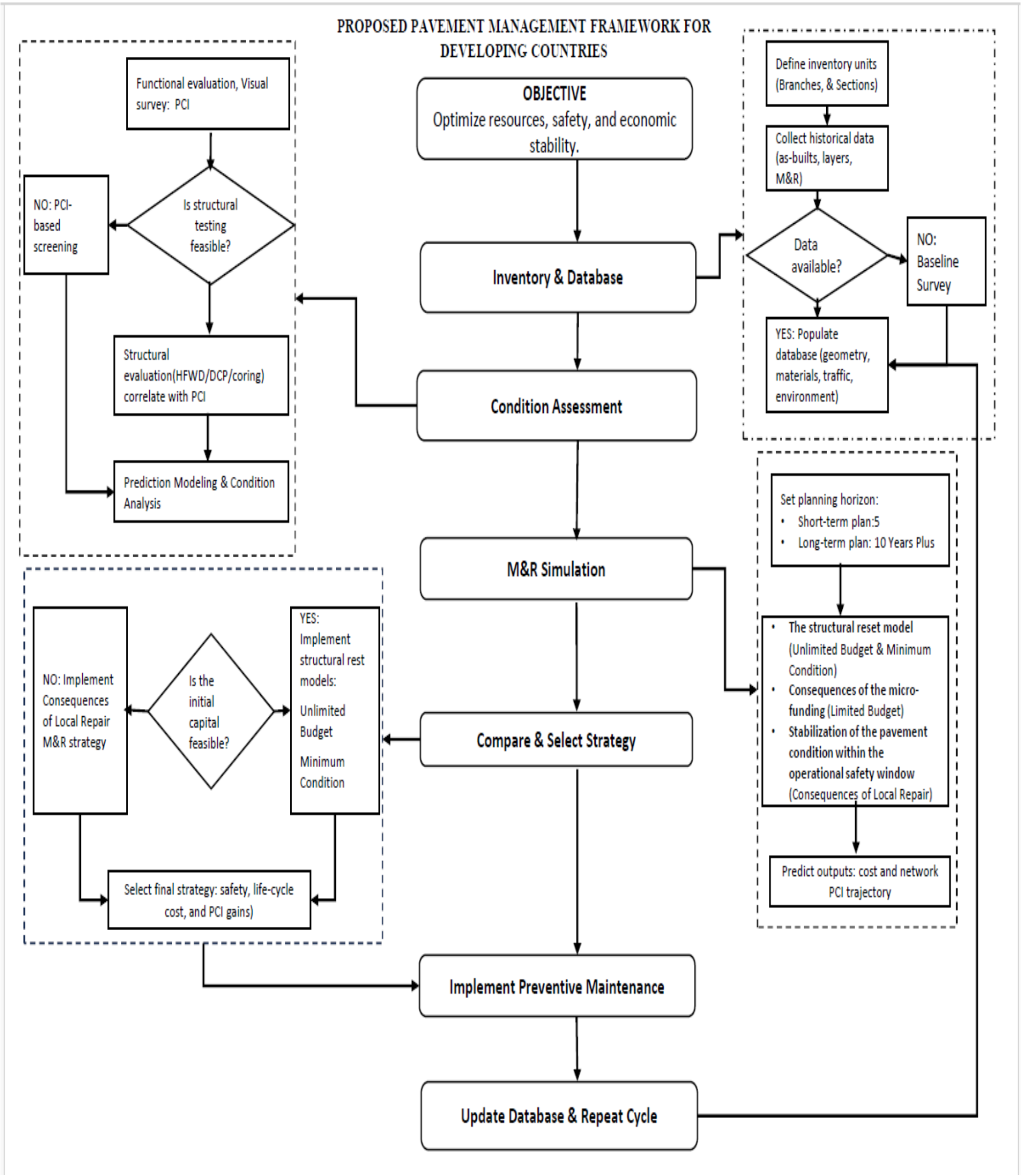


Figure 4.43 Developed Maintenance Framework for Kigali International Airport

4.7.1 Pavement Inventory and Database Establishment

The process begins with structuring the airport network and defining distinct inventory units, such as branches and sections. This is achieved by the collection of historical data, including as-built records, pavement layer thicknesses, and previous M&R activities. Recognizing that many developing countries' airports lack these archives, the framework includes a data-availability logic check; if historical records are absent, a mandatory baseline survey is triggered to populate the database with essential geometry, materials, and environmental data. This ensures the management system is built on accurate, verified inputs rather than assumptions.

4.7.2 Condition Assessment and Evaluation

This phase focuses on acquiring current performance data through an evaluation process. Functional evaluation via visual surveys to calculate the Pavement Condition Index (PCI) is recommended as the primary screening metric. The framework also includes a decision node to assess the feasibility of structural testing; when resources allow, structural evaluations using HFWD, DCP, or coring are conducted to correlate surface distress with load-bearing capacity. These functional and structural data are used to generate predictive models that establish deterioration curves to forecast future pavement performance.

4.7.3 Multi-Scenario M&R Simulation

The Multi-Scenario M&R Simulation phase serves as the analytical core of the framework, where the network's future performance is modeled under distinct management strategies. Using the data from the condition assessment, this stage projects the long-term evolution of the Pavement Condition Index (PCI) and associated Life-Cycle Costs (LCC) for varying intervention levels. The simulation includes structural reset models (such as Unlimited Budget and Minimum Condition), which aim for complete restoration, against stabilization models (such as Consequences of Local Repair), which focus on maintaining operational safety under financial constraints. These simulations generate the quantitative cost and performance trajectories necessary to determine which strategy is financially feasible in the subsequent comparative analysis.

4.7.4 Comparative Analysis and Maintenance Strategy Selection

In this phase, the selection of the optimal M&R strategy is strictly governed by the feasibility of the initial capital investment. The framework evaluates the financial capacity to execute major interventions versus the need for stabilization. The decision process follows two distinct paths:

Feasible initial capital (The structural reset model): If the necessary upfront capital is available (YES path), the framework prioritizes a structural reset by implementing capital-intensive models, such as the Unlimited Budget or Minimum Condition strategies. The goal is to fully restore the structural integrity of the pavement network, effectively resetting the Condition Index (PCI) to 100.

Infeasible initial capital (The stabilization model): If the initial capital is not feasible (NO path), the framework shifts to a stabilization strategy of Consequences of Local Repair, instead of seeking immediate perfection or full reconstruction, this approach aims to maintain the pavement condition within a manageable operational safety window.

Final Selection, regardless of the path taken, the final strategy is validated by comparing the outcomes based on three key metrics: Operational safety, Life-Cycle cost, and PCI gains.

4.7.5 Implementation of Maintenance Strategy and Monitoring

The final phase operationalizes the selected strategy, moving from analysis to execution of the M&R work plan and restoring pavement condition to a desirable serviceability level. This is followed by implementing preventive maintenance, which involves applying cost-effective treatments at the right time to sustain the restored pavement condition. The framework is designed as a closed-loop system to enable continuous monitoring through inspections. Following implementation, the database is updated with the new condition data.

CHAPTER 5

CONCLUSION

The implementation of effective Maintenance and Rehabilitation (M&R) strategies is paramount to airport infrastructure management, as these interventions directly safeguard operational safety and ensure the reliable serviceability of pavement networks. A well-defined strategy provides a basis for allocating limited funds to the highest-risk sections and timing interventions before deterioration escalates into costly emergency repairs or operational disruptions. For resource-constrained airports, strategic M&R planning is therefore both a safety requirement and a life-cycle cost control mechanism.This study applied FAA PAVEAIR to assess the functional condition of the Kigali International Airport (KIA) pavement network and to compare alternative Maintenance and Rehabilitation (M&R) strategies over a 10-year planning horizon, supported by structural adequacy checks for critical sections using FAARFIELD. The pavement condition assessment and simulations indicate that the network has deteriorated with a weighted average Pavement Condition Index (PCI) of 39.7, to the level where preventive preservation alone is insufficient and targeted rehabilitation is required to maintain operational safety and serviceability. Among the evaluated strategies, the Unlimited Budget and Minimum Condition scenarios can comprehensively restore the network; however, they require an initial capital expenditure of approximately \$26.8 million, which is not financially feasible under the airport's resource constraints. In contrast, the Limited Budget approach (\$1 million per year) is insufficient to address safety-critical needs and allows sections to deteriorate below the adopted critical condition threshold. Based on comparative performance and cost metrics, the Consequence of Local Repair (CLR) strategy is recommended as the most feasible safety-to-cost option for KIA. By prioritizing safety and stabilizing network condition within the operational PCI range of 40-55, CLR maintains operational continuity with a total 10-year investment of

$13,897,974, approximately 50% of the funding magnitude associated with full-network restoration approaches. Overall, the study proposes a practical, KIA-specific M&R framework that supports a transition from reactive, worst-first repairs to a proactive, performance-based, and safety-focused management approach. With appropriate local calibration of condition thresholds, costs, and operational constraints, the framework can inform decision-making for other resource-constrained airports in similar environments.

5.1 Major Findings

FAA PAVEAIR was successfully applied to develop the KIA pavement inventory and perform condition analysis and M&R scenario simulations. The PCI outputs generated within PAVEAIR were cross-checked against the 2024 inspection report results produced in MicroPAVER and found to be consistent. In addition, FAA documentation confirms that PAVEAIR is a web-based system and is available free to the public, which strengthens its practicality for resource-constrained airport authorities.

The condition analysis quantified a critically deteriorated network condition, with a network-weighted average PCI of 39.7 for the baseline inspection year (2024). This indicates that a substantial portion of the network is below typical preventive-maintenance thresholds, implying that rehabilitation and safety-driven corrective actions are required in the near term rather than routine preservation alone.

FAARFIELD identified a structural capacity shortfall relative to the current aircraft traffic demand. Except for Apron Bravo and Apron Charlie, the assessed sections generally require increased structural capacity rather than surface-focused treatments only. This finding supports the conclusion that the observed distress patterns reflect not only surface aging but also load-related structural deficiency.

The developed performance prediction models indicate that, without timely and adequate interventions, pavement condition will continue to decline over the 10-year planning horizon, increasing the likelihood of sections falling below the adopted critical/safety thresholds and expanding the rehabilitation backlog.

The 10-year analysis period of four different M&R strategies revealed three outcome categories:

- **Full restoration strategies** (Unlimited Budget and Minimum Condition), which provide the strongest technical recovery but require financially unrealistic upfront capital.
- **Underfunded strategy** (Limited Budget), which is insufficient to address safety-critical needs in time and leads to continued decline and deferred high-risk repairs.
- **Phased, safety-driven rehabilitation strategy** (Consequence of Local Repair-CLR), which prioritizes immediate safety needs while enabling staged recovery and resource mobilization. Overall, CLR demonstrated the most feasible safety-to-cost and performance trade-off for KIA under constrained funding.

The study produced a KIA-specific M&R framework that operationalizes the transition from reactive, worst-first maintenance to data-driven decision-making. With local calibration of thresholds, costs, and traffic assumptions, the framework is adaptable for other resource-constrained airports in similar contexts.

5.2 Significance and Contribution

The primary contribution of this study to the Kigali International Airport (KIA) is the demonstration of a feasible transition pathway from reactive, worst-first repairs to a safety-driven and preventive preservation culture that improves operational safety while remaining financially realistic. The analysis shows that a full-network restoration approach, although technically effective, is not implementable under current resource constraints because it requires an unaffordable upfront capital outlay of approximately \$26.8 million. In response, the study recommends the Consequence of Local Repair (CLR) strategy as the most feasible safety-to-cost alternative. CLR requires a substantially lower initial investment of approximately \$4.63 million, enabling the airport to prioritize safety-critical sections and high-severity distress while maintaining serviceability without immediate full reconstruction. Over the 10-year planning horizon, CLR supports staged recovery through a phased funding approach totaling approximately \$13.9 million, allowing gradual resource mobilization while stabilizing the network within acceptable operational condition levels.

Beyond Rwanda, this research contributes a practical approach for airport pavement management in resource and data-constrained environments common in developing countries. First, it proposes a zero-based baseline condition and inventory survey as a structured starting point for airports lacking reliable historical performance records, enabling the creation of a functional pavement management database for planning and prioritization. Second, the study demonstrates the practical applicability of FAA PAVEAIR for network-level condition analysis and scenario-based M&R planning and shows consistency of its PCI outputs with results obtained from MicroPAVER in the available inspection dataset. Because PAVEAIR is web-based and publicly accessible, its adoption can reduce dependence on costly proprietary software and lower a key barrier to modern pavement management implementation. Collectively, these contributions support the broader digital transformation of pavement asset management and provide a transferable framework for African airports seeking to implement data-driven, safety-focused M&R planning under constrained budgets.

5.3 Limitations of The Study

This section presents the key limitations of the study that may influence the interpretation and accuracy of the results. These constraints arise primarily listed as follows.

The analysis relied on condition data extracted from the 2024 pavement inspection report. Due to time and resource constraints, independent on-site verification of distress identification, severity classification, and sampling procedures could not be conducted. Accordingly, the accuracy of the reported Pavement Condition Index (PCI) and subsequent analyses is contingent on the quality and consistency of the original inspection process.

Historical information on pavement construction details, materials, past maintenance actions, and locally measured unit costs was incomplete or unavailable. As a result, cost estimates for the evaluated M&R scenarios were derived primarily from FAA PAVEAIR default unit costs rather than locally calibrated rates. While this approach supports relative comparison among strategies, it may reduce the accuracy of absolute budget estimates for implementation.

This study utilized current air traffic mix and frequency data but did not incorporate the annual growth rate. The analysis, therefore, assumes a static load profile for the entire 10-year horizon. This limitation means that the study does not account for the temporal acceleration of distress, where rising traffic volumes consume pavement fatigue life faster than predicted, potentially leading to an underestimation of future M&R costs.

FAA PAVEAIR applies simplified rehabilitation-performance assumptions, including treating major rehabilitation as restoring pavement condition to an idealized state (e.g., PCI resetting to 100). In practice, the achieved post-treatment condition depends on construction quality, traffic control, materials variability, and unresolved structural deficiencies. Therefore, simulated post-rehabilitation performance may be optimistic relative to real-world outcomes.

The study relied primarily on PCI, which reflects functional condition based on visual distress and does not directly quantify other performance dimensions such as roughness (IRI), skid resistance, foreign object debris (FOD) risk, or detailed structural condition indices. Incorporating additional performance indicators and field measurements would strengthen prioritization and treatment selection, particularly for safety-critical decision-making.

There is a scarcity of published airport pavement management case studies and calibrated deterioration models for African airports and Sub-Saharan tropical environments. This constrained the ability to benchmark KIA performance trends and model assumptions against regional peers, increasing reliance on international references that may not fully capture local environmental and operational conditions.

5.4 Future Work

Based on the findings and limitations of this study, the following areas are recommended for future research:

- Future research should move beyond reliance on the single visual Pavement Condition Index (PCI). The following studies should integrate additional indices to correlate structural and functional metrics, enabling more precise M&R decisions that address subsurface failures before they become surface distress.
- Future research should also focus on implementing the proposed M&R framework in Rwanda and other African nations with pavement conditions and maintenance challenges similar to those in Rwanda. Because many regional airports face identical constraints, including data scarcity and reactive maintenance backlogs due to financial constraints, testing the framework's adaptability in these environments would be valuable.
- To improve the accuracy of financial forecasting, a dedicated study should be conducted to establish standardized unit-cost data for airport pavement works in Rwanda. This research should compile historical contract data and current market rates for specific M&R activities to replace general estimates.

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